Communication from Public

Name:	Travis Longcore
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Comments for Public Posting:	Please see attached letter from Los Angeles Audubon Society.

Los Angeles Audubon Society
P.O. Box 411301
Los Angeles, California 90041-8301

Via email (tcn@metro.net)

October 24, 2022

Shine Ling, Development Review Team
One Gateway Plaza, Mail Stop 22-9
Los Angeles, California 90012

Re: Transportation Communications Network Draft Environmental Impact Report

Dear Ms. Ling:

The Draft Environmental Impact Report (DEIR) for the Transportation Communications Network (TCN) acknowledges that the facilities would be constructed in locations that would impact sensitive species, including federally and state listed endangered species, and sensitive bat species (see Biological Resources Technical Report, All Vision LLC, August 2022). The analysis of biological impacts does not include a description of or even an attempt to quantify the effects of light pollution on these sensitive species.

The environmental impacts of light pollution on sensitive species are well-documented. See attached reports and papers for an introduction to these issues.

The lighting study for the DEIR only addresses impacts to humans, not to sensitive wildlife. Notwithstanding existing light pollution, its impacts on wildlife are cumulative and must be evaluated under CEQA. Therefore, the DEIR must be revised and recirculated so that the impacts to sensitive wildlife are evaluated, and the U.S. Fish and Wildlife Service must be consulted because of the potential adverse impacts to species listed under the U.S. Endangered Species Act at the Ballona Wetlands Ecological Reserve.

Sincerely,

Travis Longcore, Ph.D.
President

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Review of Biological Impacts Analysis in Mitigated Negative Declaration for State Route 78 Digital Sign, City of Oceanside, California

June 22, 2015

Travis Longcore, Ph.D.

1 Introduction

This report addresses the analysis of biological impacts from a proposed digital billboard in the City of Oceanside, California. As an expert on the effects of artificial night lighting on wildlife and ecosystems and in environmental impact analysis, I have been asked for technical comments on this particular aspect of the project by the firm DeLano & DeLano. I have reviewed the following documents:

- U.S. Fish and Wildlife Service, Comments on the Draft Mitigated Negative Declaration for the State Route 78 Digital Sign, City of Oceanside, California (SCH #2014111075);
- Response to USFWS Comments in Final Mitigated Negative Declaration;
- Mitigation Measures in Final Mitigated Negative Declaration for the State Route 78 Digital Sign, City of Oceanside, California;
- Letter report on “State Route 78 Sign” from John Muse and Associates, Inc.;
- Night Lighting Study in Coastal California Gnatcatcher Occupied Habitat, State Route 78 Digital Sign Project Located in the City of Oceanside, California.

The analysis of the impacts of artificial night lighting from the proposed sign on biological resources contains many errors of fact and relies on evidence, specifically the “Night Lighting Study,” that is scientifically useless. The applicant’s own reports show that the sign will cause nightly illumination on the order of that caused by the full moon (>0.1 lux) over 1,000 feet away from the sign site. This level of illumination is biologically relevant and should be considered a significant impact when experienced in sensitive natural communities or at sites where sensitive species will be found.

2 Factual Basis of Analysis Is Faulty

CEQA analysis should be based on facts and expert opinion based on facts, and should use the best available information at the time of the review. The Mitigated Negative Declaration (MND) and the response to comments in the MND fail in this regard.

2.1 Claim That Little Information Is Available About Effects on Songbirds Is False

In the response to the U.S. Fish and Wildlife Service (USFWS) comment letter, the preparers of the MND assert that "there was very little applicable information regarding night lighting effects on songbirds, including gnatcatcher for the proposed project. Nonetheless, the IS used the best available information at the time of preparation" (Response to Comments A-4).

It is factually incorrect that little information exists about the impacts of night lighting on songbirds. The research on the effects of ambient and artificial lighting on bird reproduction goes back to the 1920s (Rawson 1923, Rowan 1938). Birds can be extremely sensitive to illumination, and extension of foraging by species under artificial lights is documented in the literature (Goertz et al. 1980, Sick and Teixeira 1981, Frey 1993, Rohweder and Baverstock 1996). Established research also shows an earlier start to seasonal breeding of birds in urban (lighted) environments than rural (dark) environments (Havlin 1964, Lack 1965). Many of the physiological impacts of lighting on birds are conveniently reviewed by De Molenaar et al. (2006) and Longcore (2010). Further studies illustrate the growing knowledge on this topic that was available to the preparers of the MND, had they used a scientific indexing research tool to search for it:

- Dawn song in American Robins (*Turdus migratorius*) is influenced by ambient illumination (Miller 2006);
- Dawn song and lay date in a songbird have been shown to be associated with proximity to streetlights, with evidence that this affected mate choice, which has implications for fitness (Kempenaers et al. 2010);
- Light of 0.3 lux can move reproductive seasonality of songbirds by a month and cause irregular molt progression (Dominoni et al. 2013a, Dominoni et al. 2013b);
- Light is a major driver of the daily activity patterns of songbirds (study animal European Blackbird; *Turdus merula*), causing them to be active earlier in the morning (Dominoni et al. 2014);
- A songbird (Tree Sparrow; *Passer montanus*) exposed to 6 lux in the laboratory secreted luteinizing hormone earlier than controls, and urban birds exposed to 3–5 lux exhibited this pattern in the field; both of these response were statistically associated with night lighting (Zhang et al. 2014);
- Artificial light outside of nest boxes affects perceived photoperiod of Great Tits (*Parus major*), which the authors interpret as creating an ecological trap (Titulaer et al. 2012);
- Artificial light rather than traffic noise affects dawn and dusk song timing in common European songbirds (Da Silva et al. 2014).

Even more recent research, although not available to the preparers of the environmental review, must now be considered because it is available before a final decision is reached. These studies continue to support the proposition that lighting at levels associated with streetlights affects the daily and seasonal timing of song in songbirds and these parameters are tied to fitness (Da Silva et al. 2015).

Finally, the MND takes the narrow view that only impacts directly on birds themselves are relevant, failing to recognize that impacts to their prey items could also be significant. Many families of insects are attracted to lights, including moths, lacewings, beetles, bugs, flies, wasps, and bush crickets (Sustek 1999, Kolligs 2000, Eisenbeis 2006, Frank 2006, Pawson and Bader 2014, Poiani et al. 2014, Longcore et al. 2015). Such impacts are relevant both for the potential effects on the prey base and as a direct impact on a sensitive vegetation type that receives independent consideration under CEQA.

2.2 Assertion That Diurnal Species Are Not Affected by Lighting Is False

The response to the USFWS comment letter contains the following assertion (Response to Comments A-4):

> Gnatcatchers and most other passerine birds are active during the daylight not nighttime hours. As a result the sign illuminance would be non-substantial during bird activity periods and of little consequence to gnatcatcher activities.

Artificial night lighting affects diurnal species substantially. As noted above, it affects timing of dawn and dusk song, seasonality of reproduction, mate choices, and can extend activities of diurnal species into the night (Stracey et al. 2014). This is true for impacts across species, where diurnal species are affected in numerous ways by an altered nighttime environment (Miller 2006, Kempenaers et al. 2010, Titulaer et al. 2012, Dominoni et al. 2013a, Dominoni et al. 2013b, Da Silva et al. 2014, Dominoni et al. 2014, Zhang et al. 2014, Da Silva et al. 2015). Although California Gnatcatchers do not participate in a dawn chorus, they do vocalize from the early morning through the day (Preston et al. 1998). The interruption of circadian signals causes significant impacts on the physiology and behaviors of other species. There is no evidence to suggest that California Gnatcatchers would not be similarly affected.

2.3 Assertion That Illumination Less Than 2 Lux Does Not Differ From Background Is False

The “Night Lighting Study,” and the engineer’s study upon which it relies, sets an arbitrary standard of 2 lux below which the authors of both reports assume that the impacts of the proposed digital billboard are not significant. They base this assumption on a single passage in the engineer’s report, stating:

> Based on my measurements, the light from freeway vehicles would often be over of 0.2 footcandles (2.15 lux) at the line extending from the center of the proposed sign. Therefore, outside the 274 foot radius circle, the light from the sign would often be less than the lights from vehicles on SR78.

The engineer does not share any raw measurements of illumination from freeway lights. He also creates an equivalency between the potential impacts of intermittent lighting from vehicles and constant lighting (until midnight) from the proposed sign. The sign itself may increase and decrease in illumination as images change, but it will remain on constantly until midnight. Both the engineer and the biologists also ignore that the light from the two sources is cumulative and the increase in illumination from the sign will establish a minimum level below which illumination cannot fall during the operational period of the sign. They ignore that the illumination levels caused by the sign will increase greatly in foggy and cloudy conditions because of the scattering of light by particulates and reflection from clouds (Kyba et al. 2011). Finally, they ignore that the sign will be creating illumination levels that exceed that of the full moon (defined as 0.1 lux, by their own table, "Night Lighting Study," Table 3) by 20 times at 274 feet and would extend lighting equivalent to the full moon more than 1,000 feet from the sign (John Muse & Associates, State Route 78 Sign, Appendix; see Distance 9, 1,000 feet would create illumination of 0.16 lux).

Any time a natural environment is experiencing illumination greater than the full moon (>0.1 lux), or even greater than a quarter moon (0.01 lux), one can assume that species are being affected. This is the case because many species show lunar cycles in behavior, often driven by predator–prey relationships that can be interrupted by elevated illumination (Price et al. 1984, Daly et al. 1992, Upham and Hafner 2013). For example, light as dim as 0.01 lux can inhibit foraging by small rodent species (Kotler 1984).

The entire ensuing analysis of the effects of lighting from the sign that is limited to a 274-foot radius is therefore faulty. In truth, the sign will contribute, cumulatively, to ecological impacts on nocturnal ecology for well over 1,000 feet.

3 Study of Lighting at Gnatcatcher Habitats Is Not Useful for Assessing Impacts

The "Night Lighting Study" presented in support of the analysis of impacts of lighting from the proposed sign on California Gnatcatchers has a number of fatal flaws.

3.1 Study Design Is Flawed

The investigators measured illumination levels under lighting sources that were in the vicinity of California Gnatcatcher territories that had been occupied. Instead of measuring lighting levels throughout the territories, they concentrated on spots under illumination sources. This is not useful for understanding the relationship between territories being maintained and illumination levels because the measurements describe neither the nest site nor the territory as a whole. Perhaps the investigators thought this was acceptable because their light meter read "0 lux" once they were a certain distance from the lighting. This, however, is a fatal flaw in the equipment that they used, which apparently could not resolve illumination less than 1 lux (which is 10 times brighter than the full moon).

3.2 Equipment Unable to Measure Natural Lighting Levels at Night

The "Night Lighting Study" was undertaken with a piece of equipment that is identified as a "LuxMeter." No manufacturer is given, so it is difficult to determine what device this was. It is evident from the way in which the investigators describe the results, however, that the device had a resolution of 1 lux. The "Night Lighting Study" contains many statements that the illumination levels dropped to 0 lux and there are no reports of any measurements that have precision to 0.1 lux or 0.01 lux. The implication of measuring light with a device of this nature is that it is impossible to tell the difference between 10 times brighter than the full moon (1 lux), the full moon (0.1 lux), and 10 times dimmer than the full moon (0.01 lux, which is still important to species at night). That is, the equipment cannot measure light at illumination levels that matter to species. Humans have visual systems that are several times less sensitive than most other species (Gaston et al. 2012) and therefore equipment to measure light that is not specially designed for biological investigations is usually inappropriate.

3.3 Assumption That Lower Illumination in Foliage Eliminates Impacts Is Misguided

The authors of the "Night Lighting Study" make the assertion that because California Gnatcatchers roost in the foliage of shrubs, and by the authors' measurements (with equipment that could not measure illumination below 1 lux) the illumination in the shrubs is "0 lux," the additional light from the sign could not have an effect. Of course the illumination in the shrubs is not 0 lux, but rather some fraction of 1 lux, which the authors did not measure. The illumination in the foliage around light sources would be elevated; the "Night Lighting Study" just did not have the proper equipment to measure it. It is therefore impossible to conclude that the shade of the foliage would reduce impacts to a less than significant level.

3.4 All Measurements and Discussion Pertain to Clear Weather Conditions

Even if the measurements in the "Night Lighting Study" were to be of sufficient accuracy, they would not come close to describing the range of night lighting conditions that are experienced near illumination sources. Fog is extremely efficient at reflecting light and recent research has shown that foggy conditions result in a 6-fold increase in night sky brightness (a measure of light pollution) (Ściężor et al. 2012). Fog also scatters light down into habitats. Furthermore, clouds reflect light downward, so even if it were only cloudy (and not also foggy), the light reflected downward would be substantially greater than that under a clear sky (Kyba et al. 2011, Ściężor et al. 2012). These basic facts about the propagation of light in the atmosphere are not considered in the "Night Lighting Study"; the measurements of sites in that study are all under clear skies and the modeled illumination from the proposed sign is under clear sky conditions.

4 Sign Would Exceed Allowable Lumens for an Entire Acre in Pattern Outdoor Lighting Code

The Pattern Outdoor Lighting Code is designed to help jurisdiction wishing to reduce light pollution and its adverse impacts. The code sets limits per acre for the amount of outdoor lighting, measured in lumens. Depending on the zone (roughly corresponding to residential and commercial), the number of allowable lumens is either 50,000 per acre or 100,000 per acre (Pattern Outdoor Lighting Code, Standard ver. 2). By comparison, the proposed sign, a single structure, would emit 69,000 lumens, according to the engineer's report. That is, the proposed sign itself would emit more than the allowable number of lumens for an entire acre of a residential area under this model ordinance.

5 Author Qualifications

Dr. Travis Longcore is a principal of Land Protection Partners. He is Associate Professor (Research) at the USC Spatial Sciences Institute and formerly Associate Adjunct Professor at the UCLA Institute of the Environment and Sustainability. He has taught, among other courses, Bioresource Management, Environmental Impact Analysis, Field Ecology, and in the

Environmental Science Practicum. He was graduated *summa cum laude* from the University of Delaware with an Honors B.A. in Geography, holds an M.A. and a Ph.D. in Geography from UCLA, and is professionally certified as a Senior Ecologist by the Ecological Society of America. He is co-editor *Ecological Consequences of Artificial Night Lighting* (Island Press, 2006) has authored or co-authored over 30 scientific papers in top peer-reviewed journals such as *Conservation Biology*, *Biological Conservation*, *Current Biology*, *Environmental Management*, and *Frontiers in Ecology and the Environment*. Dr. Longcore is among the world's leading authorities on the effects of artificial night lighting on species and ecosystems. Land Protection Partners has provided scientific review of environmental compliance documents and analysis of complex environmental issues for local, regional, and national clients for 17 years.

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Journal of Coastal Research	00	0	000–000	Coconut Creek, Florida	Month 0000

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

www.cerf-jcr.org

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ABSTRACT

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Simons, A.L.; Martin, K.L.M., and Longcore, T., 0000. 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. *Journal of Coastal Research,* 00(0), 000–000. Coconut Creek (Florida), ISSN 0749-0208.

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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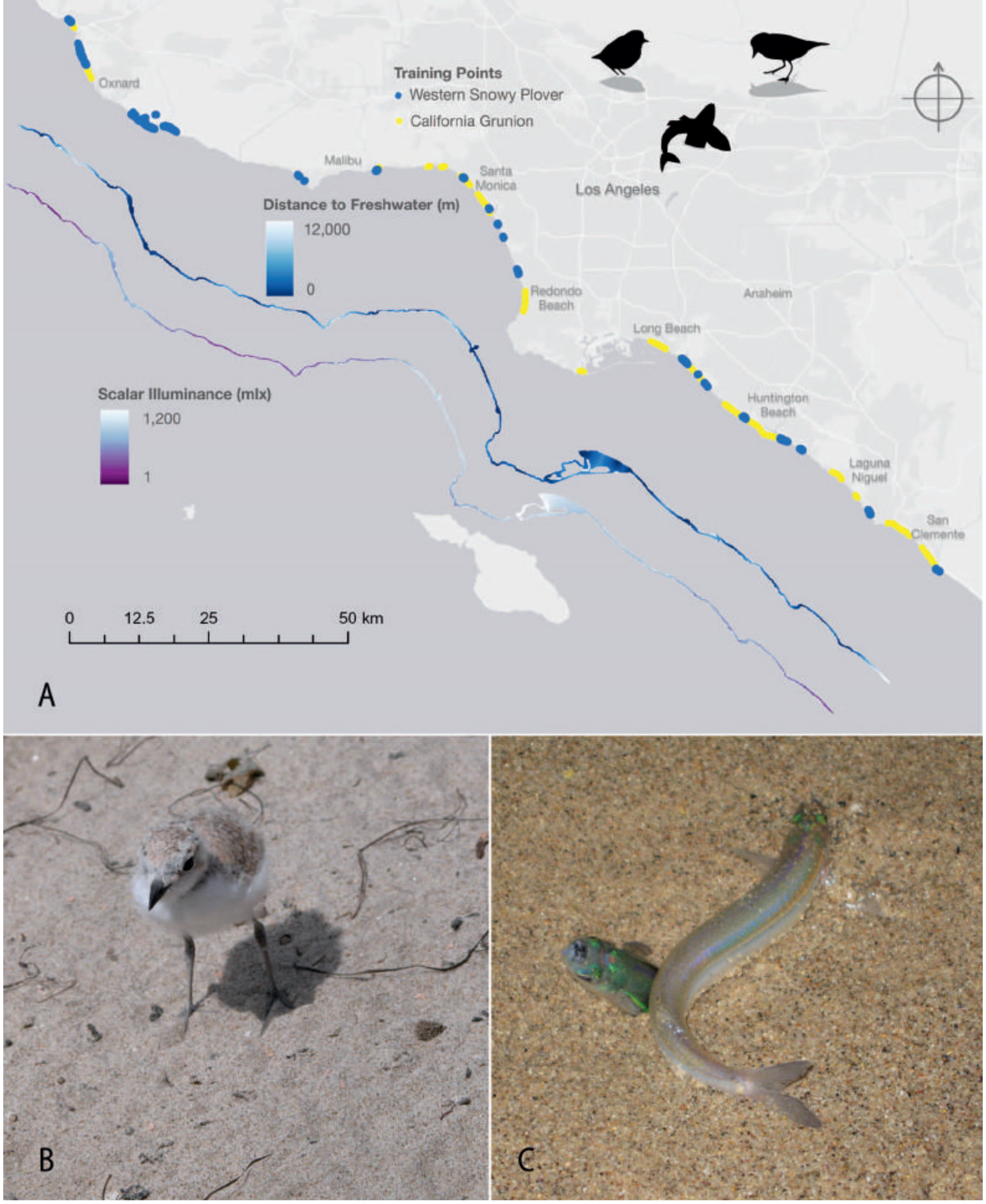

Figure 1. (A) Project area with species data. Distribution of training points for plover roosts and grunion run locations on sandy beaches in Los Angeles, Orange, and Ventura counties, California. Included are examples of environmental layers for hemispherical illuminance (mlx) and distance to freshwater (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

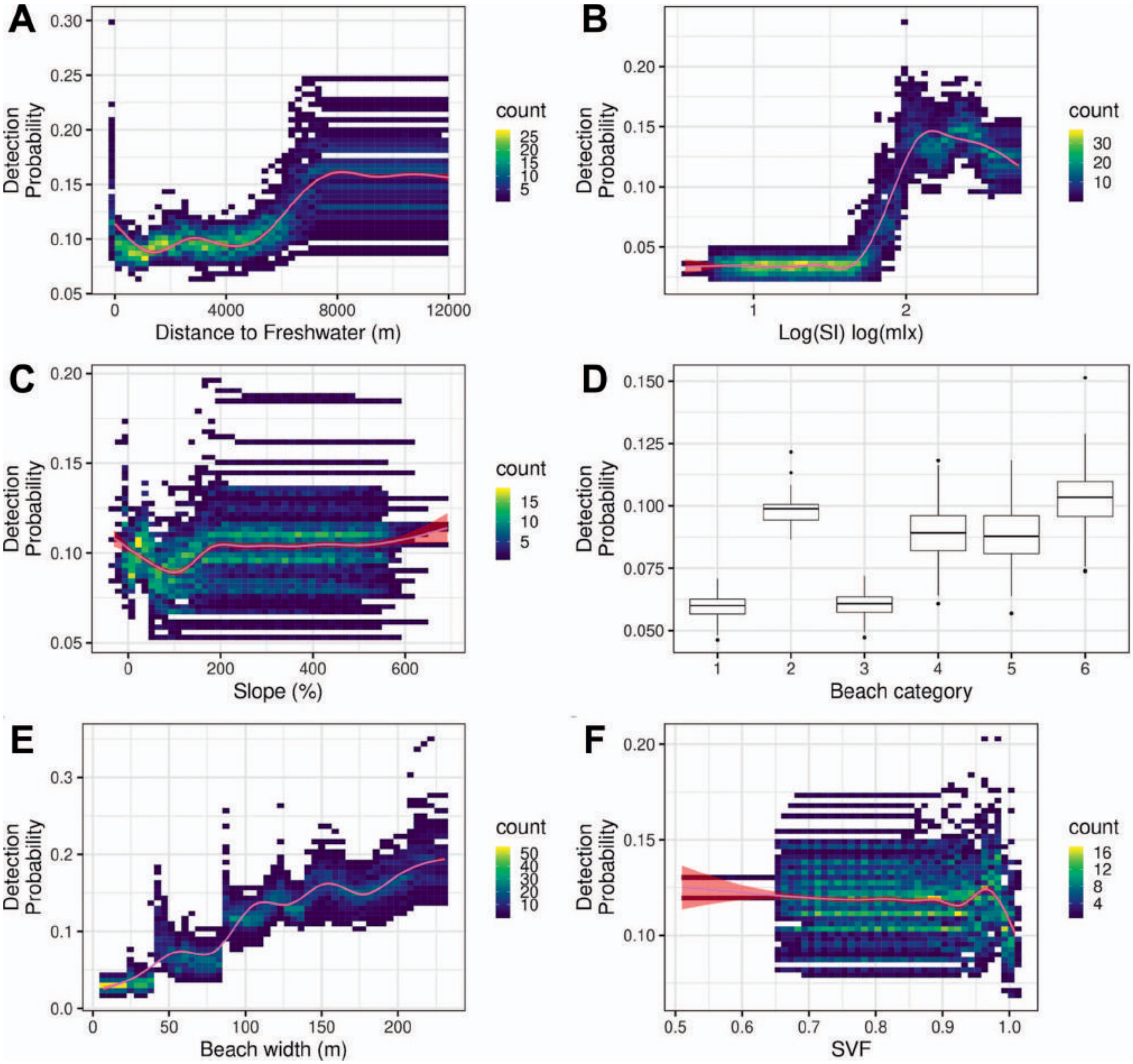

Figure 2. Partial dependence plots for grunion runs for environmental variables. Density of 100 partial dependence plots for random forest models of the likelihood of significant grunion runs for distance to freshwater (m), log-transformed scalar (hemispherical) illuminance (log[SI]; mlx), slope (%), 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

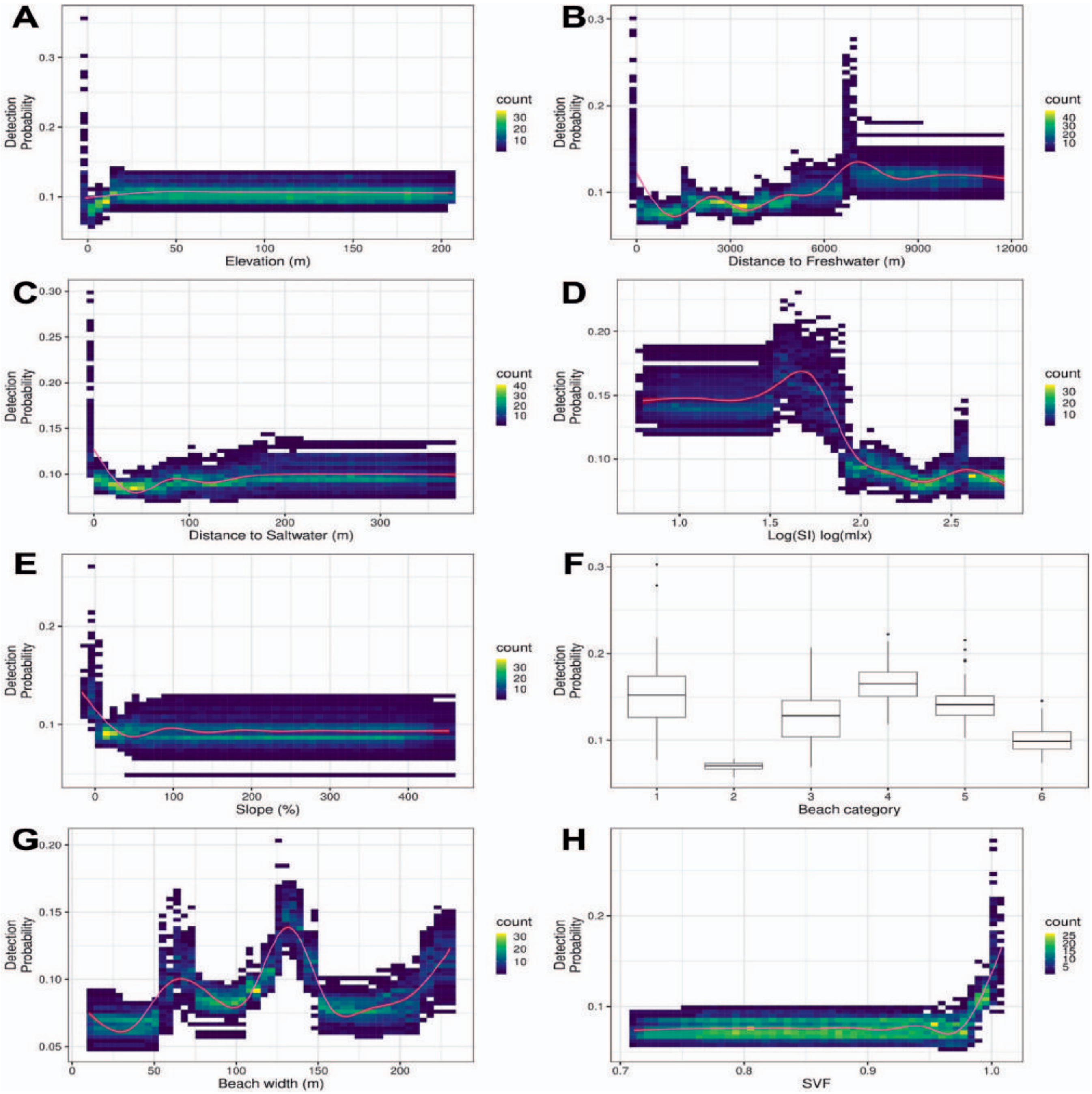

Figure 3. Partial dependence plots for plover roosts. Density of 100 partial dependence plots for random forest models of the likelihood of significant grunion runs for elevation, distance to freshwater (m), distance to saltwater (m), log-transformed scalar (hemispherical) illuminance (log[SI]; mlx), 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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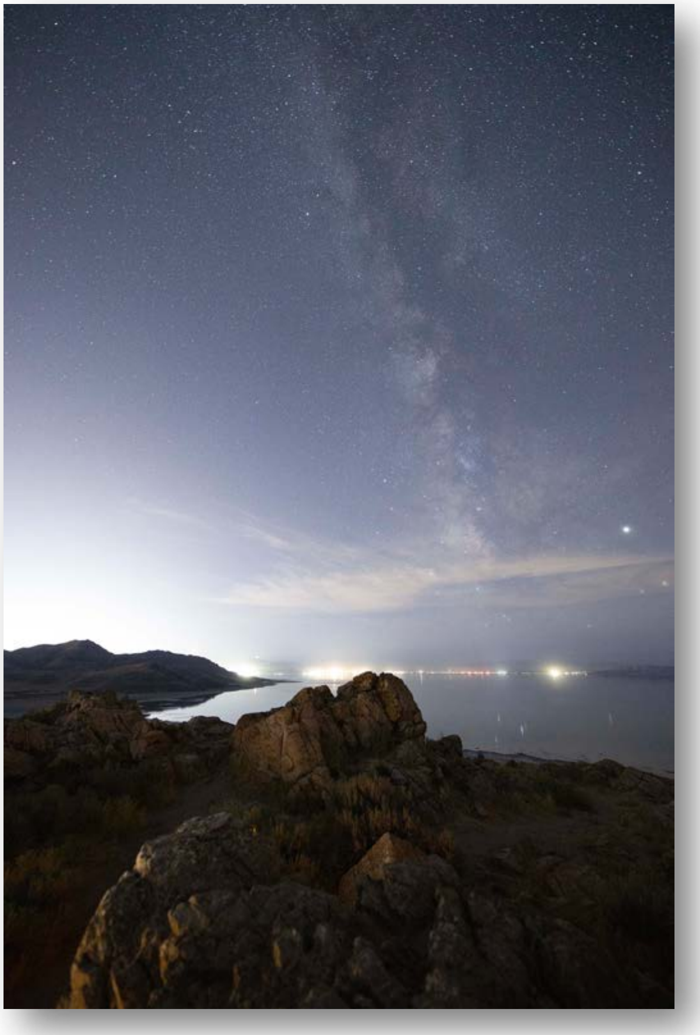
Salt Lake City Street Lighting Master Plan

Nocturnal Infrastructure for Ecological Health

Prepared by: Travis Longcore, Ph.D.
Prepared for: Clanton and Associates, Boulder, Colorado

May 2020



Lights of Salt Lake City wash out the Milky Way viewed from Antelope Island State Park. Photograph: Ryan Andreasen.

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1 Introduction

Salt Lake City is located in a region connected to its night sky. The awe and wonder inspired by a view of the Milky Way and sky overflowing with stars attracts visitors to Utah and contributes to the identity of the region for residents. Salt Lake City itself is brightly illuminated, with its cultural and institutional centers, commercial zones, and unique urban design. But just north of the city, Antelope Island State Park has sought and received recognition as a Dark Sky Park by the International Dark-Sky Association, joining eight other Dark Sky Parks, a Dark Sky Community, and a Dark Sky Heritage Place in Utah (Figure 1). The future of Antelope Island's long-term status as a Dark Sky Park depends on the decisions of the cities along the Wasatch Front in protecting the night sky (see cover).

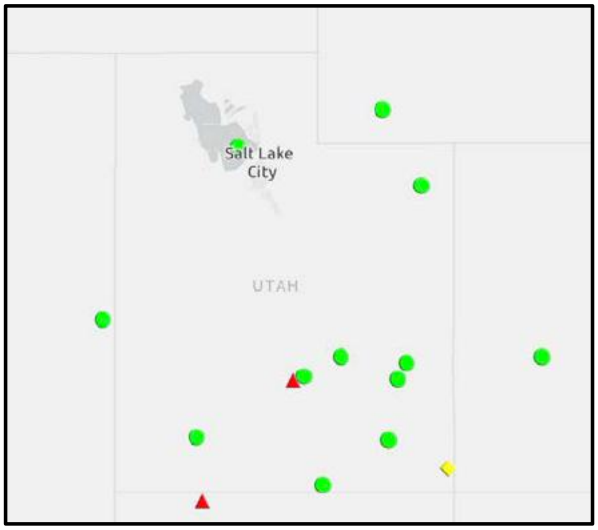


Figure 1. Distribution of recognized dark sky places in and near Utah. Circles are Dark Sky Parks, triangles are Dark Sky Communities, and diamonds are Dark Sky Heritage Sites. Source: List of Dark Sky Places maintained by Dark Skies Advisory Group, IUCN.

Cities set the tone for night lighting in a region. They are the most brightly lit, and their size influences the markets, practices, and professionals in a region. Commercial zones of cities and towns tend to contribute the most light escaping upward (and therefore wasted), along with lighted sports fields when they are illuminated (Luginbuhl et al. 2009). Historically, street lights contributed a significant and constant amount to both useful and wasted light through the night, while residential lights and lighting from vehicles declines substantially through course of the night (Bará et al. 2017). Within residential zones, most of the light is from the streetlighting system, especially later in the evening when traffic rates are low and ornamental lighting is switched off (Bará et al. 2017). Decisions made at municipal level about its street lighting system therefore have a large contribution to the overall amount of useful and wasted light in a city. Because perception of lighting is based on contrasts (the same light appears dim next to a brighter source and bright next to a dimmer source), the decisions made in terms of municipal street lighting systems have ramifications to the nocturnal environment that extend beyond the system itself. As a metropolitan area, compared with the 125 largest metropolitan areas in the United States, Salt Lake City is well above average in terms of the average amount of light escaping upward that can be measured by satellites (Figure 2). It does not waste as much light as other larger cities with their greater areas, but on a per area basis it contributes more to regional light pollution than the average city, although not so much as New Orleans, which is a similar size.

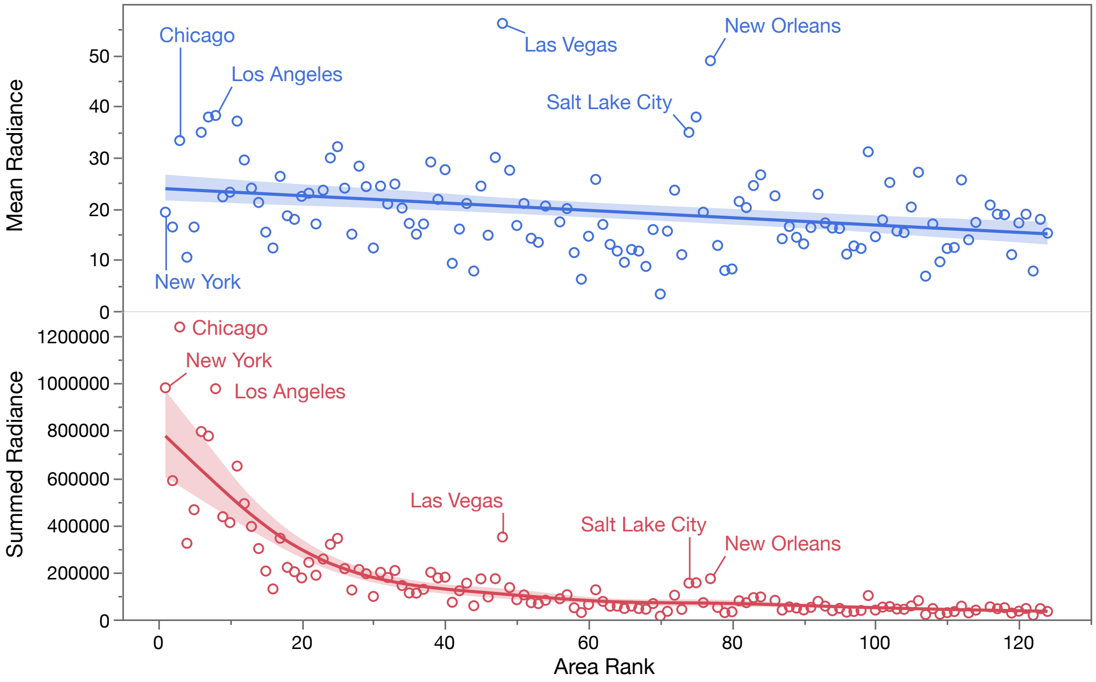


Figure 2. Light escaping upwards from Salt Lake City 2012–2017 within the 125 largest metropolitan regions in the United States. Top: radiance normalized for area. Bottom: total radiance from entire city extent. Data from VIIRS DNB as analyzed by Horton et al. (2019).

Large-scale transformations of municipal street lighting systems have occurred over the past decade as older lighting technologies have been replaced by light emitting diode (LED) systems. Because of the history of the technology, where the early high-efficiency LEDs had a high content of blue light, residents of many jurisdictions objected to the new lights. The bluish-white light of LEDs in those installations was perceived as brighter because of the visual sensitivity of the human eye to the greater proportion of shorter (blue) wavelengths in the light produced. In addition, when lights are more efficient and less expensive to operate, there is a tendency to use more light (Kyba et al. 2014). Not only does the color of light affect how humans perceive the lights; the color of lights is recognized as influencing the contributions lights have to light pollution (Aubé et al. 2013, Kinzey et al. 2017), wildlife (Longcore et al. 2015b, Donners et al. 2018, Longcore 2018), and human health (Garcia-Saenz et al. 2018).

Researchers and engaged lighting designers are developing techniques to minimize undesirable effects of outdoor lighting on both astronomical and ecological light pollution. These include guidance for protected lands (Longcore and Rich 2017), recommendations for specific groups of species (Voigt et al. 2018), and recommendations balancing human vision and wildlife impacts (Longcore et al. 2018a). As Salt Lake City prepares a new Street Lighting Master Plan, this research can be synthesized and applied to inform decisions about the design of the future street lighting system that is consistent with the values embodied in the plan.

This report provides guidance for minimizing the adverse impacts of unnecessary light at night on species, habitats, and ecosystems in the development of a Street Lighting Master Plan for Salt Lake City. The organization of the report is as follows. In the next chapter, the potential impacts of street lighting on wildlife in Salt Lake City are reviewed, based on the published scientific research. The following chapter explores the role of spectrum in determining the level of impact on dark skies, circadian rhythms, and wildlife. Then, this information is synthesized in a chapter outlining spatially explicit design strategies to reduce adverse impacts of street lighting on sensitive biological resources within the context of the further development of Salt Lake City's municipal lighting system. With these strategies, Salt Lake City can build a nocturnal infrastructure that supports ecological health by providing high-quality lighting for human safety and well-being while protecting the night sky and nighttime environment within the city and across the region, setting an example for others to follow.

2 Potential Impacts of Streetlights on Wildlife in Salt Lake City

Street lighting has a large spatial footprint within the area of a city. For a medium-sized city like Salt Lake City, street lighting is provided throughout its residential, commercial, and industrial districts to different extents. In this chapter, the potential effects of this system on wildlife are considered, which requires assessment of the geographic extent of the city.

To describe the environment potentially affected by lighting in Salt Lake City, the physical geography and habitats of the city were described and lists of sensitive species were compiled. Together, these natural features and species distributions can provide the background to devise spatially explicit schemes to minimize potentially adverse effects.

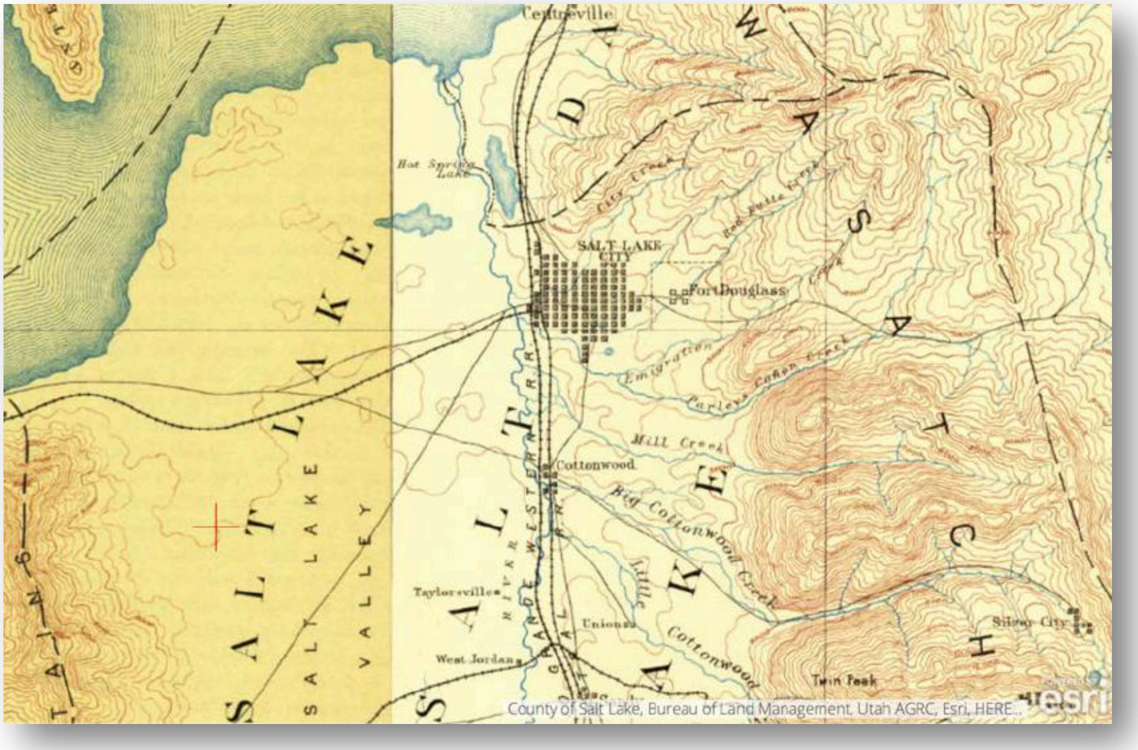


Figure 3. Location of Salt Lake City within the physical geography of the region (USGS topographic maps, 1885, from http://historicalmaps.arcgis.com/usgs/).

2.1 Physical Geography

Salt Lake City is located on lacustrine terraces between the Wasatch Mountains and the Great Salt Lake. It grew up as a central location for travel, commerce, and mining, supported by a swath of irrigated lands extending north-south along the Wasatch Mountains. Although other regional cities were established first (e.g., Ogden), Salt Lake City arose as the most significant city through a confluence of its irrigation resources and its importance as a religious center.

The growth of Salt Lake City depended in part on the array of some 35 streams that flowed downward from the Wasatch Mountains to the rich soils of the terraces above the Great Salt Lake (Harris 1941). These streams were not deeply incised and therefore they could be diverted for irrigation, compared with the rivers of the region, which although larger, are incised into canyons and consequently could not be used easily be irrigation by the white settlers in the 1840s. The climate is mild, with a long growing season extended by proximity to the Great Salt Lake. Snow accumulation in the mountains and a long melt season made agriculture attractive and productive within the region. The creeks flowing out of the Wasatch Mountains, City Creek, Red Butte Creek, Emigration Creek, Parley's Cañon Creek (now Parley's Creek), Big Cottonwood Creek, in turn flowed into the Jordan River, which flowed northward to debouche through a small distributary delta into the Great Salt Lake (Figure 3). The Jordan River has a winding, low-gradient pathway that remains to this day, dividing the territory of the city into eastern and western halves. The eastern half is characterized by the rising terraces climbing up toward the mountains with the remaining extents of the westward-flowing creeks, while the western portion of the city is an almost entirely flat open plain extending toward the shore of the Great Salt Lake (Figure 3).

These features of the physical geography of Salt Lake City are a useful organizing framework to discuss zones that remain important to the ecology and sensitive species of the City today: 1) the Salt Lake shorelands, 2) the Jordan River, 3) the urban creeks, and 4) the Wasatch Mountains.

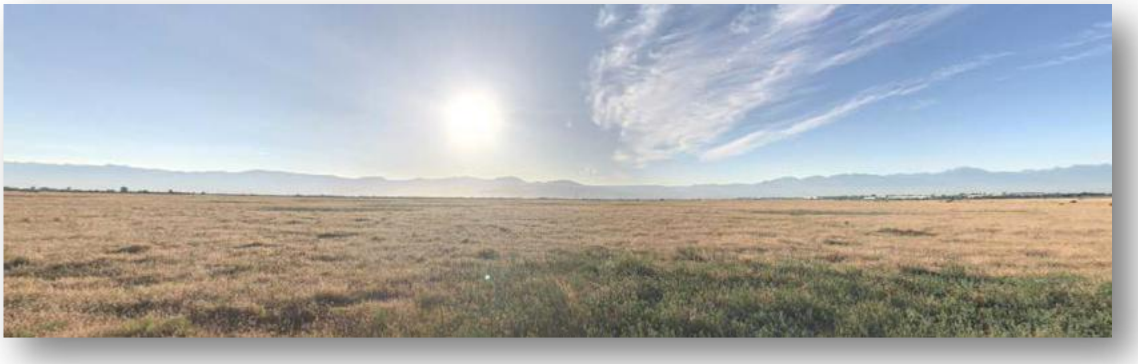


Figure 4. Example of the open landscape of the Great Salt Lake shorelands. Photo from Google Local Guide Neil Martin, looking due east toward Salt Lake City.

2.1.1 Great Salt Lake Shorelands

The shorelands surrounding the Great Salt Lake extend far into the City limits of Salt Lake City. The airport and western commercial and industrial areas extend into this zone. These flat, open areas are made up of deep lacustrine sediments of clay and loam (Flowers 1934). Although the vegetation changes by zones extending away from the lake, the plains and ponds within them tend to be saline, which leads to a flora free from trees and dominated by low succulent herbs and low shrubs, such as pickleweed, salt bush, salt grass, and seepweed (Flowers 1934). Open habitats such as these (Figure 4) are vulnerable to disruption by light pollution because light encounters no barriers and even a single unshielded streetlight can be seen from a great distance

(De Molenaar et al. 2006, Longcore and Rich 2017). Birds in landscapes like this can be influenced by the direct glare from streetlights and will locate nests farther from lights when such sites are available (De Molenaar et al. 2006).

These shoreland ecosystems are extremely important to shorebirds for foraging and breeding. The brine shrimp and salt flies that feed on algae in and around the lake provide food and the undisturbed open areas are used by Snowy Plovers, American Avocets, Black-necked Stilts, Long-billed Curlew, and dozens of other shorebird and waterbird species (Jones 2008). A portion of this area with Salt Lake City has been established and managed as the Inland Sea Shorebird Reserve by Rio Tinto/Kennecott as mitigation for impacts from its nearby mining operations. They took advantage of existing shallow depressions with soils high in clay that naturally held water and managed the drainage system to extend inundation times and provide high-quality bird habitat. The 3,670-acre reserve provides habitat for around 120,000 birds annually.

The Great Salt Lake as a whole has been recognized as a site of "hemispheric importance" within the Western Hemisphere Shorebird Network (Andres et al. 20016). Nearly all the western shorelands with Salt Lake City have been designated as Very Important Bird Areas (IBAs) by Birdlife International. They are the Gilbert Bay/South Arm IBA and the Farmington Bay IBA, which each extend into and cover the undeveloped reaches of the shorelands. These IBAs are of global importance (the highest possible ranking).

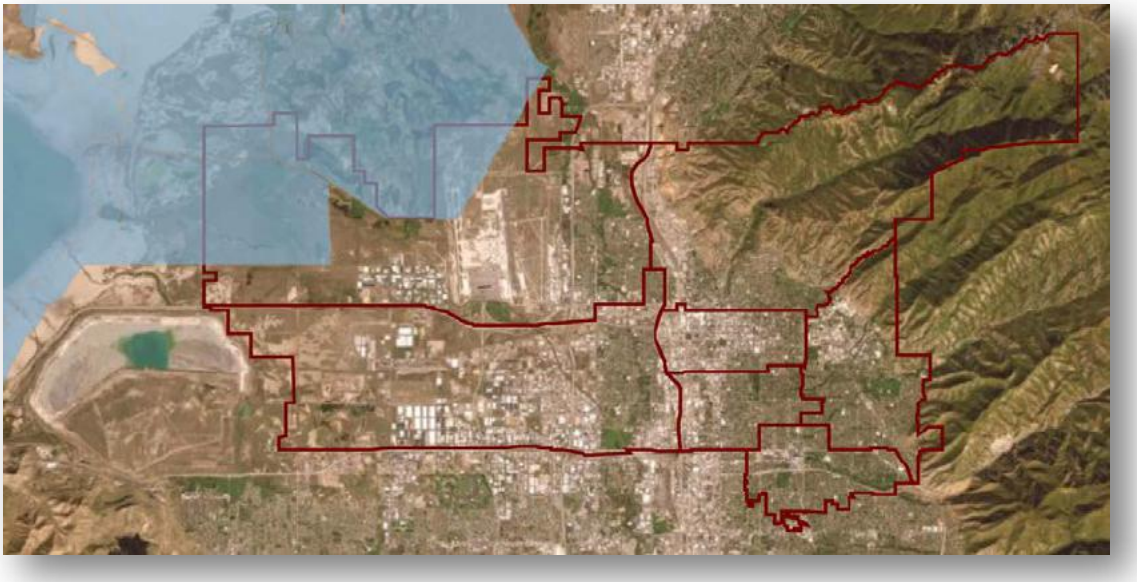


Figure 5. Extent of globally significant Important Bird Areas (blue) in Salt Lake City with City Council districts (red) for reference.

Figure 6. Example of the vegetation of the Jordan River as it winds through Salt Lake City. Image from Google Local Guide Ross Pincock.

2.1.2 Jordan River

The Jordan River is a low-gradient, meandering river that flows north to south through Salt Lake City. Considerable development has affected the banks and floodplain, but recent years have brought attention and restoration efforts to enhance the river, its habitats, and its water quality.

The Jordan River supports riparian (streamside) habitats that are used for nesting by neotropical migratory bird such as Bullock's Oriole, Willow Flycatcher, and Yellow-breasted Chat, all of which nest along the Jordan River and then migrate to Central America for the winter.

The Tracey Aviary conducts surveys and nest monitoring along the Jordan River and birding hotspots along the river include Glendale Golf Course, Jordan River Parkway (200 S to 2100 S), Fife Wetlands Preserve, and Rose Park Golf Course.

2.1.3 Urban Creeks

Salt Lake City has a series of creeks that flow down from the Wasatch Mountains and cut east to west across the city toward the Jordan River (Figure 7). Over time, the lower extents of these creeks have been undergrounded, cutting off the surface flows and diverting them to underground pipes. For example, City Creek, was undergrounded along North Temple Street in 1909 (Love 2005). These creeks have been the focus of daylighting and restoration activities that may

Figure 7. Footprint of the Jordan River running south to north through the center of Salt Lake City.

extend into the future (Love 2005). Because of the water flows and support of riparian vegetation, the remaining aboveground creeks remain important habitats for wildlife. They are now surrounded by neighborhoods and receive heavy recreational use and provide valuable access to nature within the urban fabric (Figure 8).

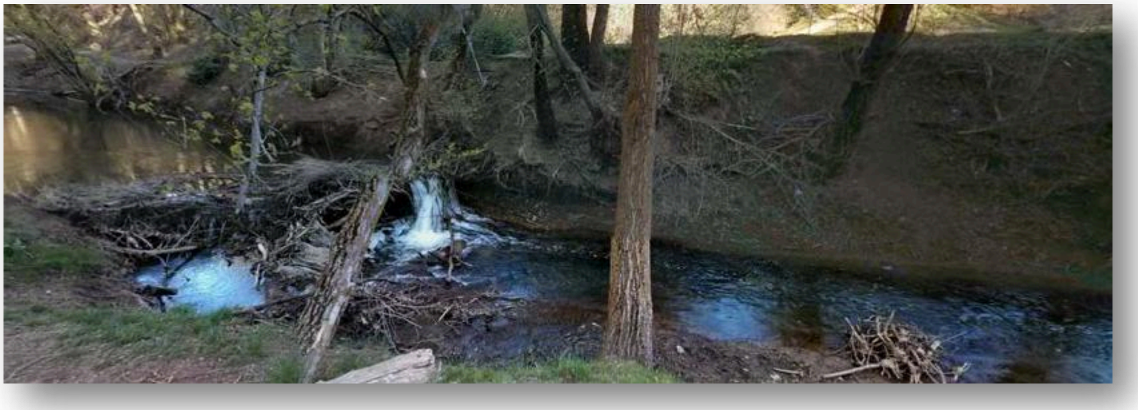


Figure 8. Image of Emigration Creek as it flows through the Wasatch Hollow Open Space. Photo by Google Local Guide Joseph Muhlestein.

2.1.4 Wasatch Mountains

The foothills of the Wasatch Mountains to the west of the Salt Lake City are contiguous with a large block of contiguous open space and wilderness area and therefore are easily recognized as being environmentally sensitive. One of the vulnerabilities of mountainous habitats to light pollution is that their slopes are directly in the light of sight for any light that is emitted upward from nearby sources (Longcore and Rich 2017). Any light from Salt Lake City that is emitted above the horizontal plane and directed toward the east has the potential to degrade the habitats of the Wasatch Mountains.

Figure 9. Four urban creeks (purple) extending out of the Wasatch Mountains into Salt Lake City.

2.2 Sensitive Species

Important wildlife species of Salt Lake City were reviewed in a 2010 program for the acquisition of natural lands. The program identified and mapped the distribution of critical habitat for wildlife. A list of species for which potential habitat is found in the City was also provided. This map identified all parcels within the city that intersected with areas that had potential habitat for Black Bear, Bandtailed Pigeon, Blue Grouse, Chukar Partridge, Moose, Mule Deer, Ring-necked Pheasant, Rocky Mountain Elk, Ruffed Grouse, or Snowshoe Hare. The resulting map forms a ring around the core of Salt Lake City, with critical wildlife habitat extending down the slopes of the Wasatch range to the urban edge on the east and also enveloping the shorelands and extending from the west to and around the north of the airport (Figure 10).

The city also has potential habitat for a range of sensitive plant and wildlife species. These species include birds of the open shorelands (Bobolink, Burrowing Owl, Long-billed Curlew, Northern Goshawk, Short-eared Owl) those associated with the foothills and creeks (Lewis's Woodpecker, Three-toed Woodpecker, Greater Sage Grouse, and some found throughout (e.g., Ferruginous Hawk, Grasshopper Sparrow). Other sensitive wildlife species include the Smooth Greensnake, found in the mountains, spotted bat and Townsend's big-eared bat.

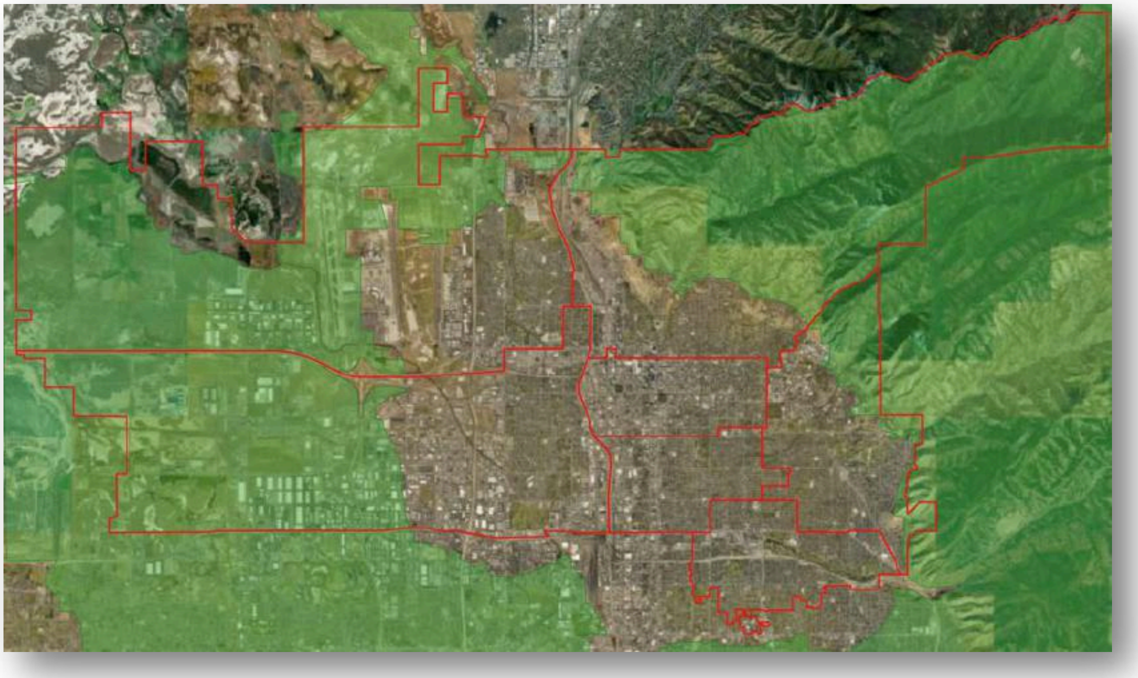


Figure 10. Distribution of parcels (green) that intersect with critical wildlife habitat, with City Council districts for reference.

Other wildlife species, although not recognized formally as sensitive, deserve attention in a street lighting plan intended to reduce and avoid impacts. Fireflies are known to be sensitive to light pollution and have popular appeal as wondrous symbols of the dusk and nighttime environment (Lloyd 2006). The Natural History Museum of Utah is collecting firefly sightings from around the state and has reports from both north and south of Salt Lake City and a few records have been reported from within Salt Lake City.

Bats are also significantly influenced by lighting conditions. Mexican free-tailed bats (*Tadarida brasiliensis*) are well-known to residents because they roost at West High School near downtown during migration. Other documented species include hoary bat (*Lasiurus cinereus*; https://www.inaturalist.org/observations/3742269). It is likely that more species and locations for bat foraging and roosting would be documented if acoustic surveys were conducted (O'Farrell et al. 1999).

2.3 Effects of Lighting on Key Wildlife Groups

Artificial light at night can have a range of lethal and sub-lethal effects on wildlife (Longcore and Rich 2004, Rich and Longcore 2006, Gaston et al. 2012, Gaston et al. 2013, Meyer and Sullivan 2013). Some wildlife species will avoid areas with additional lighting (Beier 1995, 2006, Stone et al. 2009, Stone et al. 2012) or otherwise be adversely impacted (Hölker et al. 2010a, Hölker et al. 2010b, Longcore 2010, Gaston et al. 2013).

The formally recognized sensitive species in Salt Lake City, or at least potentially present, include large and small mammals, migratory and resident birds, bats, one reptile, and at least one plant species. The types of disruption from lighting that could occur for these groups include attraction and disorientation leading to injury or death, disruption of connectivity between habitat patches, interference with predator-prey relations and circadian rhythms that influence foraging decisions, and disruption of pollination.

2.3.1 Attraction and Disorientation

Attraction/repulsion and disorientation are possible outcomes of encounters between wildlife and artificial light at night (Longcore and Rich 2004). The most well-known situation is the attraction and disorientation of hatchling sea turtles on ocean beaches, which results in the death of the juvenile turtles that do not reach the ocean (McFarlane 1963). The two most relevant instances of attraction and disorientation for Salt Lake City are the impacts on migratory birds and on insects.

Migratory Birds. Research with weather radar over the past five years has dramatically improved understanding of the influence of city lights on migrating birds. Most songbird species migrate at night and they can be detected and mapped on weather radar. A massive trove of radar data has been accumulated over the past 25 years and so researchers can now use those data and powerful new computing approaches to understand the influence of lights on the migratory paths of birds.

Light at night escaping upwards so that it can be measured by a satellite is associated with greater numbers of birds present during the day, especially in the fall when juveniles are migrating south (La Sorte et al. 2017). As the birds are migrating southward they are attracted to the lights of the city and then end up disproportionately using habitats in and around cities as compared with potentially better habitats farther from cities (McLaren et al. 2018). Lights can rapidly increase the density of migratory birds in an area at night. A study of the Tribute in Light installation in New York documented an increase from 500 birds within 0.5 km of the vertical light beams before they were turned on to 15,700 birds within 0.5 km 15 minutes after illumination (Van Doren et al. 2017).

Attraction at night is only the first hazard. Urban habitats and especially business districts are quite hazardous to these birds because once they are on the ground, they are susceptible to collisions with glass, which they do not perceive as a barrier (Klem 1990, Sheppard and Phillips 2015). The combination of night-time lights followed by daytime glass exposure is a significant threat to songbirds during the already strenuous migratory period (Cabrera-Cruz et al. 2018).

Radar data have been used to track the relative exposure of migratory birds to lights within U.S. metropolitan areas ranked by area. The Salt Lake City–West Valley City urban area ranks 74th in area among cities in the continental US by area. When evaluated for the number of migrating birds based on radar tracking (average for 1995–2017) and the intensity to light as measured by the VIIRS DNB satellite (average for 2012–2017), the city ranks 120th in exposure for the spring and 112th in exposure for the fall (Horton et al. 2019) (Figure 11). Other cities have far more migratory birds flying overhead per unit area. For example, New Orleans has many more birds flying overhead because of its location on the Gulf Coast, where all of the birds heading to the northern forests and back again to Central and South America funnel overhead.

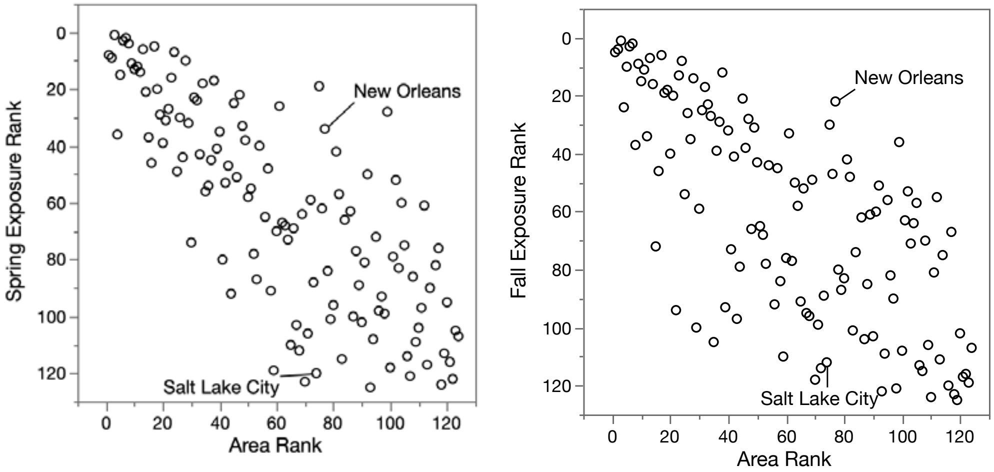


Figure 11. Relative exposure of migrating birds to light in Salt Lake City within the 125 largest metropolitan regions in the United States (Horton et al. 2019). Salt Lake City has relatively fewer migratory bird species overhead during migration than other similarly sized metropolitan regions.

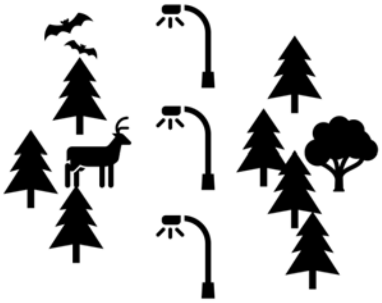
Even though the relative exposure is low compared with other similar-sized cities, birds are attracted to and die at the buildings of Salt Lake City. The city can take a leadership position by reducing the amount of light escaping upward from lighting throughout the city and especially downtown to reduce this unfortunate outcome.

Insects. Many families of insects are attracted to lights, including moths, lacewings, beetles, bugs, caddisflies, crane flies, midges, hoverflies, wasps, and bush crickets (Sustek 1999, Kolligs 2000, Eisenbeis 2006, Frank 2006, Longcore et al. 2015a). Any lamp with significant emissions in the ultraviolet or blue wavelengths is highly attractive to insects (Eisenbeis 2006, Frank 2006, van Langevelde et al. 2011, Barghini and de Medeiros 2012). Insects attracted to lights are subject to increased predation from a variety of predators, including bats, birds, skunks, toads, and spiders (Blake et al. 1994, Frank 2006).

Moths are especially attracted to lights and they play a special role in the ecosystem as pollinators. Moths are killed in collisions with the lights or by becoming trapped in housings (Frank 1988, 2006). Short of death, this attraction removes native insects from their natural environments (Meyer and Sullivan 2013) in what Eisenbeis (2006) calls the "vacuum cleaner effect." Attraction of insects by light results in significant reduction in pollination (Macgregor et al. 2015, Macgregor et al. 2017) and this effect spills over into daytime insect communities because of the decreased seed set and reproduction of plants (Knop et al. 2017).

Bats. The responses of different bat species to lighting are complex (Rydell 2006). Some faster-flying and more maneuverable species will be attracted to lights, where they forage on insects also attracted to the lights. Slower and less maneuverable species will avoid lights, essentially being repulsed by their presence (Stone et al. 2009, Stone et al. 2012, Stone et al. 2015). Light at the entrance of a roost can keep bats from emerging for their nightly foraging (Boldogh et al. 2007).

2.3.2 Loss of Connectivity

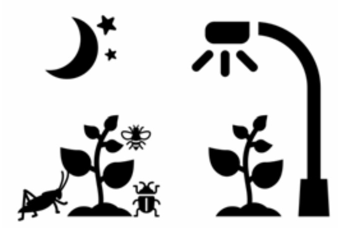


As is implied by the repulsion of some bat species by nighttime lighting, the presence of permanent outdoor lighting can severe landscape connectivity for wildlife species (Stone et al. 2009). The existence of the lights themselves, shielded or not, is sufficient to influence wildlife movement (Beier 1995, 2006). This phenomenon was illustrated by a radio telemetry study of young mountain lions in Orange County, California (Beier 1995):

> All travel in corridors and habitat peninsulas occurred at night. During overnight monitoring, the disperser usually avoided artificial lights when in the corridor or peninsula. For example, M12 [a juvenile mountain lion] consistently used dark areas as he rapidly (<4 hr) traveled the grassy ridge (6.0 X 1.5 km) separating San Juan Capistrano from San Clemente (Fig. 1). Also M12 seemed to use light cues when he negotiated the tightest part of the Pechanga Corridor; his consistent movements in the direction of the darkest horizon caused him to miss the only bridged undercrossing of I-15.
>
> Overnight monitoring showed that dispersers especially avoided night-lights in conjunction with open terrain. On M12's initial encounter with a well-lit sand factory and adjacent sand pits, he took 2 hours and 4 attempts to select a route that skirted the facility, after which he rested on a ridgetop for 2 hours. During 2 nights in the Arroyo Trabuco, M8 explored several small side canyons lacking woody vegetation. He followed each canyon to the ridgetop, where city lights were visible 300–800 m west. He stopped at each canyon ridgetop for 15–60 minutes before returning to the arroyo, without moving >100 m into the grasslands west of the ridgeline in view of the city lights.

Further data on the use of underpasses and the influence of lighting on landscape connectivity have been reported. An experimental evaluation of underpass use by wildlife found that for mule deer, even nearby lights affected movement compared with a reference period (Bliss-Ketchum et al. 2016). Research conclusively shows that artificial night lighting can have an adverse impact on the foraging behavior of bat species, and exclude certain species from foraging routes or areas (Stone et al. 2009, Polak et al. 2011).

2.3.3 Foraging



Small mammals respond to illumination in their foraging activities. For example, artificial light of 0.3 and 0.1 lux reduced the activity, movement, or food consumption of a cross-section of rodent species (Clarke 1983, Brillhart and Kaufman 1991, Vasquez 1994, Falkenberg and Clarke 1998, Kramer and Birney 2001). This phenomenon also has been shown in natural (in addition to laboratory) conditions (Kotler 1984a, Bliss-Ketchum et al. 2016, Wang and Shier 2017, Wang and Shier 2018).

The driving force behind patterns of activity and foraging by animals influenced by artificial lights is presumably predation. Additional (artificial) light might increase success of visually foraging predators, thereby increasing risk to their prey, with one critical exception: prey species with a communal predator defence, such as schooling or flocking, have decreased risk of predation with additional light. Evidence for this general pattern continues to accrue. Partridge are documented to roost closer to each other on darker nights and can see predators farther away on lighter nights (Tillmann 2009). Some species of bats avoid artificial lights to reduce predation risk (Stone et al. 2009, Polak et al. 2011). A general review of nocturnal foraging suggests that night is a refuge with decreased overall predation on birds and mammals, and that foraging groups are larger at night, especially for clades that are not strictly nocturnal (Beauchamp 2007). Songbirds that were experimentally relocated moved back to their home ranges at night, a result that is most consistent with predator avoidance (Mukhin et al. 2009). Pollination is determined by foraging activities and the distribution of insect foragers, which in turn are susceptible to attraction, disorientation, and other behavioral disruptions from artificial lights (Knop et al. 2017).

Predator-prey systems are tightly tied into lunar cycles, with many relationships affected by lunar phase (Williams 1936, Sutherland and Predavec 1999, Topping et al. 1999, Riou and Hamer 2008, Upham and Hafner 2013). Even within species, variation in color interacts with lunar cycle to affect foraging success. White-morph Barn Owls have an advantage foraging during the full moon because the light reflecting off their white feathers triggers their rodent prey to freeze in place, while Barn Owls with darker colored feathers do not have this advantage (San-Jose et al. 2019). Light pollution can be expected to interfere with such patterns (San-Jose et al. 2019).

Predator-prey relations probably also drive the influence of artificial lighting on bird nest location. The one experimental study of the effect of streetlights on breeding bird density shows a negative impact (De Molenaar et al. 2006). The streetlights in De Molnenaar et al.'s study created a maximum illumination of 20 lux (1.8 footcandles). The adverse effects of these lights (decreased density of Black-tailed Godwit nests) were experienced up to 300 m (984 ft) from these lights, extending into areas with negligible increased illumination, which means that the adverse impact results from the light being visible, rather than the amount of light incident on the sensitive receptor.

2.3.4 Interference with Visual Communication

Artificial light at night affects species such as fireflies that communicate visually at night with light. Although the distribution of fireflies is limited within the city, their recovery could be a laudable urban conservation goal. Artificial light washes out the signals that fireflies use for communication and is potentially contributing to the decline of fireflies and other organisms that rely on bioluminescent communication (Lloyd 2006, Hagen and Viviani 2009, Viviani et al. 2010, Bird and Parker 2014). A Brazilian study documented lower species richness of fireflies in areas of 0.2 lux and greater (even from sodium vapour lamps, which are otherwise considered to be more wildlife friendly), except for those few species that naturally fly at greater illumination (Hagen and Viviani 2009).

2.3.5 Physiological Responses

Birds. The research on the effects of ambient and artificial lighting on bird reproduction goes back to the 1920s (Rawson 1923, Rowan 1938). Birds can be extremely sensitive to illumination, and extension of foraging by species under artificial lights is documented in the literature (Goertz et al. 1980, Sick and Teixeira 1981, Frey 1993, Rohweder and Baverstock 1996). Research shows an earlier start to seasonal breeding of birds in urban (lighted) environments than rural (dark) environments (Havlin 1964, Lack 1965). Many of the physiological impacts of lighting on birds are reviewed by De Molenaar et al. (2006) and Longcore (2010).

- Dawn song in American Robins (*Turdus migratorius*) is influenced by ambient illumination (Miller 2006);
- Dawn song and lay date in a songbird have been shown to be associated with proximity to streetlights, with evidence that this affected mate choice, which has implications for fitness (Kempenaers et al. 2010);
- Light of 0.3 lux can move reproductive seasonality of songbirds by a month and cause irregular molt progression (Dominoni et al. 2013a, Dominoni et al. 2013b);
- Light is a major driver of the daily activity patterns of songbirds (study animal European Blackbird; *Turdus merula*), causing them to be active earlier in the morning (Dominoni et al. 2014);
- A songbird (Tree Sparrow; *Passer montanus*) exposed to 6 lux in the laboratory secreted luteinizing hormone earlier than controls, and urban birds exposed to 3–5 lux exhibited this pattern in the field; both of these response were statistically associated with night lighting (Zhang et al. 2014);
- Artificial light outside of nest boxes affects perceived photoperiod of Great Tits (*Parus major*), which the authors interpret as creating an ecological trap (Titulaer et al. 2012);
- Artificial light rather than traffic noise affects dawn and dusk song timing in common European songbirds (Da Silva et al. 2014).

Artificial night lighting affects diurnal species substantially as well. As noted above, it affects timing of dawn and dusk song, seasonality of reproduction, mate choices, and can extend activities of diurnal species into the night (Stracey et al. 2014). Birds that sing earliest are responding to increases in illumination so faint that they are undetectable by humans (Thomas et al. 2002). This is true for impacts across species, where diurnal species are affected in numerous ways by an altered nighttime environment (Miller 2006, Kempenaers et al. 2010, Titulaer et al. 2012, Dominoni et al. 2013a, Dominoni et al. 2013b, Da Silva et al. 2014, Dominoni et al. 2014, Zhang et al. 2014, Da Silva et al. 2015).

Mammals. Similar impacts on both seasonality and daily rhythms are documented for mammals. For example, lighting from a military base was shown to desynchronize the breeding time of tammar wallabies in the field in Australia, as well as to suppress nightly melatonin production (Robert et al. 2015). Studies on the physiological effects of light at night on mammals are abundant, partly because of the implications for understanding human health (e.g., Zubidat et al. 2007, Zubidat et al. 2010). As a whole, they show that artificial light at levels far less intense than previously assumed are able to entrain circadian rhythms and influence physiological functions such as immune response (Bedrosian et al. 2011). For example, extremely dim light is sufficient to entrain rhythms in mice, and can be done without phase shifting or reducing production of melatonin (other physiological indicators of light influence) (Butler and Silver 2011). For shorter wavelengths (blue and green) entrainment takes place at 10^{-3} lux. Much greater intensity, 0.4 lux, is needed for red light to entrain rhythms (Butler and Silver 2011). This research is consistent with recently documented differences in mice behaviour for exposure to 20 lux vs. 1 lux at night (Shuboni and Yan 2010). Mice that were exposed to dim (5 lux) light at night consumed the same amount of food as those under dark controls, but gained weight as a result of the shift in time of consumption (Fonken et al. 2010).

Plants. Plants “anticipate” the dawn with a synchronized circadian clock and increase immune defence at the time of day when infection is most likely (Wang et al. 2011). The timing of resistance (R)-gene mediated defences in *Arabidopsis* to downy mildew is tied to the circadian system such that defences are greatest before dawn, when the mildew normally disperses its spores (Wang et al. 2011). Preliminary experiments show that carbon assimilation is lower in trees exposed to continuous night lighting, compared with controls in a “stereotypical urban setting” (Skaf et al. 2010). Some plants might use light-triggered circadian rhythms to synchronize expression of anti-herbivory compounds with periods of peak herbivory, leading to increased loss from herbivory in out-of-phase plants (Goodspeed et al. 2012). The importance of circadian rhythms in plants, for everything from disease response and flowering time to seed germination, and the potential for disruption by night lighting, has not been explored widely (Resco et al. 2009, Bennie et al. 2016).

Light at night also affects the perception of seasonal change by plants and their associated physiological responses. Exposure to light at night is associated with earlier budburst in plants in the United Kingdom, in a pattern that cannot be explained by the greater temperatures in cities (ffrench-Constant et al. 2016). Trees exposed to nearby lights have long been observed to hold on to their leaves later in the fall (Briggs 2006, Škvareninová et al. 2017, Massetti 2018) and prevent seed set in plants cued to shorter daylengths (Palmer et al. 2017).

3 Consideration of Spectrum in Municipal Street Lighting Systems

The LED revolution in outdoor lighting has created new possibilities to select the spectral composition of lights. Unlike lighting technology of the past, such as high-pressure sodium or metal halide lamps, the range of colors that can be deployed using LEDs is wide. As a result, it is possible to select spectral profiles that can either reduce or increase the effects of a street lighting system on the visibility of stars in the night sky, on human circadian rhythms, and on wildlife (Longcore 2018).

3.1 Effects on Wildlife

This review of the effects of lighting spectrum on wildlife is drawn from my recent article (Longcore 2018), which can be consulted for additional details.

The effects of lights of different spectral composition on wildlife depends on the responses of different wildlife groups to those lights. A limited number of “response curves” are available that track the response for a species or group of species to light throughout the entire visible spectrum (and into the portion of the spectrum invisible to humans). These curves have been developed for insects in general, bees, moths, juvenile salmon, seabirds, and sea turtles. My colleagues and I have developed methods to compare different lamp types for their effects across these groups (Longcore et al. 2018a).

Some patterns are clear. Insect attraction to LEDs is lower across the board when compared with lamps that emit ultraviolet light. Both “warm” and “cold” LEDs have been compared with metal halide and mercury vapor lamps and found to attract less than a tenth of the number of insects, a finding that is attributable to the difference in ultraviolet emissions (Eisenbeis and Eick 2011). Conversely, most broad-spectrum LEDs used in outdoor lighting do have a potential to adversely impact the perception of daylength (and thus seasonality) in plants, because the peak sensitivity of the phytochromes that detect daylength are in range of LED peak emissions for most full-spectrum LEDs.

Several approaches are available to summarize the quality of light from different sources. One is to use the Correlated Color Temperature (CCT). This metric, although imperfect, is widely used in lighting design. Some jurisdictions that regulating lighting to protect species have a hard cut-off (e.g., no light allowed < 540 nm) or measure the amount of light emitted below certain thresholds. Another possible metric is the degree to which a light interferes with the non-image forming photoreceptors that result in disruption in circadian rhythms in humans, because nearly all vertebrates will have a similar response curve for suppression of melatonin production at night. Drawing on data from Longcore et al. (2018a), the response of different wildlife groups against these possible metrics describing spectrum were plotted (Figure 12). Across all groups, less blue light (shorter wavelengths) resulted in lower effects. As for metrics to describe this pattern, correlation with CCT was strong, but melanopic lux (the brightness of the light as sensed by melanopsin) correlated the best. These results will only hold true for lamps without ultraviolet or violet emissions, however.

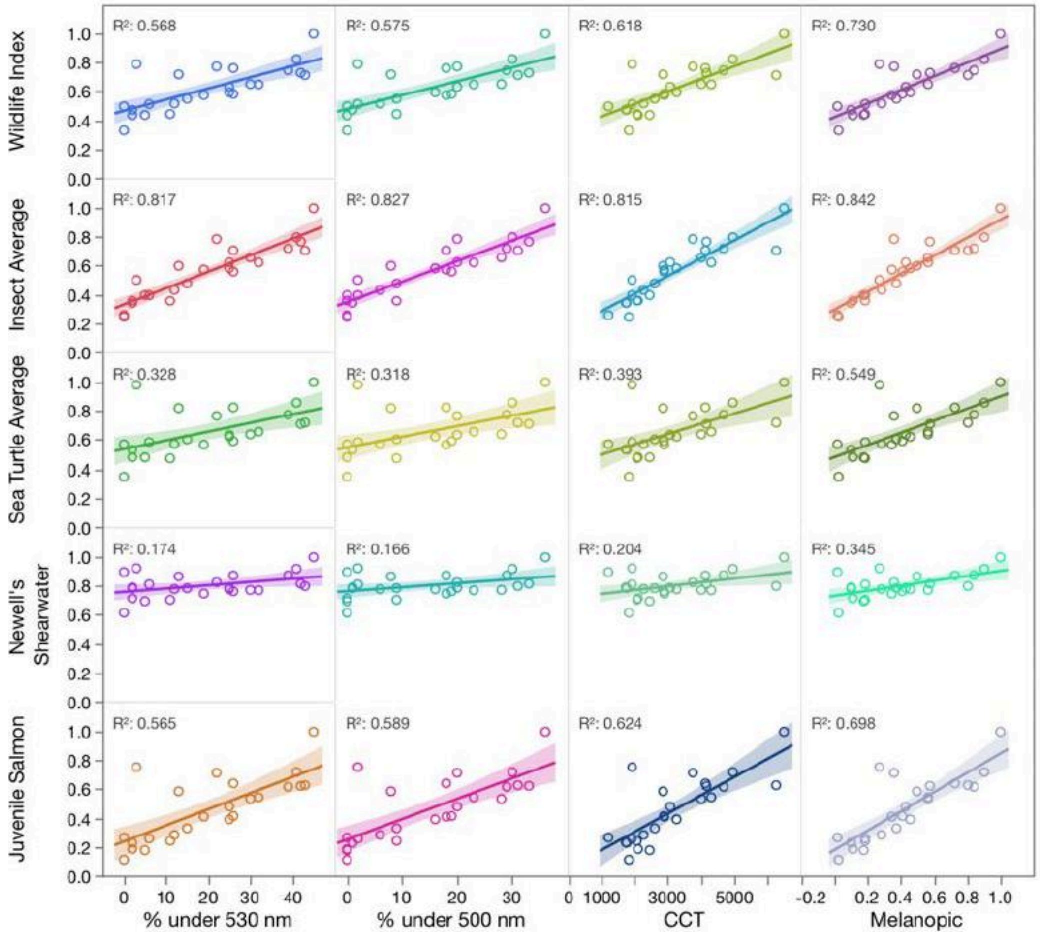


Figure 12: Relationship of modeled effect of lamps on different wildlife species or groups (juvenile salmon, Newell's shearwater, sea turtles, insects, and their average) with percent emissions <530 m, % emissions < 500 nm, correlated color temperature (CCT), and melanopic power of the lamps. Data from (Longcore et al. 2018b).

CCT is not a perfect predictor of effects on wildlife, but it is a reasonable rule of thumb that lower CCT will be less disruptive to wildlife and we already know that it will be less disruptive for circadian rhythms and astronomical observation (Aubé et al. 2013). The lamps with the lowest projected influence on wildlife overall were low pressure sodium (which is being phased out), high pressure sodium, PC amber LEDs, and filtered LEDs (Figure 13).

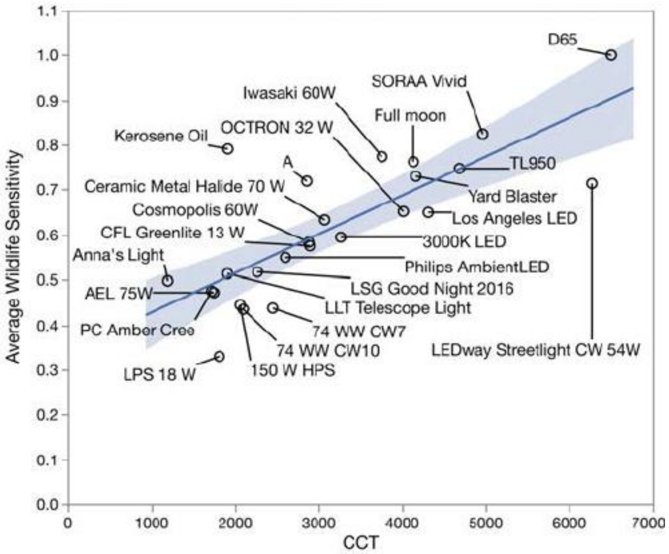


Figure 13: Relationship of correlated color temperature to average wildlife sensitivity with lamps and illuminants labelled. Data from (Longcore et al. 2018b).

These results represent the predicted effects of the lamps on wildlife. To account for preferences in outdoor lighting, another ranking was created that incorporated a penalty for low color rendering index (CRI). Any lamp with a CRI over 75 was assumed to have adequate color rendering, while those with lower CRI were penalized in the overall index. The resulting ranking of lamps is notable in that low pressure sodium ranks lower because of its extremely low CRI, while PC Amber and filtered LEDs rank the highest, balancing both lower wildlife impacts with reasonable if not high CRIs (Figure 14).

As a rule of thumb, CCT can be used as an indicator of wildlife effects, but this may not hold true across all applications. Migrating birds cannot orient under red light and therefore solid red lights are to be avoided on communication towers (Longcore et al. 2008). Green light has support for minimizing attraction of nocturnal migrant birds (Poot et al. 2008). Many other special cases exist and would require consultation with experts on a taxonomic group or species at risk. For the species of concern in Salt Lake City, however, including insects as indicators of riparian health, bats, and nesting birds, lower CCT will decrease ecological impacts when combined with other good street lighting practices (low glare, no uplight, appropriate intensity, and only lighting when warranted).

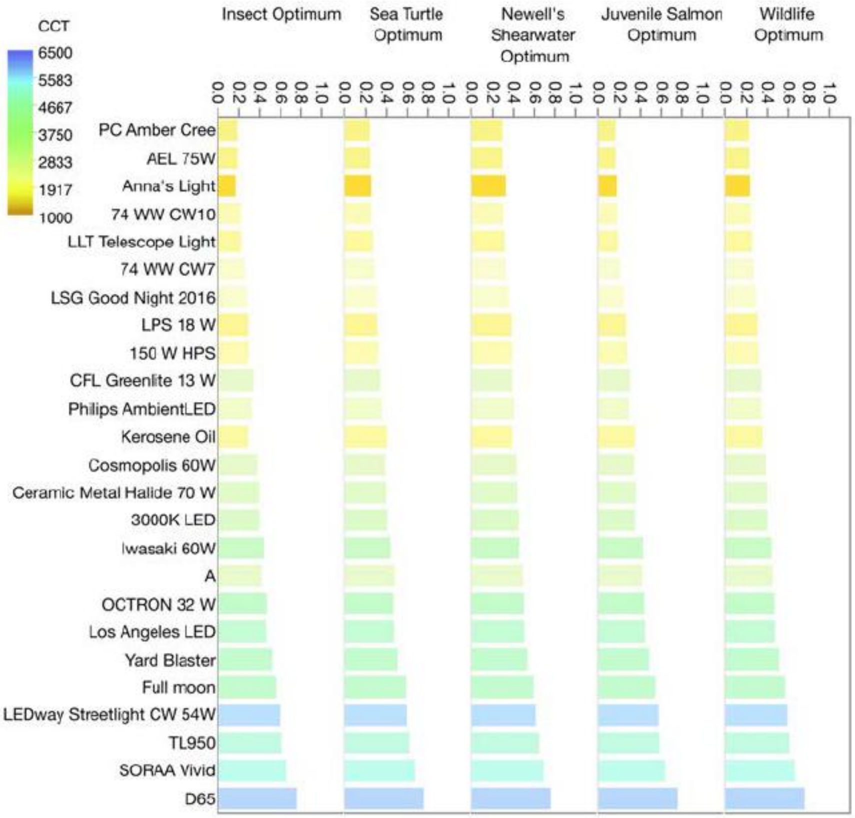


Figure 14: Ranking of lighting sources that equally weights wildlife response, melanopic response, astronomical light pollution (Star Light Index (Aubé et al. 2013)), and Color Rendering Index. Reprinted from (Longcore et al. 2018b). Shorter bars represent a combination of lower wildlife responses and higher CRI.

None of the effects measured with these metrics addresses the scattering of light in the atmosphere, but tools to evaluate the effects of different spectra on astronomical light pollution are available to do that.

3.2 Effects on Dark Skies

The introduction and widespread adoption of 4000K and greater LED streetlights poses a significant threat to astronomical observation and the quality of the night sky as a recreational amenity. It is well-established that the preponderance of light at shorter wavelengths found in high color temperature LEDs scatters more in the atmosphere and if replacing high-pressure sodium lamps with similar intensity and shielding, will result in degradation of the night sky (Kinzey et al. 2017). The effects of the adoption of high color temperature LEDs were quickly noticed and documented by night sky advocates, who could see the degree to which full-spectrum white lights adversely impacted the aesthetics of the night sky when compared with lower color temperature high-pressure sodium systems (Figure 15).

Figure 15. View eastward from Antelope Island State Park, showing visible effect of spectrum on night sky aesthetics. Photo from park's application to become recognized as a Dark Sky Park by the International Dark-Sky Association (2017).

Although the U.S. Department of Energy originally paid little attention to the adverse environmental impacts of high-color temperature LEDs, focusing instead solely on energy savings, it has recently returned to this question and issued a report (Kinzey et al. 2017) investigating the role of lamp spectrum in degradation of the night sky, measured as sky glow.

Rather than focusing solely on spectrum, the report investigates the influence of associated variables that are commonly adjusted in the process of converting from older lighting technology to LEDs. For example, it is common for older lamps to have a drop lens below the lamp that results in a portion of the light being reflected upward, above the horizontal plane from the lamp. It has also become increasingly common for full-spectrum LEDs (e.g., at CCT 2700–4200 K) to be reduced in measured intensity for daytime (photopic) vision when compared with the high-pressure sodium lamp that the LED is replacing. Such reductions in intensity result from complaints from residents that the new LEDs, although producing the same (photopic) illumination (in lux) as the HPS, are perceived as far brighter because they intersect more with the sensitivity of human dark-adapted (scotopic) vision. It is therefore often possible to reduce the intensity of LEDs (measured in photopic lux) compared with HPS and still achieve equal or greater visibility.

The study modeled the effects of different combinations of spectrum, uplight, and intensity under different weather conditions, human vision adaptation levels, and distance from the lights. For the purpose of illustration, the nearby viewer results are reproduced here (Figure 16). These results compare high-pressure sodium as the baseline, with PC Amber LED (1872 K), and 2700–6100 K LEDs. When compared on an equal basis for other factors (same uplight and intensity), only the PC Amber produced roughly equivalent light pollution compared with HPS and all full-spectrum LEDs produced significantly more light pollution, especially when considering human night vision. When both HPS and LEDs were assumed to have 0% uplight and the LEDs were set at half the intensity of the LEDs, then LEDs with CCT < 3000 K were comparable to or produced less light pollution than HPS. Results were similar with HPS at 2% uplight and LEDs at 0% uplight and 50% intensity.

The take-home message of this research for the Salt Lake City street lighting master plan is that for LED lamps lights to reduce light pollution compared with the previously common HPS lamps, they must be 0% uplight, 50% less bright, and with a CCT of no greater than 3000 K. The minimum impact on light pollution could be achieved with PC Amber or comparable filtered LEDs that produce a similar CCT as HPS (~ 1800 K).

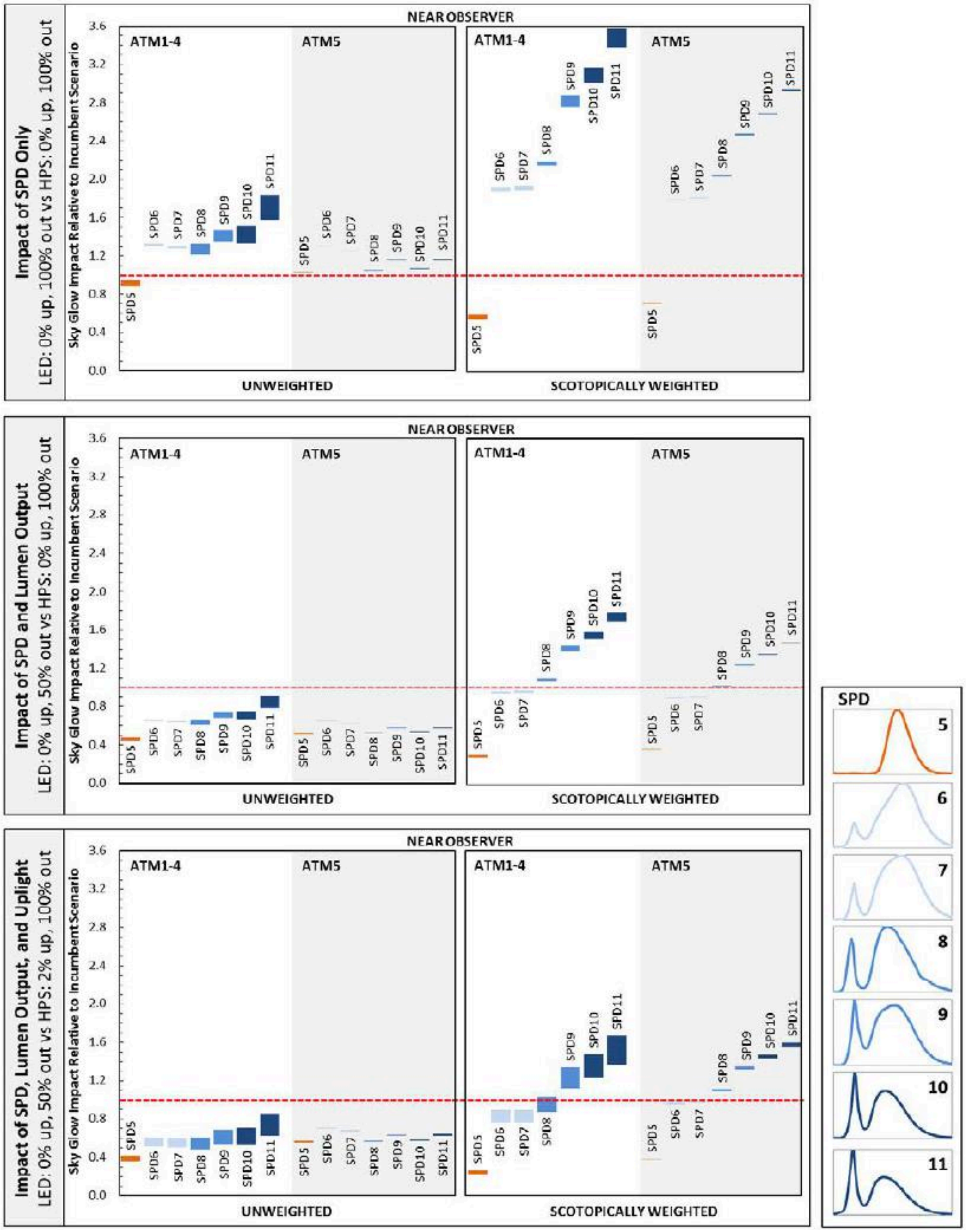


Figure 16. Comparison of light pollution from different LED spectral power distributions (SPDs) with light pollution from a high-pressure sodium light (horizontal dotted red line). SPDs (see right): SPD5: 1872 K (PC Amber), SPD6 = 2704 K, SPD7 = 2981 K, SPD8 = 3940 K, SPD9 = 4101 K, SPD10 = 5197 K, SPD11 = 6101 K.

3.3 Human Circadian Rhythms

It is only in the last twenty years that the mechanism by which light affects human circadian rhythms has been discovered (Berson et al. 2002). The human eye has non-image forming retinal ganglion cells that detect light and perhaps contribute to perception of brightness but not to discerning objects (Hattar et al. 2002). The pigment that detects the light is called melanopsin and it differs in its sensitivity to light from the rods and cones that humans use for vision (Brainard et al. 2001, Schmidt and Kofuji 2009). The peak sensitivity of melanopsin is around 480 nm, in the middle of the blue portion of the spectrum.

Evidence is strong that chronic exposure to light at night increases risk of cancer, diabetes, obesity, and heart disease (Fonken and Nelson 2014, Bedrosian et al. 2016, Lunn et al. 2017). The question for human circadian impacts from outdoor lighting is whether the exposures are bright enough and whether time of exposure is sufficient to affect circadian rhythms.

Circadian rhythms can be affected by light in many pathways. The first pathway is suppression of melatonin through exposure in the evening, especially after dusk. This exposure could be indoors or outdoors, either in the sleeping habitat or not. Dose-response curves for light exposure and melatonin suppression have been developed and it is the basis for the definition of Circadian Light (Rea et al. 2010). The second pathway is through sleep disruption through exposure to light in the sleeping habitat, even if the light levels are insufficient to suppress melatonin. Lack of sleep and reduced long wave sleep, which is critical to recovery and repair (Cho et al. 2016), can result from disturbance glare, as anyone ever awakened by moonlight can attest.

It remains an open question whether indoor exposure to street lighting is of sufficient magnitude to affect circadian rhythms directly, but recent research investigating light spectrum and cancer risk suggests that the color of light outdoors in the vicinity of residences is an important risk factor (Garcia-Saenz et al. 2018).

The influence of outdoor lighting on sleep has been investigated through epidemiological studies that measure exposure using satellites, epidemiological studies using portable individual-level measuring devices (comparing with satellite measures), and experimental studies in humans.

A set of studies from Haim, Kloog, Portnov, and colleagues provided correlational data connecting satellite-measured light at night from the DMSP OLS system to breast and prostate cancer, indicating a connection between outdoor lighting levels and rates of these cancers (Kloog et al. 2008, Kloog et al. 2009a, Kloog et al. 2009b, Kloog et al. 2010, Kloog et al. 2011, Haim and Portnov 2013). Similar studies have reinforced these findings in different populations around the world (Bauer et al. 2013, Hurley et al. 2014, James et al. 2017).

Studies investigating sleep as the outcome also find an association with satellite-measured outdoor lighting. For example, those in the higher exposure to light at night in South Korea as measured by DMSP were 20% more likely to sleep less than 6 hours per night and on average slept 30 minutes less than subjects in areas with lower outdoor lighting levels (Koo et al. 2016). In a study in the United States, higher levels of outdoor lighting as measured by DMSP was significantly associated with reporting < 6 hours of sleep per night, an effect that remained in place even after accounting for noise and population density (Ohayon and Milesi 2016). In this study, people who lived in the brightest areas were more likely to go to bed later, get up later, and sleep less. They also were more likely to report that they were dissatisfied with sleep quality or quantity and to be sleepy during the day. DMSP-measured light at night was negatively associated with restorative long wave sleep. Importantly, this study validated that brightness in bedrooms correlated positively with satellite-measured outdoor light (Ohayon and Milesi 2016).

Satellite-measured light at night was also associated with the use of more drugs for insomnia in a second South Korean study (Min and Min 2018). Residents living in the lowest two quartiles of light at night as measured by DMSP used significantly less insomnia medication, even after accounting for age, sex, population density, income, body mass index, smoking status, alcohol consumption, exercise, and psychiatric disease. Mean use of insomnia medication increased with each quartile of light exposure from lowest to highest for each of three insomnia medications (Min and Min 2018).

Most recently, a study of the NIH-AARP Diet and Health Study cohort in the United States investigated sleep and exposure to light at night as measured by the DMSP satellite (Xiao et al. 2020). The highest levels of light exposure associated with 16% (women) and 25% (men) increased probability of reporting short or very short sleep duration. Probability of reporting short or very short sleep increased from lowest to highest quintiles of light at night in models that adjusted for age, race, marital status, state of residency, smoking, alcohol, vigorous physical activity, TV viewing, and median home value, population density and poverty rate at census tract level (Xiao et al. 2020). The authors concluded that, “Taken together, these findings suggest that the prevalence of sleep deficiency is higher in places with higher levels of LAN [Light at Night]” (Xiao et al. 2020).

While studies using remotely sensed data detect associations between sleep disturbance, circadian disruption, and associated diseases and light at night, others question the relationship between outdoor lighting and indoor exposure to light at night. Leaving aside the point that outdoor exposure to lighting can also contribute to circadian disruption, these studies focus on relationships between indoor and outdoor exposure. Recent work confirms the relationship between ground-level irradiance outdoors and satellite-based proxies for light at night. Using a dataset or 515 ground-based measurements of illumination from the upper hemisphere, Simons et al. (2020) showed that ground-based light exposure correlates highly with remotely-sensed light (VIIRS DNB annual composite) and even more with the New World Atlas of Artificial Night Sky Brightness (Falchi et al. 2016). This work conclusively establishes that satellite-measured light at night is a proxy for ambient light in the environment on the ground at night, as one would expect.

With this relationship now established (Simons et al. 2020), in retrospect the individual-level studies of correlation between indoor light levels and satellite-measurements of light at night are testing whether increased outdoor light levels correlate with higher indoor light levels and documenting what those indoor levels might be. Along these lines, Rea et al. (2011) used a Daysimeter device with a resolution of 0.1 lux and found that DMSP measurements had “no apparent relationship” with personal-level exposure. The study concluded that outdoor lighting could have little effect on circadian rhythms in their study population of teachers in upstate New York, basing this conclusion on the assumption that measurable melatonin suppression would be needed to cause sleep disruption. That is, they assume that light equivalent to a full moon shining into a sleeping environment cannot affect sleep or circadian rhythms, which is a dubious assumption. In a more recent Dutch study, individual-level light exposure for children was measured indoors with a device that had a resolution of 0.1 lux (Huss et al. 2019). They found an influence of outdoor light on indoor light during the darkest time period with a correlation of 0.31. It should be noted, however, that 94% of the children in the study had curtains that controlled light entering the room. In a survey of lighting designers using their own light meters, Miller and Kinzey (2018) reported measurements in a number of different contexts within homes. At windows without drapes a maximum of 20 lux was reported, with a mean of 5 lux and median of 0.5 lux. All of these dramatically elevated above natural conditions (a full moon would produce 0.1–0.2 lux).

Experiments that involve exposures to light at night document illumination levels that affect health and sleep outcomes. Sleeping under 5 lux of 5779 K light caused more frequent arousals, more shallow sleep, and more REM sleep (at the expense of long wave deep sleep) (Cho et al. 2016). Light greater than 3 lux during the last hour of sleep was associated with weight gain in an elderly population (Obayashi et al. 2016). In another study of an elderly population, increased light at night and especially light at night > 5 lux was associated with 89% increased risk of depression (Obayashi et al. 2013). Further studies indicate that elevated illumination is associated with higher blood pressure as well, with associated excess deaths, at 3, 5, and 10 lux exposures (Obayashi et al. 2014). Metrics of sleep quality (efficiency) were also consistently lower with higher illumination at each category (3, 5, and 10 lux) (Obayashi et al. 2014).

Taken together, this research is consistent with a few different interpretations of the influence of outdoor lighting on human circadian rhythms and health outcomes. It is possible that the correlations between light at night and adverse health outcomes indicate instead variation in another factor, such as air pollution, as suggested by Huss et al. (2019). The robustness of sleep disruption correlations when controlling for population density, however, argues against that interpretation (Ohayon and Milesi 2016). Xiao et al. consider this question and conclude: "[I]t is also possible that the observed associations in our study population represent a true relationship, but primarily driven by individuals whose ALAN exposure was more heavily influenced by outdoor ALAN (e.g. individuals living in rooms facing bright streets and/or with insufficient window treatments to block out light, or individuals with a high amount of nighttime activities outside home)." Such an interpretation, that outdoor light can influence indoor sleeping environments and associated sleep and health outcomes, is consistent with the literature as it currently stands.

Accepting a plausible argument that outdoor lighting affects human sleep in at least some contexts that depend on factors associated with socioeconomic status, the following areas of concern follow for design of a street lighting system.

First, attention should be paid to minimize direct glare into windows of any habitable structure. One cannot assume that people only sleep in bedrooms; residents challenged by housing costs often use many rooms in apartments and houses for sleeping environments and the safest assumption is that any room in a residence might be used for sleeping. The assumption should also not be made that all residents have or can afford blackout shades or curtains. This becomes an issue of environmental justice; circadian disruption is exacerbated in low income communities

(Xiao et al. 2020), presumably because the same amount of light results in more impact because of a lack of capacity to block light.

Second, circadian responses that result from melatonin suppression are heavily dependent on the spectrum of light. As light is concentrated closer to the wavelengths of peak sensitivity for melanopsin, the intensity of light (measured in lux) required to suppress melatonin decreases (Grubisic et al. 2019). At 424 nm, the minimum illuminance for melatonin suppression is 0.1 lux (Souman et al. 2018). The relative impact of different lighting sources can be predicted using the melanopic response curve (Aubé et al. 2013, Longcore et al. 2018a). To illustrate this approach, the melanopic power of lamp sources was standardized to compare with high pressure sodium (HPS; Figure 17). All full-spectrum LED sources have a greater potential circadian impact than HPS, including 2200 K (1.5 times HPS), 3200 K (2.5 times HPS), and 4300 K (3 times HPS).

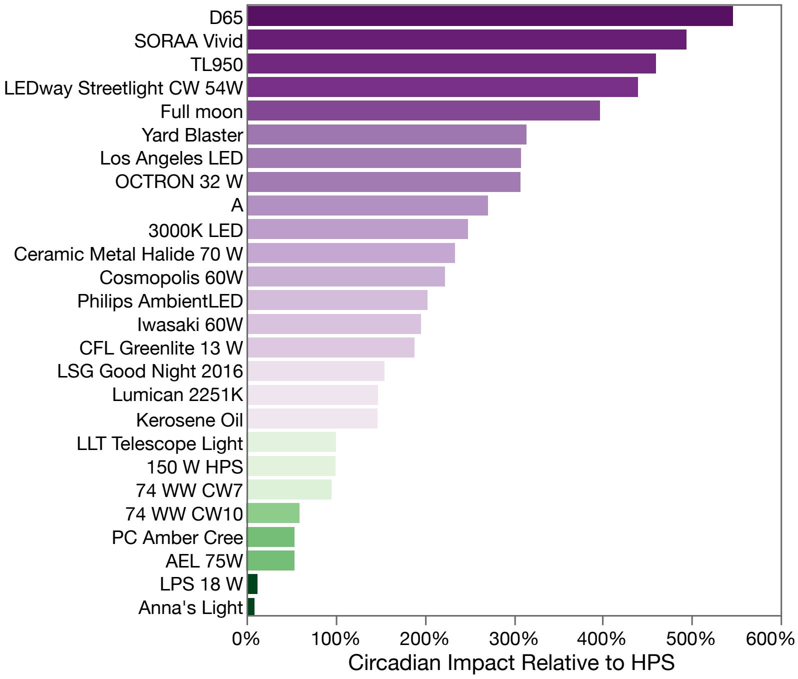


Figure 17. Ranking of light sources by melanopic response (i.e. potential for circadian disruption), compared with a typical High Pressure Sodium (HPS) lamp. Green colors have equal or less melanopic response per lux, while purple colors have more melanopic response per lux than HPS.

The sources that would have the lowest circadian impact are filtered LEDs that avoid the blue portion of the spectrum almost entirely, or PC amber LEDs that do the same. Calculations have not been done to compare LEDs at 50% intensity as has been done for astronomical light pollution impacts. It is reasonable to assume that a similar result would be obtained, with a reducing 50% in intensity for a ~3000K LED compared with HPS bringing it into parity with the potential circadian disruption potential of HPS.

Third, planning for a healthy circadian environment should recognize high variation between individuals in their sensitivity to light, including a 50-fold variation between people in melatonin response to light exposure (Phillips et al. 2019). Children are more sensitive to disruption from light at night than adults (Nagare et al. 2019). Office workers exposed only to dim light during the day are more sensitive to disruption from light at night than those who work outside. Men are more sensitive to light at night, including decreased "long sleep" with increased exposure (Xiao et al. 2020). Some individuals are debilitated by the visual glare from LEDs that are not properly directed and diffused (Ticleanu and Littlefair 2015).

A fair and equitable lighting design approach would recognize a need to accommodate the most sensitive individuals in society in a manner that still allows lighting to achieve its goal of providing a safe environment for pedestrians, cyclists, and people in vehicles. Because some of the medical conditions that are exacerbated by glare may be considered disabilities, it furthermore might be a prudent risk management step to explicitly incorporate these concerns in design to ensure compliance with the Americans with Disabilities Act. Published studies thus far have not shown a decrease in traffic accidents associated with conversion to full-spectrum white LEDs (e.g., >2700 K) (Marchant et al. 2020). Total pedestrian and cyclist deaths in Los Angeles have increased since conversion from HPS to 3000–4300 K LEDs in 2009.[1] Whatever marginal benefits might be associated with higher CCT street lighting, they have not been sufficient to result in significant decreases in accidents that have been documented in published studies. Although a full cost-benefit analysis is beyond the scope of this report and should be the subject of future research, a prudent approach to balance these human health and safety issues is to: use the lowest CCT deemed acceptable, specify high-quality optics to ensure delivery of light on desired surfaces instead of as glare, and avoid light trespass onto windows of any residential property.

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[1] See https://la.streetsblog.org/2019/10/29/vision-non-zero-the-human-and-financial-toll-of-los-angeles-dangerous-roads/

4 Design Strategies for a Healthy Nocturnal Infrastructure

With the adoption of a Street Lighting Master Plan, an opportunity arises to reduce unwanted outcomes from outdoor lighting that might include degradation of the experience of the night sky in the region, disruption of human circadian rhythms, and interference with behavior of sensitive wildlife species within the city. Strategies are available to reduce these impacts, some of which can be implemented at all locations where street lighting is warranted, and others that could be applied in zones with sensitive resources or known adverse impacts.

4.1 Systemwide Approaches

Reducing the adverse effects of artificial light at night is a matter of ensuring that the light is away enough for the identified need, but not more.

4.1.1 Need-based Lighting

In defining the terms under which street lighting is warranted, consideration should be given in all instances to the threshold for need to ensure that the installation is supported by verifiable benefits. The need for lighting at night is in part a subjective judgment based on human feelings, so equal consideration should be given to those who are more comfortable with less light as to those who desire more light and final determinations made through a transparent and fair process that evaluates the costs and benefits.

4.1.2 Shielding and Directionality

For all of the reasons discussed in this report, lights should be directed toward their intended targets (mostly roads and sidewalks) and not upwards or into other locations where sensitive receptors might be present (e.g., bedroom windows, habitats). This consideration will usually be built into a modern street lighting plan through specification of luminaire performance in terms of backlight, uplight, and glare. Uplight should be assiduously avoided throughout the system. This step alone will significantly reduce the current contribution of Salt Lake City to light pollution in the region as viewed from the surrounding open spaces and natural lands.

4.1.3 Intensity, Dimming, and Controls

Any time a natural environment is experiencing illumination greater than the full moon (>0.1 lux), or even greater than a quarter moon (0.01 lux), one can assume that species are being affected. This is the case because many species show lunar cycles in behavior, often driven by predator–prey relationships that can be interrupted by elevated illumination (Price et al. 1984, Daly et al. 1992, Upham and Hafner 2013). For example, light as dim as 0.01 lux can inhibit foraging by small rodent species (Kotler 1984b).

Strategies that could be deployed around light intensity across the street lighting system include setting the maximum intensity of lights lower, dimming or extinguishing lights according to a pre-set schedule, and use of programmable and flexible controls to adjust intensity in response to need.

1. If full-spectrum LEDs are to be used (e.g., 2700K, 3000K), then the intensity must be at least half of that measured (in lux) for high pressure sodium to avoid increased light pollution impacts. Lower color temperature LEDs (e.g., 1800K, 2000K, 2200K) would require testing to set the maximum operational intensity to achieve system objectives.
2. Regularly programmed dimming or shut-off is a possibility for the system. Part-night lighting, where lights are shut off after a curfew is an improvement over whole-night lighting for bats but not adequate to reduce all impacts (Azam et al. 2015, Day et al. 2015). For the whole system in Salt Lake City, a dimming schedule, especially for residential areas, that reduced output from (for example) midnight to 5 a.m. seems feasible and would reduce overall contribution to regional light pollution, reduce human circadian disruption, and save energy.
3. Controls can be used as a complement to a lower overall intensity setting. When additional illumination is needed, in coordination with City officials, lighting levels can be increased during the period of the need and then reduce to the "normal" level. Controls can also be used on a neighborhood by neighborhood basis to find the illumination level that is most consistent with and useful within the character of the neighborhood.

4.1.4 Spectrum

The unwanted impacts of the street lighting system would be minimized by using the lowest possible CCT for the most lights in the system. For wildlife, human health, and preserving dark skies, the preferable choice would be lamps with CCT <2000K. Other considerations lead to the use of higher color temperatures in some zones, but the lower the color temperature can be kept on average, the greater the environmental benefit.

Low CCT lights are commercially available. For example, Signify makes 1800K cobra-head street lights (StreetView, RoadView, EcoForm, RoadStar) and decorative models as well (Domus, MetroScape, UrbanScape, LytePro). Cyclone produces a 1800K street light, as does Ignia Light (Figure 18). SNOC provides a 2200K light that mixes white and amber diodes, as does Ignia Light (Figure 19). Lumican also sells a range of street light luminaires that include 1700K through 2200K. RAB lighting sells a 2000K luminaire (Triboro) to match the color of HPS (https://www.rablighting.com/feature/led-roadway-lighting-triboro; Figure 20). Siteco sells 1750K, 1900K and 2200K street lights. CWES builds luminaire systems that use a warm white LED and a filter to avoid blue light emissions while keeping lumens per Watt high in comparison with 2700K and 3000K LEDs (Figure 21). Some communities in Utah are even manufacturing their own filters to protect the night sky and the tourism industry associated with it (Figure 22).

Where full-spectrum light is desired for aesthetic reasons or other considerations, it should in no instance exceed 3000K and preferably not 2700K. Lower CCTs should be considered for residential neighborhoods citywide as acceptable to City officials and residents.

Figure 18. Application of PC Amber lights by Ignia Light.

Figure 19. Demonstration of mix of white and amber diodes to produce 2200K light for a roadway application by Ignia Light.

Figure 21. C+W Energy Solutions provides filtered LEDs that use with a warm white LED and filter blue light, resulting in a greenish yellow color that contrasts with yellow light of stop lights.

Ivins Fleet Mechanic Wilson Jimenez fits a shield onto his light-filter prototyping station in the city garage. He designed the amber insert that adapts the city's LED bulbs to be "night sky friendly" and has custom-built about 150 inserts to date.

CREDIT DAVID FUCHS / KUER

Figure 22. Ivins, Utah is using filtered LEDs to protect the night sky (https://www.kuer.org/post/fast-growing-southwest-utah-one-city-organizes-protect-night-sky#stream/).

4.2 Ecological Overlay Strategies

In addition to systemwide strategies, which would be implemented throughout all instances of land uses and road segment conditions (e.g., roadway type and associated land use combinations), several ecological overlay strategies would be appropriate that recognize the sensitive natural resources of Salt Lake City. These strategies are tailored to geographic regions where modifications to the light specifications could be used to reduce unwanted environmental impacts.

Each of these strategies is based on a geographic footprint. Spatial data to delineate these regions were either obtained from custodians of those data or digitized by hand based on aerial photograph interpretation. These data sources include:

- Important Bird Areas (from National Audubon Society spatial data webserver);
- Bird Collision Survey Zone (digitized from map provided by Tracy Aviary);
- Parcels that intersect with Critical Wildlife Habitat (digitized from Salt Lake City open space acquisition plan);
- Jordan River Habitat Zone (digitized from aerial photograph interpretation of natural habitat);
- Urban Creek Zone (digitized from aerial photograph interpretation of natural habitat); and
- Community Parks and Neighborhood Parks (from Salt Lake City spatial data webserver).

The digitized habitat zones could be revised with field checks. The purpose of these layers is only to classify roadway lengths for lighting strategies and should not be interpreted as a precise mapping of habitat values.

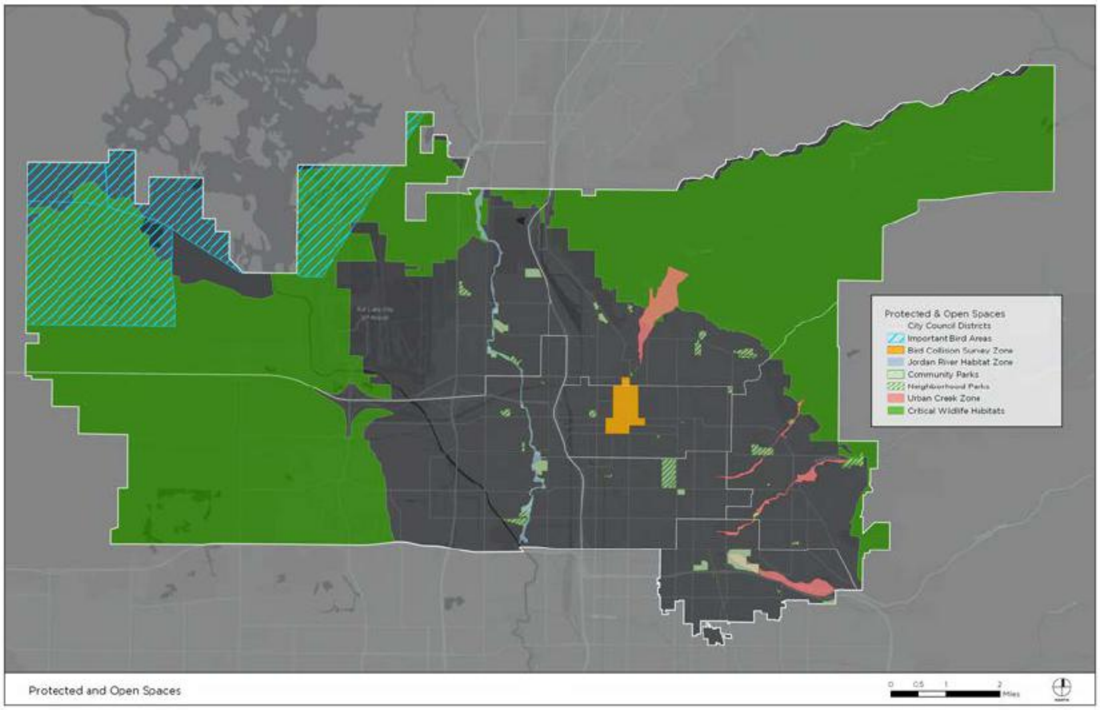

Figure 23. Zones considered for ecological lighting strategies.

A set of additional guidance to reduce impacts that are targeted to the resources in each of these zones is proposed (Table 1).

Table 1. Strategy matrix for ecological overlay zones and major land uses.

Strategy	**Uplight**	**Spectrum (CCT K)**	**Dimming**	**Part-night lighting**	**Intensity (of HPS lumens)**
Commercial / Bird collision zone	0.02	≤3000	During migration	No	50%
Critical Wildlife Habitat	0	≤2200K	No	No	50%
Community Parks Natural Lands	0	≤2200K	No	Yes	50%
Jordan River	0	≤1900K	No	Yes	50%
Urban Creeks	0	≤1900K	No	Yes	50%

4.2.1 Bird Collision Zone

The area which is currently monitored for bird collisions is found in the central business district. It is also the brightest location when observing the region from space. Mortality of birds results from the mixture of lights that attract nocturnally migrating birds with the presence of tall buildings with large expanses of glass with which bird collide. The lights draw the birds in and then the glass kills them (Sheppard and Phillips 2015). Current lighting in this zone includes many decorative lights that are not yet shielded to direct light downward. The high lighting levels provided in a commercial zone with the lack of shielding explains the brightness of this area from above at night. Recognizing the need for lighting appropriate for a commercial business district and its level of activities leads to a suggestion of compromise for lighting. Rather than proposing no uplight, even reducing uplight to 2% would represent a dramatic improvement over existing conditions. If no uplight is possible, it would be preferable. Color temperature in this area, and other commercial zones, should be capped at 3000 K. Intensity of lights should be set to 50% of that measured for previous high-pressure sodium lamps to account for human sensitivity to 3000 K lights. With full controls available for the system, a dimming program could be further implemented during peak migration periods (April/May and September/October). If only one period is chosen, it should be fall because the fall migration includes all of the young of the year, which are especially susceptible to collision. Such additional dimming could be implemented either all night or after midnight or another set time. For this area, actions on the part of the City might catalyze participation in mitigation approaches by property managers (Light Out Salt Lake organized by the Tracy Aviary); turning lights out inside buildings at night would further reduce attraction of birds and resulting mortality.

4.2.2 Critical Wildlife Habitat Zone

The region that intersects with parcels containing critical wildlife habitat is found in the foothills to the east of downtown and then in the flat shorelands to the west. The western area also includes the two globally significant Important Bird Areas. Because this zone contains a range of land uses, including commercial, industrial, and residential areas, the proposal is to match the low color temperature of previous lighting systems (e.g., 2000–2200 K) with full cut-off lighting to reduce impacts on nearby sensitive resources. This lower temperature is especially important near the Great Salt Lake, which is a source of fog (Hill 1988). Fog is extremely efficient at reflecting light and recent research has shown that foggy conditions result in a 6-fold increase in night sky brightness (a measure of light pollution) (Ściężor et al. 2012). Fog also scatters light down into habitats. Full cut-off lighting at a low enough color temperature to allow reasonable color rendering should balance the needs of the land uses in these zones with the sensitive resources found there.

4.2.3 Jordan River and Urban Creeks

The Jordan River and the urban creeks cut through the street grid such that they intersect with only a few street lights along any given segment. It might therefore be possible to minimize impacts to these riparian zones by using low color temperature lights as street segment intersect these zones. Two major considerations in riparian zones are insect attraction and bat impacts, since both groups will be found at higher density in these zones. Best practices for reducing impacts to bats (Voigt et al. 2018) include a limit on light at the edge of habitat of 0.1 lux, avoiding direct glare into habitats, and seeking to avoid light <540 nm. A low CCT light would minimize insect attraction (Longcore et al. 2018a). Red lights are being used in Europe to minimize impacts to bats (Spoelstra et al. 2017) but it is not clear if red light would be acceptable within this context.

4.2.4 Community Parks and Natural Lands

Community parks and natural lands may contain sensitive species and often have areas that are closed after dark. Lighting surrounding them could be limited in CCT to 2200 K and lights on roads within parks might be shut off after a curfew. Darkness in these instances can serve to reduce unwanted activity because any lights brought into a dark park would indicate unallowable activity. Recommendations for community parks and natural lands will probably need to be tailored by site to accommodate variations in use, park type, and surrounding land uses. Tracy Aviary is located in a community park and has captive birds that are kept outdoors. Reducing or eliminating street lighting around any outdoor exclosures with captive birds is recommended for the health of the birds.

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Ecological and Organismic Effects of Light Pollution

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Advanced article

Article Contents

Since the invention of the electric light bulb in 1879, a significant portion of the planet has been transformed from experiencing a natural pattern of light and dark determined by the sun, moon, stars and occasional other transient lights to being subjected to intermittent and perpetual illumination from human civilisation that is unprecedented in the history of Earth. The pervasiveness of this phenomenon and its exponential growth has measurable and significant consequences for living organisms. The results of recent research have extended knowledge about the geographic scope and specific impacts of artificial night lighting on animal behaviour, physiological processes and ecological interactions across a range of taxa and its broader ecosystem effects.

Introduction

Even a cursory review of satellite-derived composite maps of nocturnal light emissions reveals the global reach of human-produced disruption of the night-time environment. Remotely sensed images can be used to discern city and other electric lights, fires, flares from hydrocarbon facilities and fishing boats (**Figure 1**). The influence of lights on surrounding terrestrial and aquatic habitats depends in large part on the total amount of light directed outwards and downwards and on the amount of cloud cover and particulates in the air that are available to scatter light that otherwise would propagate upwards (Kyba *et al*., 2011). The geographic rate of increase in outdoor lighting is estimated to be 6% per year (Hölker *et al*., 2010).

Light pollution within the context of the life sciences requires a context-dependent definition. From the perspective of evolutionary history and the environment to which all life has adapted, any human-generated light can be considered pollution in that it disrupts natural conditions. Such a definition is unsatisfactory, because nocturnal illumination is a hallmark of modern society and viewed as being indispensable to economic and social well-being. Consequently, a definition of light pollution could be limited to human-generated nocturnal lighting that is excessive or unnecessary or that has adverse impacts on particular species or species groups that are of concern. This definition is also subjective, because one person's excessive lighting is another's artistic expression. For practical purposes, therefore, a definition of light pollution is negotiated in a context-dependent manner that weighs the reality that all artificial lighting disrupts natural patterns of light and dark against the utility and desirability of that light for a range of human activities. The focus on impacts to either the natural environment or the human view of the night sky leads to recognition of 'ecological light pollution' and 'astronomical light pollution' (Longcore and Rich, 2004).

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Light at night as an influence on biological processes is a global phenomenon that is highly spatially variable. Global night lights have been measured by satellites at a ~1 km resolution since 1992 and at a ~500 m resolution since 2012 (Kyba *et al*., 2015). These sensors measure the amount of light that escapes upwards, which is correlated with the amount of light that might be received by any person or organism in the environment. Across the globe, lighting visible from space is correlated with economic activity, population density, industrial production and other human activities. Night-time lights have their greatest concentration on continents and in the Northern Hemisphere but are highly variable within these regions (Gaston *et al*., 2014). The effects of lights extend far beyond locations where they occur because light is scattered and reflected in the atmosphere (Kyba *et al*., 2011). The resulting light visible on the ground is called *sky glow* and can reach intensities equal to the illumination from the full moon (**Table 1**). Extrapolation of satellite-measured night-time lights to the associated sky glow effects has shown that very few night skies in the world are entirely unaffected by scattered light from human sources (Cinzano *et al*., 2001).

The natural range of illumination between day and night is 11 orders of magnitude (**Table 1**). Illumination at a forest floor can be 10^{-4} or 10^{-5} lx or less, while a full moon usually produces around 0.1 lx (or more at high altitudes or near the equator) and full sunlight can exceed 10^5 lx. As a result of this variation, species have evolved powers of perception and navigation adapted to the large differences in ambient illumination between day and night. For example, some species have the ability to navigate, by sight, in conditions that are far darker than what

Figure 1 The global extent and intensity of artificial night lighting is visible in this photograph of the India–Pakistan border taken from the International Space Station on August 21, 2011. The border itself is entirely illuminated with the characteristic orange light of sodium vapour floodlights installed by the Indian government. Photograph ISS028-E-029679 from NASA.

humans would consider complete darkness (Warrant and Dacke, 2010). Bioluminescent organisms have evolved to exploit the natural conditions of illumination for signalling, especially in the oceans and forests. Disruption of these natural conditions, even at light levels imperceptible to the human eye, therefore has adverse consequences on a range of species and interactions (Longcore and Rich, 2004) and, potentially, their evolutionary trajectories (Swaddle *et al*., 2015). These effects could be profound; even streetlights are a million times brighter than typical ambient night-time conditions (Perry *et al*., 2008).

Processes of Biological Disruption by Light Pollution

The degree to which artificial night lighting affects biological systems depends on the species involved and the type of disruption in question, combined with the characteristics of the light itself. Gaston *et al*. (2013) identified six biological and ecological processes that could be disrupted by light at night: photosynthesis, niche partitioning, dark repair and recovery, photoperiodism/circadian rhythms, visual perception and spatial orientation. The extent of impacts varies with the duration, intensity and wavelengths of light that are in the environment (Gaston *et al*., 2013; Longcore and Rich, 2016).

Photosynthesis

Photosynthesis under artificial lighting is desirable in greenhouse agricultural production, where large amount of energy from light that is concentrated in wavelengths at which plants are photosynthetically active (400–700 nm) is required. Little photosynthesis occurs under artificial lighting outdoors and it is limited to areas close to the light sources (Raven and Cockell, 2006). Lighting can affect photosynthesis indirectly as well, through triggering of other physiological responses in plants that influence photosynthesis (Skaf *et al*., 2010).

Niche partitioning

Niche partitioning associated with lighting levels has developed as a result of the historically predictable daily, monthly and annual patterns of light and dark. Diurnal animals that exploit artificial night lighting as a means to extend activity periods occupy the ‘night light niche’, thereby disrupting normal species interactions during the time locations are illuminated. Perry *et al*. (2008) provide an extensive list of diurnal reptiles and amphibians that exploit the night light niche, including geckos, iguanas, skinks, snakes, toads and treefrogs. This phenomenon was also measured for fishes around offshore platforms, where it was referred to as a ‘visual subsidy’ for the fishes exploiting the night light niche (Keenan *et al*., 2007). Although it is tempting to interpret use of the night light niche as being ‘good’ in some abstract sense, this is misleading; every species that benefits from day-like conditions at night intrudes into a niche already occupied by species adapted to natural patterns of light and dark.

Other species that are normally active between twilight and dawn can have their niches disrupted as well. Fireflies are active during particular ambient illumination conditions that sequentially separate the activity periods of different species (Lloyd, 2006). This temporal niche partitioning is vulnerable to changes in nocturnal lighting conditions.

The logical and predictable extension of the erosion of light as a means to maintain niche partitioning is that local species diversity

Table 1 Illumination from natural and artificial sources compared with ecological consequences across taxonomic groups

Magnitude (lx)	Natural and artificial illumination levels (lx)	Species responses with illumination levels (lx)
10^5	103 000 Full sunlight	
10^4	50 000 Partial sunlight	
	10 000 Cloudy	
10^3		
10^2	188 Sunset (Nowinszky, 2004)	
10^1	10 Parking lot	
10^0	1 Light pollution in urban marsh habitat	2.1 Reduction in seed set in short-day soya beans
		1 Initiation of downstream drift and emergence from winter substrate in fishes
10^{-1}	0.5 Illumination from urban sky glow (Kiel, Germany)	0.5 Maximum for foraging in some fishes
	0.1 Typical full moon (0.4 maximum	0.3 Melatonin reduced in Senegal sole (Oliveira *et al*., 2010)
	0.18–0.71 Light pollution on beaches (Taiwan) (Santos *et al*., 2010)	0.25 Disrupted melatonin, promoted tumour growth in rats
	0.178 Illumination from urban sky glow (Vienna)	0.2 Maximum illumination for most fireflies (Brazil) (Hagen and Viviani, 2009)
		0.1 Reduced foraging in rodents and schooling in fishes
		0.1 Desynchronisation of coral planula production (Jokiel *et al*., 1985)
10^{-2}	0.01 Lower limit of many commercial light meters	0.06 Prairie rattlesnakes forage more compared with 0.35 lx
	0.01–0.04 Crescent to half illuminated moon	0.04 Maximum illumination for activity in frogs
		0.01 Delayed foraging on forest floor (Wise, 2007) and increased number of visual threat displays in salamanders
10^{-3}	0.001 Instream illumination from billboards	0.003 Less activity and females hide nest in frogs
		0.001 Foraging in brown trout
		0.001–0.01 Most moth activity (Nowinszky, 2004)
10^{-4}	0.0005 Starry sky without moon	0.0006 Circadian rhythm of *Drosophila jambulina* influenced (Thakurdas *et al*., 2010)
		0.0001 Maximum for activity of *Ascaphus truei* frogs
10^{-5}		0.00001 Lower foraging limit in fishes
10^{-6}	0.000001 Dark night in forest	0.0000004 Negative phototaxis in phantom midge

Common sources of artificial light, including light reflected in the atmosphere (sky glow), produce illumination both brighter than many naturally occurring night-time conditions and above threshold levels to influence many biological phenomena. Sources in Rich and Longcore (2006) unless otherwise noted.

will decline when the full range of light and dark conditions no longer occurs and breadth of potential light-associated niches is reduced. **See also**: **Coexistence**

Dark repair and recovery

Dark repair and recovery refers to nocturnal physiological processes that are essential to healthy functioning of organisms inactive at night. Exposure to artificial lighting during these periods, even for short bursts, can disrupt these physiological processes and have adverse consequences. The production of the hormone melatonin during dark hours and the consequent repair benefits is an example (Liu *et al*., 2013). Melatonin is produced in organisms ranging from single celled to the most complex because of its early origins in evolutionary history (Jones *et al*., 2015). In vertebrates, its function as an antioxidant and scavenger of free radicals can be suppressed by exposure to light at night.

Suppression of melatonin production is greatest for wavelengths of light in the blue portion of the spectrum (Brainard *et al*., 2001). The response to light is dose dependent, with small reductions in melatonin production documented down to within the measurement accuracy of melatonin in the saliva or blood (Rea *et al*., 2010). The lower levels of illumination associated with measurable melatonin suppression in humans is on the order of magnitude of that provided by a streetlight shining directly through a window. The epidemiological studies of melatonin suppression and associated circadian disruption of humans by exterior lighting do suggest an effect; the brightness of human sleeping environments is associated with obesity (McFadden *et al*., 2014), breast cancer (Hurley *et al*., 2014) and prostate cancer (Kloog *et al*., 2009), with the intermediate mechanism of circadian disruption and melatonin suppression assumed. Such studies involve use of satellite imagery of night lighting at multiple scales and provide epidemiological indications that light pollution affects these chronic diseases in humans through interruption of dark repair and recovery.

Photoperiodism and circadian rhythms

Light is a signal that influences the timing of activities for organisms at several scales. Circadian rhythms are entrained daily by light and dark cycles for all organisms living in illuminated environments. Similarly, daylength signals trigger physiological responses associated with seasonal changes in environmental conditions for species living in seasonal environments.

Circadian clocks have evolved to synchronise physiology, metabolism and behaviour to the 24-h cycle of Earth (Vanin *et al*., 2012). In diverse organisms, circadian oscillators can be entrained to local time through the detection of an environmental cue, known as a zeitgeber, such that the endogenous timing of peaks and troughs stably corresponds to an environmental reference point, frequently dark-to-light transition, for which specialised photoreceptive and phototransductive mechanisms have evolved to be capable of functioning as pacemakers to synchronise downstream rhythmic events to the environment. **See also**: **Circadian Rhythms**

Studies of the effects of artificial lighting on photoperiodic responses are abundant, partly because of the implications for understanding human health (Zubidat *et al*., 2010). As a whole, they show that artificial lighting can entrain circadian rhythms and influence physiological functions such as immune response at relatively low levels (Bedrosian *et al*., 2011). For example, extremely dim light is sufficient to entrain rhythms in mice and can be done without affecting the other physiological indicators of light influence such as phase shifting or reduced melatonin production (Butler and Silver, 2011). For shorter wavelengths (blue and green), entrainment takes place at 10^{-3} lx. Adverse effects of mistiming have been documented on immune response, metabolism and stress associated with exposure to dim light at night (Bedrosian *et al*., 2011; Fonken *et al*., 2010; Zubidat *et al*., 2010).

Light pollution might reset interactions among species whenever synchronisation is important because entrainment requirements are different between species. For instance, plants ‘anticipate’ the dawn with a synchronised circadian clock and increase immune defence at the time of day when infection is most likely (Wang *et al*., 2011). The timing of resistance (R)-gene-mediated defences in *Arabidopsis* to downy mildew is tied to the circadian system such that defences are greatest before dawn, when the mildew normally disperses its spores (Wang *et al*., 2011). The importance of circadian rhythms in plants, for everything from disease response and flowering time to seed germination, and the potential for disruption by artificial night lighting, has not been explored widely (Resco *et al*., 2009). Some plants might use light-triggered circadian rhythms to synchronise expression of antiherbivory compounds with periods of peak herbivory, leading to increased loss from herbivory in out-of-phase plants (Goodspeed *et al*., 2012). **See also**: **Plant Circadian Rhythms**

In animals, research on timing of morning birdsong illustrates how lights can subtly influence reproductive behaviours through influences on circadian rhythms. For forest birds in Vienna, proximity to night lights advanced the morning chorus and resulted in more extrapair copulations than would be expected for younger Blue Tits (*Cyanistes caeruleus*) that were defending lower quality territories on forest edges adjacent to streetlights (Kempenaers *et al*., 2010). Other work has shown an earlier dawn chorus in light-polluted environments e.g., (Miller, 2006).

Artificial lighting can also induce or delay seasonal changes that are asynchronous with actual conditions, described as ‘seasons out of time’ (Haim *et al*., 2005). Such mistiming leads to failure of organisms to adjust appropriately to changing seasons, with a range of results that include plants not setting seed with shortened days or failing to drop leaves in the fall (Bennie *et al*., 2016) and disruption of reproductive synchronisation necessary to exploit environmental conditions (Robert *et al*., 2015). Integrating studies of circadian disruption on species in the wild with research on human and animal models is at the frontier of chronobiological research (Dominoni *et al*., 2016).

Visual perception

Artificial lighting can allow species to see at night that would otherwise not be able to do so. This has the potential to affect a whole range of behaviours and species interactions. Many studies link foraging activity with specific lighting conditions, presumably optimised to reduce predation risk while maximising foraging efficiency for each species. For example, onset of foraging time is delayed in lesser horseshoe bats (*Rhinolophus hipposideros*) when exposed to lighting and the lit areas of hedgerows were avoided (Stone *et al*., 2009). This pattern of delay is now seen in multiple taxa, from salamanders (Wise, 2007) to sugar gliders (*Petaurus breviceps*) (Barber-Meyer, 2007) to bats (Boldogh *et al*., 2007).

A driving force behind patterns of activity and foraging by animals influenced by artificial lighting is presumably the balance between rewards of foraging and risk of predation. The general pattern that has emerged is that increased light assists predators to locate prey. As a result, primary consumers that might otherwise forage under cover of darkness avoid illuminated areas. This general rule has an exception, which is that prey species with a communal predator defence, such as schooling or flocking, experience decreased risk of predation with additional light. Observations of individual species and of communities are consistent with this pattern. The insect community under streetlights has elevated proportions of predators (Davies *et al*., 2012), while schooling fish are aided by group vigilance afforded by additional light (Nightingale *et al*., 2006). A general review of nocturnal foraging suggests that birds and mammals are subject to less predation pressure at night and that the number of animals foraging together is greater at night, especially for clades that are not strictly nocturnal (Beauchamp, 2007).

Spatial orientation

The orientation of species relative to artificial light sources at night, or the inability of species to orient in the presence of artificial light sources, is perhaps the most visible impact of artificial lighting on ecology (Verheijen, 1985). For example, migratory birds are attracted to and collide with oil platforms, cruise ships, communication towers, buildings and athletic stadia and seabirds are attracted to lighted vessels (reviewed in Longcore and Rich, 2016). Hatchling sea turtles are unable to orient properly to crawl to the ocean in areas influenced by artificial lights (Salmon, 2003) and insects are attracted to artificial light sources (**Figure 2**).

Figure 2 Different light sources along a riverside meadow verge in Germany, including cold-white LED (light-emitting diode), halogen spotlight, neutral-white LED, high-pressure sodium vapour, mercury vapour and metal halide. Greatest numbers and species of insects were collected at traps affixed to lamps rich in blue and ultraviolet lights (mercury vapour and metal halide). LEDs, which did not contain ultraviolet light, attracted the fewest insects compared with other types of lighting, but among LEDs, cold-white LEDs attracted the greatest number of insects (Eisenbeis and Eick, 2011). Reproduced with permission from A. Hänel.

Movement and distribution of animals are limited by their ability to orient within the environment. Visual cues and light detection are used by almost all species except those living in perpetual darkness. The pervasiveness of light detection in orientation is shown by the discovery in *Drosophila* larvae of photoreceptors not associated with vision, which are found in each body segment and are sensitive in the ultraviolet, violet and blue wavelengths (Xiang *et al*., 2010). These are precisely the areas of the spectrum associated with light avoidance because daylight is rich in these spectra. Even those species that restrict their activities to the darkest, moonless nights have means of using available light to orient. Nørgaard *et al*. (2008) documented the visual ability of a nocturnal spider in the Namib Desert that presumably uses spatial and temporal summation to identify landscape structures, allowing it to orient and be active in the darkest conditions, thereby minimising predation risk.

The mechanisms by which artificial lighting influences spatial orientation of different taxa may differ. For nocturnally migrating songbirds, the disorientation of birds at lighted communication towers or tall buildings tends to occur when cloud cover has precluded navigation by celestial cues and the bird has encountered a bright light on the landscape. The behaviour is described as the bird being 'trapped' within the zone of influence of the lights. Studies show that flashing lights attract far fewer birds and that turning off a light temporarily allows birds to leave an area and continue on their migratory route. The process for insect attraction and disorientation is similarly described as the animal being 'trapped' or 'dazzled' at the light, with several hypotheses for the mechanism of the phenomenon. For hatchling sea turtles, experimental evidence has established that individuals move away from the horizon with dark silhouettes, which for most of evolutionary history would have been the onshore dune and beach vegetation. Artificial lighting onshore is inconsistent with that pattern and hatchlings either orient towards lights or do not have a fixed orientation (Salmon, 2003).

Synergistic Effects

The effects of light pollution may extend beyond directly observed impacts on physiology and behaviour. In humans, disturbance by light at night could lead to behaviours that increase circadian disruption such as turning on additional lights. In ecosystems, the behavioural or physiological changes caused by artificial night lighting could have cascading effects (Bennie *et al*., 2015). The ecological and evolutionary consequences that result from the global increase in night lighting can interact synergistically with other hazards. For example, lights attract birds to other hazardous sites such as offshore petroleum platforms, wind turbines and buildings where they subsequently are at risk of colliding with glass.

Another synergistic consequence is the creation of polarised light by night lighting (Horváth *et al*., 2009). For example, mayflies are attracted to wet pavement at night because polarised light created by reflecting lights off the pavement is similar to the polarised light signal of water bodies.

The documented disruption of immune function by artificial lighting across a range of taxa has potentially synergistic adverse effects in combination with emerging pathogens and the spread of well-known pathogens under changed climates.

Mitigating Light Pollution

A comprehensive approach to mitigating the effects of light pollution on biological systems would include five considerations: need, spectrum, intensity, direction and duration (Longcore and Rich, 2016). In short, adverse impacts of artificial night lighting could be minimised if

- unnecessary lights are extinguished or not installed;
- spectrum of light is chosen to minimise impacts (especially not ultraviolet or blue, with a preference to reduce and avoid light less than 540 nm (Falchi *et al*., 2011));
- lights are only as bright as necessary for the purpose;
- light is directed only where it is needed, including shielding sensitive habitats from lights, even if those lights are directed downwards; and
- lights are only illuminated as long as necessary and are turned off when not needed (e.g. using timers, motion detectors or bilevel lighting systems that reduce light during low-use periods).

As an example of these considerations, duration and spectrum of lights are important for efforts to mitigate impacts on migrating birds. Attraction varies by wavelength of light (Poot *et al*., 2008) and much work remains to be done on the functioning of avian magnetoreception under different spectra and irradiances of artificial lighting and how these interact in the field. Both red and white solid lights attract birds in a way that flashing lights do not (Gehring *et al*., 2009). Attraction of birds to lights can be reduced by flashing (with a completely dark phase), regardless of spectrum (Gehring *et al*., 2009), so that changes to duration can mitigate spectrum. Where lights must be on all of the time, such as on offshore hydrocarbon platforms, green lights will apparently attract far fewer birds than full-spectrum (white) lights (Poot *et al*., 2008).

New technologies create both opportunities and challenges for mitigation of light pollution. LED (light-emitting diode) lamps have short warm-up time, are highly directional and can be dimmed easily to allow for a dynamic lighting system, but many also contain far more light in the blue spectrum than those lamps they might replace. These attributes provide the opportunity for better lighting control in terms of intensity and direction, but often also result in increased exposure to physiologically active short wavelengths that propagate more in the atmosphere. In 2016, the American Medical Association issued a statement warning against the use of blue-rich street lighting because of potential harmful effects on human health, public safety and the environment (see http://www.ama-assn.org/ama/pub/news/news/2016/2016-06-14-community-guidance-street-lighting.page). LEDs that are lower in blue content are reaching the market, and to reduce ecological and astronomical impacts, light and filter combinations are now being developed and installed.

Many approaches are available to mitigate the effects of light pollution on biological systems (Falchi *et al*., 2011), and unlike other forms of pollution, no costly clean-up is needed. Because other interest groups are involved in attempts to control lighting for the purpose of astronomical observation or energy conservation, full engagement by biologists and life scientists of all specialties is needed to ensure that measures proposed as solutions also reduce impacts to people, ecosystems and evolutionary processes. Testing and defining mitigation strategies for artificial night lighting will be an important research direction.

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