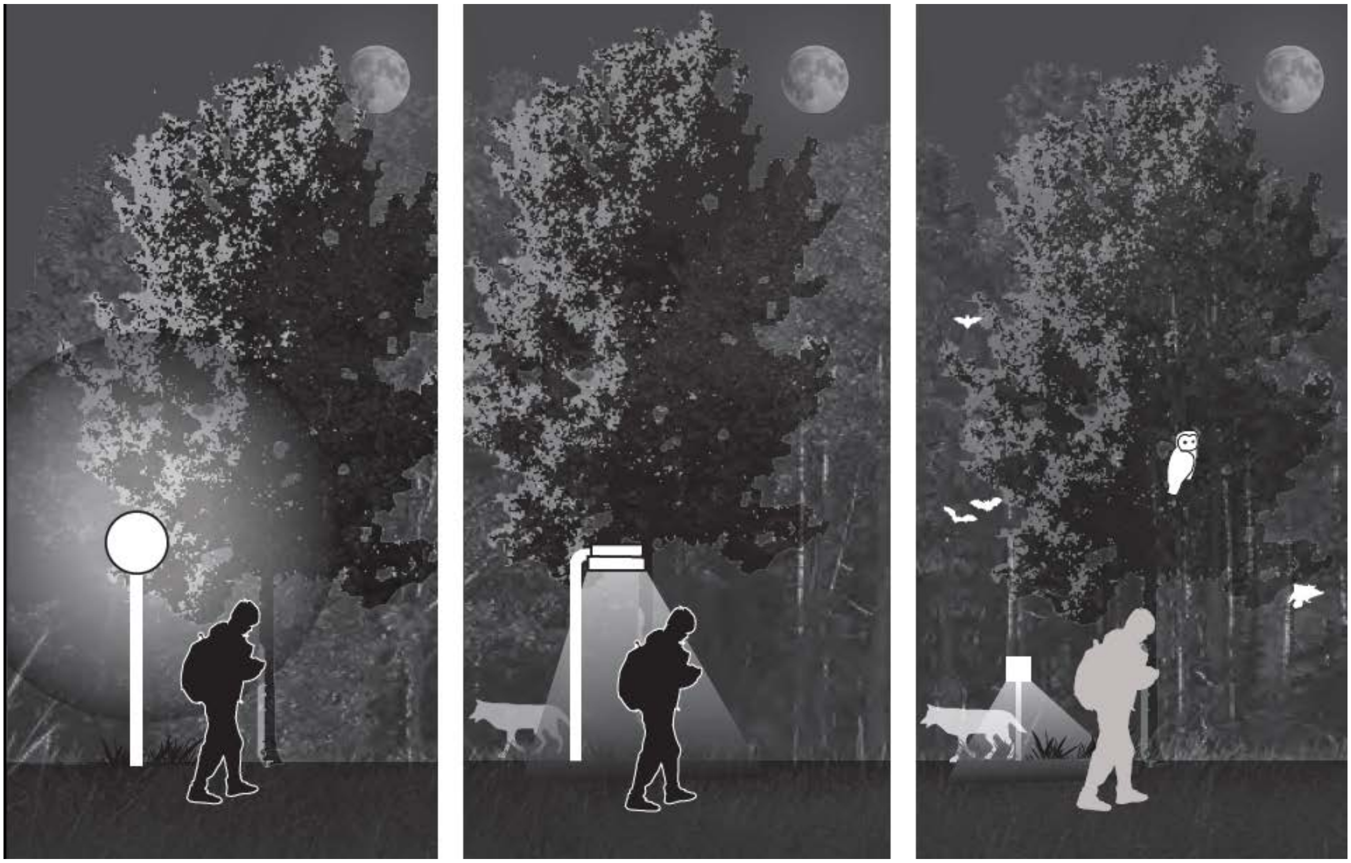
National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Artificial Night Lighting and Protected Lands

Ecological Effects and Management Approaches

Natural Resource Report NPS/NRSS/NSNS/NRR—2016/1213



THE URBAN WILDLANDS GROUP

USC School of Architecture

USC Dornsife
Dana and David Dornsife College of Letters, Arts and Sciences

ON THE COVER
Example of controlling light direction to reduce environmental consequences
Illustration by Leigha DelBusso

Artificial Night Lighting and Protected Lands

Ecological Effects and Management Approaches

Natural Resource Report NPS/NRSS/NSNS/NRR—2016/1213

Travis Longcore[1,2,3] and Catherine Rich[1] with illustrations by Leigha DelBusso[2]

[1] The Urban Wildlands Group
P.O. Box 24020
Los Angeles, CA 90024

[2] School of Architecture
University of Southern California
Los Angeles, CA 90089

[3] Spatial Sciences Institute
Dornsife College of Letters, Arts and Sciences
University of Southern California
Los Angeles, CA 90089

May 2016

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received formal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data, and whose background and expertise put them on par technically and scientifically with the authors of the information.

This report is available in digital format from the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/). To receive this report in a format optimized for screen readers, please email irma@nps.gov**.**

Please cite this publication as:

Longcore, T., and C. Rich. 2016. Artificial night lighting and protected lands: Ecological effects and management approaches. Natural Resource Report NPS/NRSS/NSNS/NRR—2016/1213. National Park Service, Fort Collins, Colorado.

NPS 999/132629, May 2016

Contents

Page

Contents (continued)

Page

Figures

Figures (continued)

Page

Two natural forms of light at night — from the moon and bioluminescent plankton — contrast with coastal urban lighting in New Jersey, United States. Artificial lighting dramatically changes the intensity and spectrum of light available at night and homogenizes the nocturnal visual environment over space and time. Photograph by Flickr user catalano82 is reproduced with permission.

Executive Summary

Artificial night lighting represents a growing challenge for managers of parks and protected lands. The disruption of natural patterns of light and dark, which have been more or less reliable for millions of years, has a range of adverse consequences for wildlife across taxonomic groups and landscape types. This document reviews effects of artificial night lighting by habitat type and discusses the approaches available to land managers to mitigate and avoid certain adverse effects of artificial night lighting.

Coastal dunes, beaches, and shorelines are a transition zone between terrestrial and aquatic habitats. They often contain gradients of lighting influence from developed shorelines to darker lakes and oceans. Sea turtles are prominent victims of these disrupted lighting regimes. The foraging decisions of many other species are influenced by lighting conditions, embodying tradeoffs between predation risk and dietary needs.

Deserts and scrublands are open habitats with few barriers to light transmission. They are also often hot in the day, with large proportions of nocturnal and crepuscular species avoiding thermal stress. Many nocturnal desert species prefer low illumination levels and have good visual performance under the faint light of the darkest nights.

Wetlands and rivers are often dark spots surrounded by lights, especially when close to human settlement. Movement of species into and out of wetlands and streams is influenced by lights, as is the movement of animals, such as fishes or aquatic invertebrates, up and down rivers and streams. Downwelling light mediates most predator–prey interactions in the water column. Changing light levels cause predators and prey to change depth. Small prey species are influenced by the phase of the moon, and lighting can degrade conditions favorable to successful foraging. Emerging research demonstrates that lighting influences the developmental rates of wetland organisms such as amphibians.

Islands, oceans, and reefs are increasingly influenced by lights from onshore sources, hydrocarbon extraction platforms, fishing vessels, and all manner of ships. Downwelling light is also a dominant factor in structuring ecosystem processes in marine water columns, and many organisms are sensitive to extremely small changes in light levels. Extensive vertical migrations are driven by changes in surface illumination. Changes in surface lighting can have effects hundreds of meters below the surface. Lighting will alter reproduction and predator–prey interactions, and can attract organisms across wide areas.

Grasslands are also open habitats with few barriers to block lights. Research shows influence of lighting on nesting behavior of birds, distribution of predators, and signaling by bioluminescent organisms such as fireflies.

Deciduous and evergreen forests can block light and reduce its influence, but also contain communities of forest floor species adapted to lighting levels much dimmer than in exposed habitats. Therefore even low levels of light can influence foraging times or timing of reproductive activity.

Alpine and tundra habitats are well represented in protected lands. Many species have annual rhythms designed to avoid the harsh winter that are potentially disrupted by lighting cues. In alpine habitats, the slope of the land potentially exposes habitats to direct glare from downslope sources in addition to light reflected in the atmosphere.

Finally, *urban environments* have many artificial light sources, but still can support significant biodiversity in the form of both resident and migratory species. Migratory birds are attracted to lighted structures at night and collide with windows during the day. Some bat species are attracted to insects found under city lights, while others avoid them.

Mitigation of adverse effects of anthropogenic light in these different habitats is guided in five ways:

1. Need. Creative solutions are often available to avoid use of lights where they are not absolutely necessary. Especially in natural areas, managers should exercise discretion in limiting the lighting infrastructure.
2. Spectrum. Although no color of light is benign in all situations, managers should avoid lights that have ultraviolet or blue light (shorter wavelengths) and in general use lights with red and yellow hues.
3. Intensity. Reducing the intensity of lights can often improve visibility for humans by reducing the contrast between light and shadow, allowing people to see a larger area than they might otherwise be able to discern. Guidelines for lighting intensity from the lighting industry should not be followed when trying to reduce impacts to wildlife, because they are usually higher than necessary for human vision and do not take into account impacts to wildlife.
4. Direction. Lights should be shielded such that they only cast light where it is needed, and never be directed upwards.
5. Duration. Timers and motion detectors can reduce the time a light is on and may therefore reduce impacts. Curfew hours for lights can also enhance visitor experience.

In this report, many lighting situations are considered, including communication towers, night hiking and mountain biking, campsite lighting, off-road vehicles, monuments, light-assisted fishing, security lighting, bridges, roadway lighting, energy production installations, indoor lighting, lighthouses, and billboards. With careful planning and collaboration, usually with nearby jurisdictions, managers of parks and other protected lands can be leaders in the control of light pollution and increase enjoyment of natural lands from inner city parks to wilderness areas.

Acknowledgments

This research was funded by the National Park Service Night Skies Program through a cooperative agreement with The Urban Wildlands Group. Illustrations were funded by the University of Southern California School of Architecture’s Graduate Research Scholar Program. We thank Chad Moore, Kurt Fristrup, Jeremy White, Jim Von Haden, and three anonymous reviewers for constructive and insightful comments. We furthermore thank Karen Treviño and acknowledge the Natural Sounds and Night Skies Division for its support.

Introduction

Americans have long recognized that parks and protected lands can provide opportunities to see and enjoy the solitude of unspoiled nature, where the natural rhythms of life are allowed to flourish with minimal influence from humans. Managers of parks and protected lands balance the need to provide visitor facilities with the impacts of such infrastructure on the environment. Although night lighting may be a requirement for visitors in some circumstances, scientific research has documented a range of adverse consequences of night lighting on ecosystems and wildlife. The effects of lighting on species and ecosystems can be reduced, and in some instances avoided altogether. This report provides examples of assessing the impacts of night lighting on wildlife, and presents options to retrofit and design lighting that minimize impacts to wildlife and the nocturnal environment.

Extensive outdoor (and indoor) electric lighting is a recent phenomenon. Thomas Edison commercialized the electric light bulb in the late 1880s, and outdoor use was largely limited to cities until well into the 1900s. Electric lights were introduced in city centers as replacements for gas lamps in the late 1880s, with lethal effects on wildlife. Nearly 1,000 migratory birds were killed in collisions after being attracted to an electric light tower in Decatur, Illinois in 1886 (Gastman 1886). Significant outdoor lighting spread with the rural electrification programs of the 1930s and 1940s. More recently, other significant sources of outdoor lighting have spread across large swaths of the globe, primarily through illumination of human settlements and associated transportation infrastructure. Other sources of artificial night lighting have proliferated as well. Lighting associated with oil and gas development illuminates large terrestrial and offshore regions. Similarly, light-assisted fishing operations illuminate oceans in many regions and oceangoing freighters and passenger ships introduce mobile light sources along oceanic routes. Together, these and other light sources introduce novel lighting conditions that have no historical precedent in natural ecosystems. Natural patterns of darkness are lost or endangered globally (Bennie et al. 2015, Duffy et al. 2015, Marcantonio et al. 2015).

This document is divided into two sections. The first section reviews the effects of artificial night lighting on major habitat types. No single solution can mitigate all adverse effects of artificial night lighting. We therefore attempt to generalize the concerns that typify each biome. The second section provides recommendations for management approaches to minimize impacts from lighting. We address the characteristics of lights in terms of need, spectrum, intensity, direction, and duration, with reference to biomes in which each method of control would be applicable. This discussion addresses common lighting applications — roadways, parking, and walkways — as well as specialized situations like night hiking and mountain biking, vanity lighting, communication towers, and light-assisted fishing.

Effects of Artificial Night Lighting on Natural Ecosystems

Natural patterns of light and dark

In the natural world, sources of light are either very predictable or notably ephemeral. The dominant and structuring source of light is the sun, through daylight and the reflected light of moonlight.

Patterns and intensity of sunlight and moonlight vary with geographic location, weather, and time, but they have certain predictable characteristics. For example, the daily, monthly, and seasonal patterns of moonlight and sunlight incident upon the Earth's atmosphere are only rarely interrupted (e.g., by a solar eclipse). Once the sun has set, the brightest possible constant light source is a full moon until the sun rises again (**Figure 1**). The length of the night varies by season and latitude and these patterns are, in the timescale of biological activity, fixed. Weather influences illumination during the day, and does not, with the exception of lightning, increase nocturnal illumination. Fires, lightning, bioluminescence, starlight, airglow, and zodiacal light contribute to nighttime illumination under natural conditions, and these transient sources are brief, rare, or dim in comparison with sunlight and moonlight.

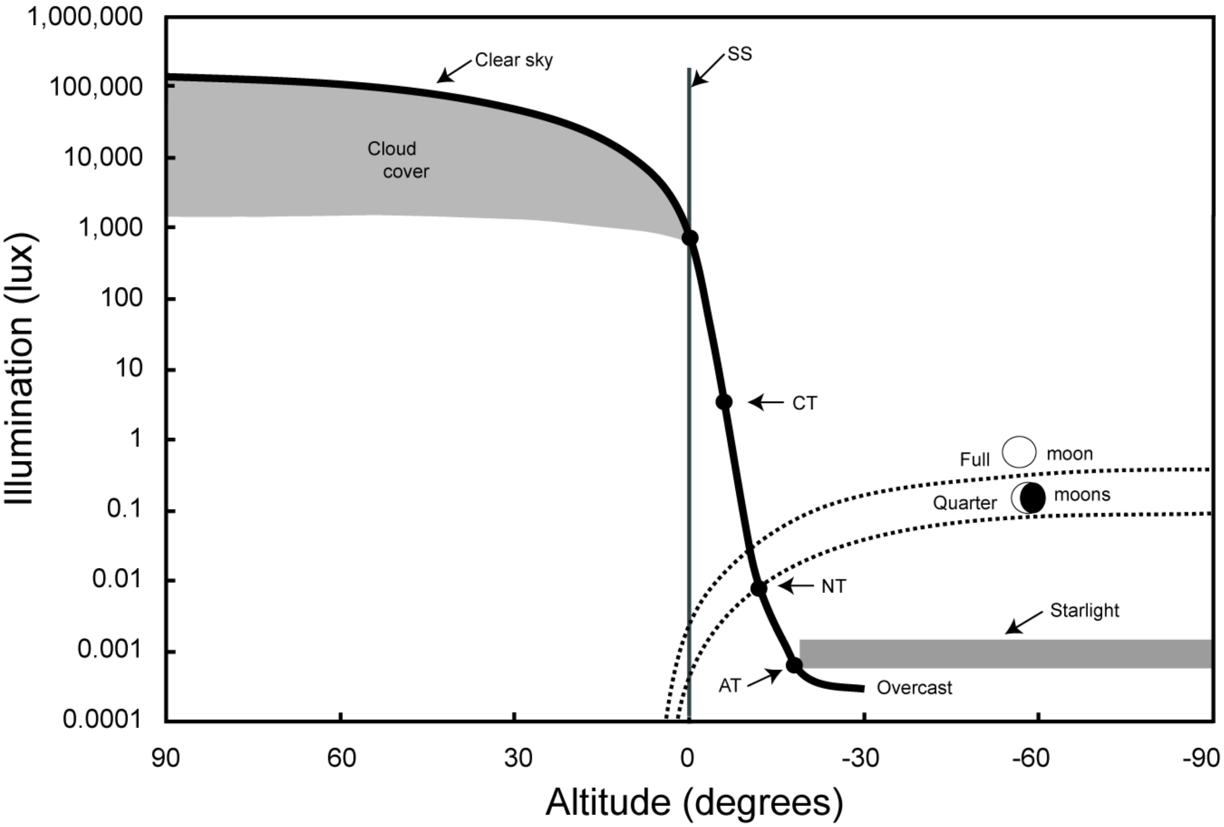


Figure 1. Natural horizontal illumination during the day, sunset, and at night (Beier 2006). Horizontal illumination on the y-axis; x-axis shows altitude above the horizon for the sun and moon. SS = sunset, CT = civil twilight, NT = nautical twilight, AT = astronomical twilight. Modified with permission from Beier (2006).

Light falling on a surface is often measured in lux, a unit of illuminance that sums electromagnetic energy after filtering in accordance with the daytime (photopic) sensitivity of the human eye. Light emitted from a source is often measured in lumens, a unit of luminance that also accounts for the photopic spectral sensitivity of the human eye. Measurements of lux and lumens place more weight on wavelengths to which the human eye responds most strongly, and less on those wavelengths to which the human eye is less sensitive. Similar measurements can be customized for the optic spectral sensitivities of different species by re-weighting the calculations to emphasize different wavelengths of light (Gal et al. 1999 and **Figure 2**).

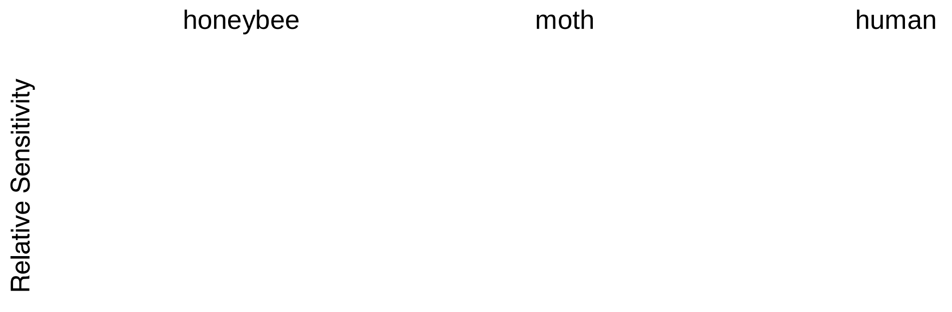


Figure 2. Relative sensitivity to light across the visual spectrum for honeybees (Menzel and Greggers 1985), moths (Cleve 1964), and human photopic vision (CIE 1932).

Outdoor illumination during the day ranges from 100,000 lux in full sunlight to 1,000 lux on a cloudy day (**Figure 1**). Dusk and dawn are transitions into and out of much darker conditions. These transitions are also characterized by predictable changes in the relative intensities of the wavelengths of light. As dusk falls, blue light increases, especially when the moon is new or not present. With moonlight, this blue pulse is diminished or absent and moonlight itself is red-shifted relative to sunlight (Sweeney et al. 2011). Both airglow and zodiacal light also contain more red light than daylight. Variations in illuminance and color trigger many behavioral and physiological processes (Sweeney et al. 2011, Walmsley et al. 2015). Circadian, circannual, and circalunar rhythms are linked to the predictable changes in the light environment. Light triggers can be at different illuminations depending on the environment. What is extraordinarily dim in one environment may be bright in another. For example, the illumination at which activity takes place on a forest floor is on average dimmer than illumination levels triggering the same activity for similar organisms in open grassland. Illumination that is within the natural range of variation on a beach may be far brighter than anything experienced at night at ground level in a dense forest.

Life evolved with predictable daily, monthly, and seasonal patterns of light and dark, and these patterns underlie the natural rhythms of nearly all living organisms. Artificial night lighting has long been known to affect these patterns. Nocturnal species, which represent the majority of some major taxonomic groups (**Figure 3**), are obviously vulnerable, as are diurnal or crepuscular species whose behavioral niches can be distorted by lighting. Concern about adverse effects of lighting dates to descriptions of the “destruction” of birds at lighthouses in the late 1800s (Allen 1880) and even the first electric urban lighting (Kumlien 1888). Mortality of hatchling sea turtles at lights was identified as a conservation issue in the 1960s (McFarlane 1963). Verheijen coined the term *photopollution* in 1985 (Verheijen 1985), which was followed by Ken Frank’s classic review of the effects of lighting on moths (Frank 1988), and a series of unpublished reports (Outen 1998), conference proceedings (Schmiedel 2001), and research reports from Europe (De Molenaar et al. 2000, Kolligs 2000). In 2004, we described *ecological light pollution* as “artificial light that alters the natural patterns of light and dark in ecosystems” (Longcore and Rich 2004).

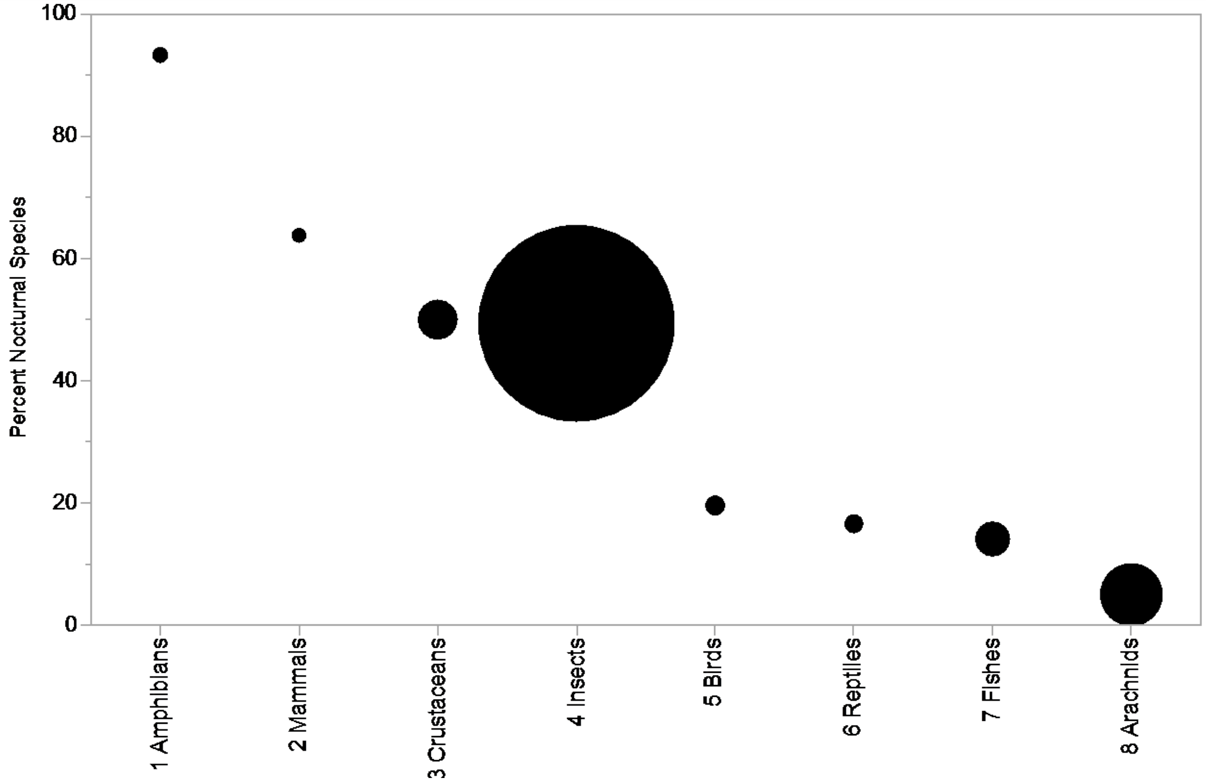


Figure 3. Proportion of major animal groups that are nocturnal. Area of markers is proportional to the number of species known in the group. Data from Hölker et al*.* (2010).

The disruptions caused by artificial night lighting occur whenever the natural patterns of light and dark are changed. This means that very low lighting levels (far below that of the full moon) can have important effects.

Reviews of the effects of artificial night lighting on different taxonomic groups can be found in Rich and Longcore (2006). Resource managers dealing with questions about specific groups of organisms should consult this source, which contains chapters on mammals, birds, reptiles and amphibians, fishes, invertebrates, and plants. Taxonomically specific information is essential to devise lighting systems that minimize impacts on sensitive species when lighting is necessary. Sensitive species should be identified relative to a specific area and might include both those species that have a formal designation as being threatened or endangered or any species of concern that would be sensitive to changes in nocturnal illumination. Nocturnal, crepuscular, and diurnal species can be affected by nighttime lighting conditions.

In the sections that follow, we present short reviews of the effects of artificial night lighting in different habitat types.

Coastal dunes, beaches, and shorelines

Coastal dunes and beaches are generally open environments with low vegetation adapted to moving sand (**Figure 4**). Dunes present unique environmental conditions that are often quite distinct from their surroundings, and they are often populated by endemic species that thrive in these unique conditions. Coastal endemic species are often a focus of management concern because of the development pressure on coastal ecosystems in the United States (Schlacher et al. 2007a). Dunes are also ecological transition zones between land and water; light from development in coastal dunes illuminates adjacent water bodies, and animals such as turtles move from water to land to nest. Shorelines are essential for organisms such as amphibians and aquatic insects that have biphasic life cycles.

Figure 4. Beach environments are vulnerable to the effects of anthropogenic light because of their open nature. Hatchling sea turtles are easily disoriented by onshore lights or sky glow and patterns of nocturnal foraging by shorebirds are also affected.

On a beach or coast under natural conditions, the view toward the land is almost always darker than the view toward the water. This is a function of landward vegetation and topography blocking light from the sky (Salmon 2006), in addition to moonlight and starlight reflected off the water. Organisms can use this pattern for orientation. Artificial lighting on the shore or from cities and other coastal development can reverse the natural conditions; the landward horizon becomes brighter, while the water is darker (Salmon 2006).

Stray light and sky glow from coastal development spread across and into many dune and shoreline environments. As in many environments, nocturnal activity near shorelines is significant (Salmon 2006). Beaches and coasts also regularly experience foggy and high-aerosol conditions, which scatter light and thereby amplify the local effects of lights (Kyba et al. 2011).

Artificial lighting has adverse consequences for sea turtles because the darkest horizon is no longer the landward horizon. Indeed, the lethal effects of lights on sea turtles have led to increased awareness of the adverse effects of artificial night lighting in general. Female sea turtles avoid illuminated beaches as nest sites, and hatchings are fatally affected by lights visible from beaches (Salmon 2003, 2006). This phenomenon was first recorded by MacFarlane (1963), and aversion of females to lights was confirmed experimentally by Witherington (1992). Habitat degradation by lights is caused both by lights adjacent to dunes and beaches and by regional sky glow (Salmon 2006).

As a general rule, additional light — whether moonlight or anthropogenic light — increases foraging efficiency of predators and reduces activity of prey (Longcore and Rich 2004, Rich and Longcore 2006, Seligmann et al. 2007). This phenomenon has been shown many times in different habitats. On dunes, Bird et al. (2004) investigated the effects of lighting on foraging behavior of beach mice. Bird et al. (2004) used low-pressure sodium lights and yellow incandescent “bug” lights, which are commonly employed on beaches in Florida because they have limited effects on sea turtle hatchlings. They found that foraging by beach mice was significantly decreased in proximity to both types of turtle-friendly lights. Similar behavior by prey species has been shown for both natural and anthropogenic light. For example, ghost crabs are active only at night, and avoid activity under both the full moon (Schlacher et al. 2007b) and artificial light (Christoffers 1986). The exception to this pattern is that prey species that flock or school together can be aided by additional light that facilitates communal vigilance (Nightingale et al. 2006).

Effects from lights on beaches and shorelines may also affect aquatic ecosystems. For example, lights affect the predator–prey dynamics of fishes and marine mammals (Hobson 1965, Hobson et al. 1981, Yurk and Trites 2000, Nightingale et al. 2006).

Shorebirds sometimes forage at night (Dugan 1981, Burger and Gochfeld 1991, Rohweder and Baverstock 1996). Various explanations have been proposed: as a defense against predation (Robert et al. 1989, McNeil et al. 1992, Thibault and McNeil 1994), as a result of slightly higher invertebrate activity on beaches at night (Dugan 1981, Evans 1987), and as a response to visual cues that are available due to higher levels of natural or anthropogenic light (Dwyer et al. 2012). Predator defenses of shorebirds are different during the night compared with the day; in an observational study, some proportion of Dunlins freeze and limit vocalizations as a defense at night while all individuals in a flock fly away in response to predators during the day (Mouritsen 1992). Owls are the major nocturnal predator of shorebirds and are aided by additional light when foraging (Clarke 1983). Timing of foraging by shorebirds, therefore, probably depends on tradeoffs between risks of becoming prey with ability to detect their own prey. Whether birds are flocking and have sufficient light for the associated communal predator vigilance probably also interacts with these factors.

Artificial night lighting on dunes and beaches can therefore have a variety of effects on species. Predator–prey relations are disrupted and key reproductive behaviors can be inhibited. Beaches and dunes also provide a gateway to adjacent water bodies, which have no barriers to block the propagation of light. Because there is usually less anthropogenic light at beaches and on shorelines than in surrounding urban or suburban areas, park visitors often use beaches and dunes to gaze at the night sky. Beaches and dunes should be kept as free from the influence of artificial lights as possible, with special attention paid to ensuring that any lights installed are absolutely necessary and that no lights are directly visible from the beach and points offshore.

Deserts and scrublands

Deserts and scrublands are open habitats with few barriers to the spread of light (**Figure 5**). Many animal species in hot deserts and scrublands adopt nocturnal behaviors to conserve water and avoid daytime temperature maxima. This shift to nocturnal activity may increase seasonally with higher temperature (Kronfeld-Schor and Dayan 2008). Consequently, artificial night lighting has the potential to change the ecology of these environments by disrupting the natural patterns of light and dark relied upon by a large proportion of fauna.

Desert animals can have narrow preferences for illumination levels. These preferences may be related to foraging opportunities, predation risk, or physiological requirements. For example, *Leucorchestris arenicola*, a trapdoor spider endemic to the Namib Desert, exhibits exclusively nocturnal activity patterns (Nørgaard et al. 2006). Males are active only during dark moonless nights, when they are able to navigate hundreds of meters across dune environments using only faint ambient light from stars, airglow, and zodiacal light (Nørgaard et al. 2006). For a species such as this, addition of illumination from any source in its habitat would eliminate its preferred habitat conditions.

Desert rodents also exhibit specific illumination preferences to manage their risk of becoming prey (Grigione and Mrykalo 2004, Beier 2006). Some species are active at twilight, others after twilight, and some during the darkest periods of moonless nights (Grigione and Mrykalo 2004, Upham and Hafner 2013). Anthropogenic light can disrupt these patterns; even the light from a camp lantern equivalent to a quarter moon (~10^{-2} lux) was sufficient to substantially inhibit foraging by a suite of rodent species (Kotler 1984). Those species vulnerable to this disruption lack other predator avoidance abilities such as exceptional hearing (Kotler 1984, Kotler 1985). Because many desert animals exhibit circalunar patterns in their activities, especially predaceous arthropods such as scorpions (Skutelsky 1996, Tigar and Osborne 1999) and granivorous small mammals (Price et al. 1984, Daly et al. 1992, Upham and Hafner 2013), it follows that any artificial light that produces light equivalent to even a quarter moon can alter these patterns.

Figure 5. Lights in desert scrublands are visible for long distances and night lighting affects a disproportionate fraction of the wildlife because high daytime temperatures induce nocturnal activity patterns.

Scrubland environments share many characteristics with deserts, especially in Mediterranean climates. A disproportionate number of species is nocturnal at high temperatures, and the open vegetation structure of drier scrublands allows for light to propagate for unusually long distances.

Perry and Fisher (2006) describe the decline of nocturnal snake species in the scrublands of southern California. Long-nosed snake (*Rhinocheilus lecontei*), a nocturnal species, showed a pattern of decline consistent with the gradient of light pollution as estimated by satellite imagery (Fisher and Case, unpub. data). Otherwise suitable scrub habitats, which supported other diurnal species of snakes, lacked long-nosed snakes. The authors hypothesized that decreases in numbers of the snake's small-mammal prey, also associated with light pollution, were responsible for the decline (Perry and Fisher 2006).

Wetlands and rivers

In some places, wetlands and lakes are the last refuges of a natural night on the landscape (**Figure 6**). The difficulty of developing wetlands often leaves them as the only remaining unlighted sites in urban and suburban regions. Many aquatic organisms depend on daily cycles of light and dark and artificial lights disrupt critical behaviors in many species (Moore et al. 2006, Perkin et al. 2011, Henn et al. 2014).

Figure 6. Lights along rivers and streams can disrupt predator–prey interactions, such as seals hunting salmon under lights.

Wetlands are often geographically fragmented, occurring as isolated patches or as linear features stretching across the landscape. Linear features are susceptible to disturbances such as artificial night lighting because they have a high edge-to-area ratio. They also tend to induce development along their edges, which leads to lighting from urban development on either side. Similarly, small wetlands are especially vulnerable to disturbances from their surroundings.

Aquatic invertebrates are important components of wetland ecosystems and provide an example of the sensitivity of wetlands to lighting levels (**Figure 7**). Many aquatic invertebrates migrate up and down in wetlands during the course of a night and day. This “diel vertical migration” presumably results from a need to avoid predation during lighted conditions so many zooplankton forage near water surfaces only during dark conditions. Light dimmer than that of a half moon ($<10^{-1}$ lux) is sufficient to influence the vertical distribution of aquatic invertebrates, and indeed diel vertical migration follows a lunar cycle. When constant light from human development is added to the natural nocturnal illumination of the moon and stars, the darkest conditions are never experienced, and the magnitude of diel migrations (both range of vertical movement and number of individuals migrating) is decreased, which has been shown experimentally for *Daphnia* (Moore et al. 2000). Disruption of diel vertical migration by artificial lighting may have significant detrimental effects on ecosystem health. Moore et al. (2000) conclude that “[decreases in] vertical migration of lake grazers may contribute to enhanced concentrations of algae in both urban lakes and coastal waters. This condition, in turn, often results in deterioration of water quality (i.e. low dissolved oxygen, toxicity, and odor problems)."

Figure 7. Light in wetlands can suppress diel vertical migration of zooplankton and influence foraging behavior of amphibians.

Amphibians found in nearshore and wetland habitats also are particularly vulnerable to artificial lighting. Amphibians are highly sensitive to light and can perceive increases in illumination that are impossible for humans to detect (Hailman and Jaeger 1976). A rapid increase in illumination causes a temporary reduction in visual acuity, from which the recovery time may be minutes to hours (Buchanan 1993, Buchanan 2006). In this manner, a simple flash of headlights can arrest activity of a frog for hours (Perry et al. 2008). Amphibians are also sensitive to changes in ambient illumination from sky glow. Frogs in an experimental enclosure ceased mating activity during night football games when lights from a nearby stadium increased sky glow (Buchanan 2006). In an experiment to investigate the effects of intermittent artificial light, male green frogs called less and moved more when exposed to the light of a handheld flashlight (Baker and Richardson 2006).

In naturally lit environments, some amphibians will forage only at extremely low light levels, and foraging times are partitioned among species with different lighting level preferences (Jaeger and Hailman 1976). The squirrel tree frog (*Hyla squirrela*) orients and forages at lighting levels as low as 10^{-6} lux and stops foraging at illumination above 10^{-3} lux (Buchanan 1998). The western toad (*Bufo* *boreas*) forages only at illuminations between 10^{-1} and 10^{-5} lux, while the tailed frog (*Ascaphus truei*) forages only during the darkest part of the night below 10^{-5} lux (Hailman 1984).

Laboratory experiments indicate that the development of amphibians is influenced by artificial light (Wise and Buchanan 2006, Wise 2007). Light interferes with the production of the hormone melatonin, which is involved in regulating many important functions, including sexual development, thermoregulation, adaptation of eyes to the dark, and skin coloration (Wise and Buchanan 2006, Wise 2007). Current research shows that artificial lighting slows larval amphibian development in the laboratory (**Figure 8**). The influence of artificial lighting on such physiological processes in the field is currently not well known, but the potential for lighting to harm amphibians and other wetland species is evident.

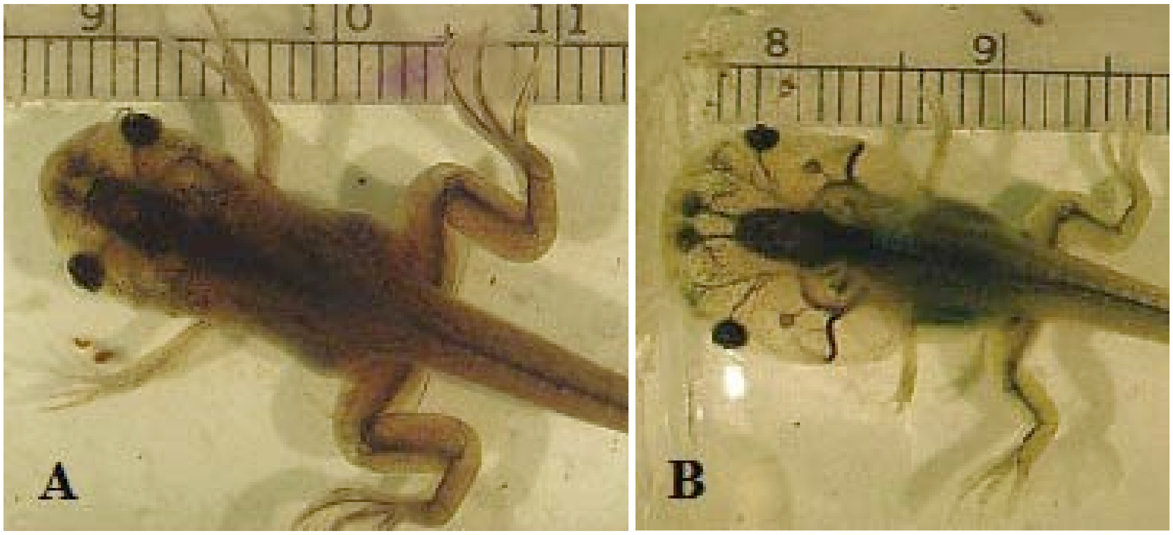


Figure 8. Two tadpoles of the same age and kept in 12:12 L:D lighting. (A) was kept in the equivalent of very dark night (10^{-4} lux) in the dark phase, while (B) was exposed to artificially bright illumination in the dark phase and is not yet metamorphosing (reprinted from Wise 2007).

Fishes are also highly attuned to natural ambient light conditions, with lighting levels influencing the distribution of predaceous species and the foraging behavior of their prey (Nightingale et al. 2006, Becker et al. 2013). Laboratory experiments have shown that the timing of downstream migration of salmon (*Salmo salar*) fry is significantly delayed and disrupted by lights of a similar illumination and spectrum as streetlights (Riley et al. 2013). Nocturnal downstream drift of insects is also delayed by artificial lighting (Henn et al. 2014).

Islands, oceans, and reefs

Light propagates unimpeded across open water, and its reach is extended beyond the curvature of the Earth by reflection off high clouds. Fog can increase local impacts of bright lights. Although light shining directly down on water tends to penetrate rather than reflect, light coming in at an angle is reflected. This physical property of water exacerbates the effects of coastal lighting as it is reflected and propagates out from the shoreline. Island, ocean, and reef environments are affected by artificial light sources that range from light-assisted fishing to urban sky glow to offshore hydrocarbon facilities (Davies et al. 2014) (**Figure 9**).

Figure 9. Cruise ships and squid boats are just two of the sources of artificial lighting on the oceans that attract seabirds and migrating songbirds.

In 1999, Xantus's murrelets (*Synthliboramphus hypoleucus*) nesting on Santa Barbara Island, part of Channel Islands National Park off the coast of southern California, were dying at twice the average annual rate. Park managers suspected this increase in mortality was directly related to a recent increase in fishing boats equipped with dusk-to-dawn floodlights to attract squid. Squid boats typically have 30,000 watts of light per boat. The number of squid boats increased dramatically in the 1990s, and in 1999 intense squid fishing occurred during murrelet nesting season (spring, while historically fishing was during fall and winter), and near important murrelet breeding islands. Managers believed that the nesting seabirds, without the safety of darkness, were subject to increased predation, especially from barn owls (*Tyto alba*). During the 1999 season, an unprecedented 165 dead Xantus's murrelets were found on Santa Barbara Island. Most of the dead were killed by barn owls, while five were victims of western gulls (*Larus occidentalis*). Researchers also recorded high nest abandonment closest to the most intensive squid boat activity. Faced with these observations, managers closed the areas around the islands to squid fishing, and death rates for the birds returned to normal. The excluded areas were subsequently incorporated into a permanent marine preserve with no fishing allowed to allow for replenishment of fish stocks. Also, the California Fish and Game

Commission listed Xantus's murrelet under the California Endangered Species Act, citing artificial night lighting as one of the major threats to the species.

Nearly all seabirds are nocturnal, and an adverse response to decidedly unnatural conditions such as those suffered by Xantus's murrelets should not be surprising (Montevecchi 2006). Years of studies have shown that nocturnal seabirds are less active during moonlit nights, and those that are active suffer more predation during those times. Seabird chicks are directly affected by lighting levels; they are far less likely to be fed by adults during bright nights (Riou and Hamer 2008). Seabirds are attracted to lights perhaps because they naturally cue in on bioluminescent plankton to find prey (Montevecchi 2006). They have, therefore, long suffered from collisions with light sources on and adjacent to the ocean, including lighthouses, cruise ships, fishing vessels, lighted buoys, oil derricks, and streetlights on and near islands where they nest (Rodríguez and Rodríguez 2009, Rodrigues et al. 2012, Wilhelm et al. 2013); many of these collisions are fatal. Where lights correspond with critical habitat or high-use zones such as feeding or breeding areas, or migratory routes, the effects could be significant.

Other sources of artificial night lighting threaten the nighttime environment of the oceans. Cruise ships are pervasive, large, and are often brightly illuminated. Ships in the path of bird migrations, or near undersea food sources, may attract both migratory birds and foraging seabirds, which collide with the ships and can be stunned or killed. Anecdotal accounts have emerged where cruise ship staff frantically work to clear the decks of dead birds before passengers awake in the morning. Offshore hydrocarbon extraction platforms are also significant sources of light, and attract and kill birds through collision, exhaustion, and even by incineration in flares burning off natural gas. Many of these birds are long-distance migrants, and the losses at oil platforms may affect regional and global breeding populations.

Coral reefs are also threatened by artificial night lighting. Lighting has been used as a proxy for other impacts (urban development, intense fishing, hydrocarbon extraction) to assess risk to coral reefs on a global scale (Aubrecht et al. 2008). Aubrecht et al. (2008) also illustrated how artificial lighting would adversely impact reefs directly. Corals themselves are highly sensitive to light and synchronize spawning according to lunar cycles (Jokiel et al. 1985, Gorbunov and Falkowski 2002). Many coral reef species exhibit marked light-driven diel cycles or synchronize reproduction by monthly cycles (Sebens and DeRiemer 1977, Bentley et al. 2001, Levy et al. 2001). Predator–prey interactions are influenced by light levels, with diel vertical migration of both zooplankton (Yahel et al. 2005) and planktivorous fishes observed (Leis 1986). Natural light signals, such as bioluminescence, are important to marine organisms (Johnsen 2012), and can both attract and repel fishes (Holzman and Genin 2003, 2005). Artificial lighting at similar and greater intensity must affect a range of marine organisms. Experimental investigation has now confirmed that lighting affects the colonization of marine invertebrates on surfaces (Davies et al. 2015).

Grasslands

Like other open habitats, light has few barriers in grasslands (**Figure 10**). Lights can thereby influence both illumination and direct glare over hundreds of meters or more, depending on topography. Artificial night lighting can be expected to influence habitat use and behavior of grassland species.

The lights of a road bisecting wet grassland in the Netherlands were shown to influence the spatial distribution of black-tailed godwit (*Limosa limosa*), a rare ground-nesting bird (De Molenaar et al. 2000, De Molenaar et al. 2006). When road lights were turned on during a breeding season, the birds nested slightly farther away from the road, with the effect extending 300 m (984 ft) from the lights. Birds that arrived first to the breeding area nested farther from the lights while those arriving later nested closer (De Molenaar et al. 2000, De Molenaar et al. 2006). The same research group investigated the behavior of mammals in wet grasslands and showed that some species (polecat, *Mustela putorius*, stout, *Mustela erminea*, weasel, *Mustela nivalis*, and fox, *Vulpes vulpes*) were more likely to take paths near lights, while other species were not influenced or preferred darker areas (De Molenaar et al. 2003). Such differences in habitat use have the potential to change predation rates and distribution of prey species as well (Lima 1998).

Figure 10. Grasslands are vulnerable to disruption from even distant lights because of their open character. Fireflies, often found in wet grasslands, can have their signals disrupted or be excluded by high illumination, while some grassland bird species, such as black-tailed godwit (*Limosa limosa*), have been shown to avoid streetlights in selecting nest sites (De Molenaar et al*.* 2006).

Fireflies are another group of grassland species that can be adversely affected by artificial night lighting (Lloyd 2006). Because light is used for firefly communication, both for sexual behavior and in some interspecific interactions (where females attract males of other species to capture and eat them), any disruption of the ability to see light will have adverse effects. Artificial light washes out the signals used 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, Bird and Parker 2014).

Deciduous and evergreen forests

Although the structural complexity of forests blocks light and reduces its propagation, species that inhabit the forest floor are sensitive to illumination at levels appropriate to the darker nighttime environment there (**Figure 11**). A review of the research on forest species shows some general patterns that illustrate the potential for lights to affect wildlife behavior.

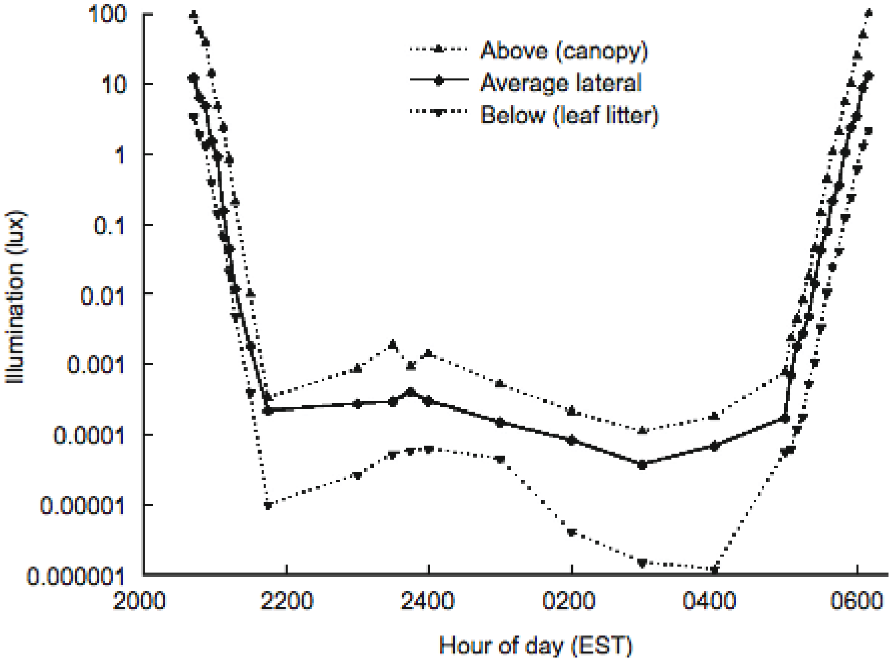


Figure 11. Illumination in deciduous forest (Buchanan 2006). Reprinted with permission.

As in many other ecosystems, salamanders in forests exhibit reactions to light equivalent to moonlight, under which foraging is reduced or delayed (Wise 2007) (**Figure 12**). This has been shown experimentally with dim artificial lights installed in a forest environment (Wise 2007). In two different experiments, lighting delayed the emergence time of nocturnal mammals (DeCoursey 1986, Barber-Meyer 2007) and reduced foraging activity (Barber-Meyer 2007). For sugar gliders, a nocturnal forest mammal native to Australia, light equivalent to that produced by streetlights (7–12 lux) reduced the time individuals were active at night (Barber-Meyer 2007).

In other instances, reproductive behavior can be affected by artificial lighting. The leafcutter ant *Atta texana* usually undertakes nuptial flights approximately 15 minutes before dawn, but in instances where security lights from homes and businesses were visible, the colonies flew 15 minutes after dawn (Moser et al. 2004). This change in timing interferes with behaviors that are carefully synchronized across colonies. Furthermore, artificial lights are also attractive to the flying ants and, as a result, may both decrease mating success and increase predation at the lights (Moser et al. 2004).

Figure 12. Species of the deciduous forest are adapted to the lower light levels found under the canopy. Flying squirrels and salamanders will delay their foraging under artificial lights.

Alpine and tundra habitats

Alpine and tundra habitats are disproportionately represented in parks and other protected lands. They are on average less developed than other habitat types but can be, and are, developed for recreational and industrial infrastructure. Control of artificial lighting in alpine and tundra habitats is important to avoid disruptions of predator–prey interactions and to avoid disrupting annual rhythms that are entrained by day length.

The topography of mountainous habitats also makes them vulnerable to sky glow from distant sources (**Figure 13**). Because sky glow brightens horizons, areas of steep slopes are positioned to be exposed to that light. In these locations, the aspect of the slope becomes important. Those facing bright horizons will be substantially brighter than nearby locations facing a different direction and therefore will be exposed to far less artificial lighting.

As in other habitats, predator–prey interactions in alpine environments are mediated by illumination (**Figure 14**). For example, small mammals of rocky outcrops typical of alpine regions are often nocturnal, foraging in open areas at night and retreating to the safety of outcrops for shelter (Kramer and Birney 2001). In experimental conditions one such species, long-eared mouse (*Phyllotis xanthopygus*), foraged less under 1.5 and 3.0 lux treatments (up to very bright moonlight) when compared with a 0.0 lux control (Kramer and Birney 2001). Similar results have been found for snowshoe hares (Gilbert and Boutin 1991), which are subject to more predation under brighter nocturnal conditions, especially during the winter (Griffin et al. 2005). Such small mammals depend on natural darkness for foraging to keep up body weight (Vasquez 1994).

Figure 13. Alpine habitats can be affected by distant lights and those from recreational and industrial facilities.

Circannual rhythms are found in most animals, but the environmental conditions that influence them are less well understood because of the long period necessary to conduct experimental research (Beier 2006). Light appears to have a large influence in setting these cycles, although temperature is also important (Beier 2006). Light can be important in determining when species react to the seasons (e.g., hibernation, Hock 1955), and consequently disrupting these signals has the potential to put species out of phase with climate. In alpine and tundra environments, where conditions change so dramatically between the seasons, appropriate synchronization of activities is important. For example, reindeer (*Rangifer tarandus*) eyes change seasonally to reflect different wavelengths of light; color of the tapetum lucidum shifts from yellow in the summer to blue in the winter, which is associated with increased retinal sensitivity during the dark winter nights (Stokkan et al. 2013). Captive reindeer exposed to sodium vapor streetlights, not directly visible but just over the horizon, are reported to have green eyes in the winter, not completing the normal transition from yellow to blue, and with reduced visual sensitivity (Yong 2013).

Figure 14. Predator–prey interactions are affected by artificial lights during long nights on the tundra.

Urban environments

Even though urban environments have many sources of artificial lighting at night, variations within already light-polluted environments still make a difference to wildlife (**Figure 15**). For example, American crows (*Corvus brachyrhynchos*) choose roost sites in urban areas that are on average more brightly illuminated than non-roost sites (Gorenzel and Salmon 1995). Presumably, this allows the communal predator response behaviors of the flock to operate more efficiently, reducing predation from owls. Elevated populations of this native species have adverse consequences for other native species for which the crows are predators. In another example, urban-tolerant bat species are influenced by the degree of illumination on the exit hole of their roosts. Nightly emergence is delayed by illumination of the exit hole, which reduces fitness of individuals in the colony and can eliminate the colony altogether (Boldogh et al. 2007). Because of the importance of bats as consumers of insects, and their conservation status, the adverse impacts of lighting are concerning (Stone et al. 2015).

Cities are also sites of mortality for nocturnally migrating birds, which are attracted to lights. Birds die either in collisions with buildings at night, or during the day when they attempt to regain their orientation and continue migration. This phenomenon is well documented in Chicago, Toronto, New York, and Washington, D.C. A notable example in a national park is the ongoing mortality of nocturnal migrant birds at the Washington Monument, which started when it was illuminated (Overing 1938).

The profusion of light in urban areas also has spillover effects on surrounding natural areas and open spaces within cities. For example, extremely high levels of ambient light are measured in the Santa Monica Mountains National Recreation Area near Los Angeles, with all-sky brightness exceeding natural levels by 18.4 times and maximum nocturnal vertical illuminance 32.4 times brighter than natural levels (J. White and C. Moore, pers. comm.). Although it is difficult to address the multitude of sources of light, it is worthwhile for parks to incorporate lighting and the night sky as part of their education, outreach, and engagement in communities adjacent to and near parks (Aubé and Roby 2014).

Figure 15. Cities are affected by altered light environments, which are exploited by synanthropic species such as crows and some bat species.

The evidence from across habitat types indicates that artificial lighting at night is either proven to, or has the potential to, disrupt the natural behavior of wildlife species, sometimes with lethal consequences. From this context we can identify practices that can reduce and minimize the effects of lighting in parks and other lands managed for natural resource values.

Mitigating the Effects of Lighting on Protected Lands

Knowledge about the effects of lighting on wildlife continues to grow. All indications are that lighting can have cumulative and additive consequences that are especially important for vulnerable species. Many general approaches to minimizing the effects of artificial lighting on wildlife are known. To reduce effects on certain target species, these mitigations may need to be adapted to craft desirable solutions for specific locations. In the following two sections, considerations for developing such mitigation measures are discussed. First we introduce the attributes of nighttime lighting that might be manipulated — spectrum, intensity, direction, and duration — and how different groups of species might be affected by them. Then we review the many contexts in which light is used (e.g., security lighting, vanity lighting, communication towers) and identify preferred mitigation strategies for them.

Approaches to minimize lighting impacts

The impacts of artificial lighting to wildlife can be reduced in five ways: 1) avoiding use of lighting that is not needed, 2) controlling color spectrum, 3) limiting light intensity, 4) managing the direction of light emissions, and 5) limiting the duration of light output. For some of these characteristics, a single approach applies in all instances. For others, the recommendation depends upon the context of use or the species that might be affected. A combination of mitigation approaches is likely to be more effective (e.g., reducing intensity and adjusting color spectrum) than would be any approach taken individually.

Need

The first question that should be asked about artificial lighting, especially in natural areas, is whether it is in fact needed. In some situations, a creative solution, such as the choice of a pale color for a pathway, curb, or steps, is all that is needed to guide visitors (**Figure 16**). In others, lighting can be left to the visitor to provide in the form of headlights or a flashlight. Only when the need is demonstrated and necessary for visitor experience, safety, or security, should lights be installed.

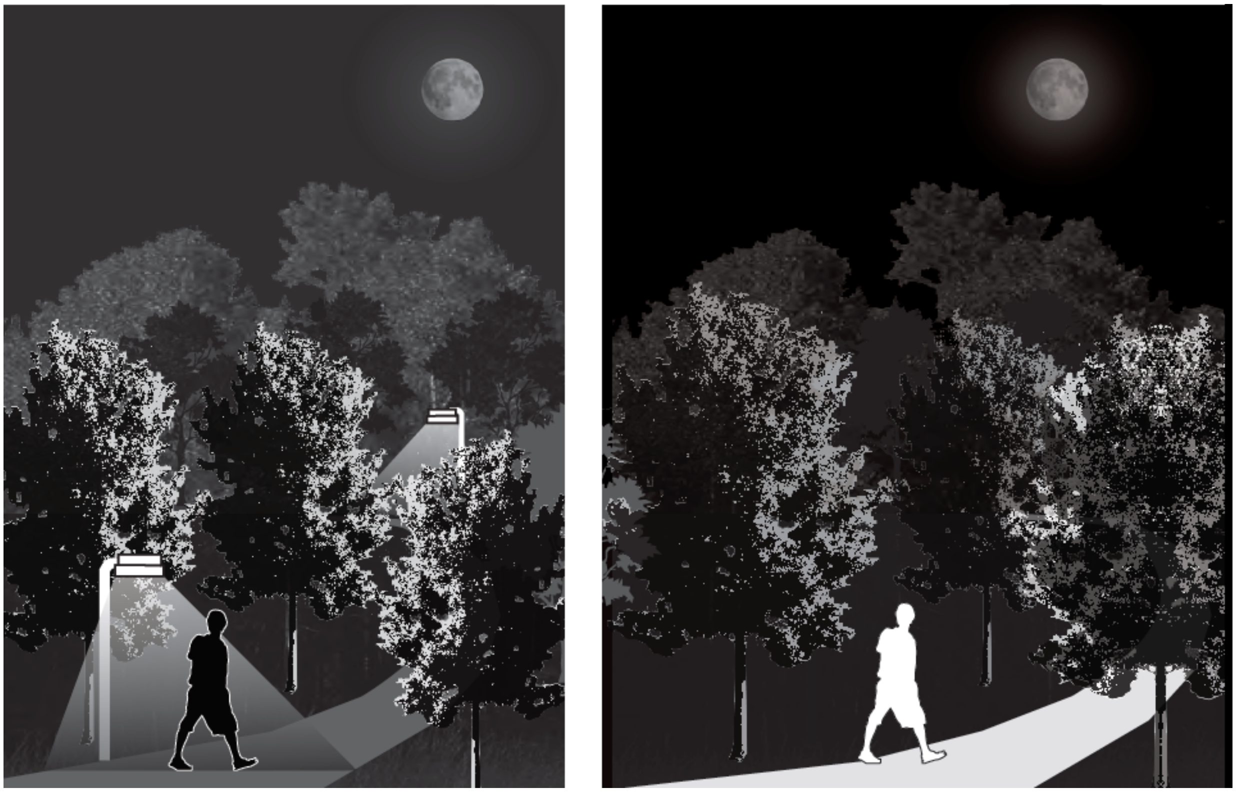


Figure 16. A pale-colored path can be just as effective as electric lights in some park situations.

Spectrum

It is tempting to believe that a certain spectrum of light will minimize the effects of lighting in all situations. Unfortunately, no universal solution exists. Rather, it is possible to identify spectra of light that have shown to affect wildlife less in certain contexts. The only 100% wildlife-friendly light is one that is switched off or never installed.

The higher efficiency of high-pressure and low-pressure sodium lamps resulted in their widespread adoption in street lighting applications and security lighting, replacing the older mercury vapor lamp technology. Recently, however, full-spectrum light sources such as metal halide lamps, compact fluorescent lamps, and LEDs are becoming more common (Gaston 2013). Full-spectrum lights appear white, in contrast with other lights such as sodium vapor lamps that appear yellow or orange. Earlier technologies, such as mercury vapor lamps, were also full-spectrum, but have largely been replaced by sodium vapor lamps. LEDs are more efficient than older lamps used for outdoor lighting, and have greater color rendition than sodium vapor light sources. This return to white light sources brings certain advantages for human use, but includes a wider range of wavelengths, potentially impacting more species (Stone et al. 2012) and exacerbating sky glow (Aubé et al. 2013).

The combination of colors that make up a full-spectrum light is described by the correlated color temperature (CCT) of the light. CCT is measured in degrees Kelvin and corresponds to the appearance of light that would be emitted from an idealized “black body” if it were heated to that temperature. Lower CCTs are dominated by yellow and other longer wavelengths, while higher

CCTs are dominated by blue and other shorter wavelengths. For example, an incandescent bulb has a CCT of around 2400–2800 K, while a metal halide lamp has a CCT of 4000 K and direct sunlight 4800 K. LEDs are offered in many color temperatures, from 6500 K to 2700 K, and can also contain mixes of colors that do not have color temperatures associated with them (i.e., "off the black body curve") and are measured in other ways. High-pressure sodium lamps have a CCT of around 1800 K and low-pressure sodium lamps, which are all yellow, do not have an associated color temperature.

One general rule is to avoid any light that has emissions in the ultraviolet spectrum and adjacent short wavelengths. Ultraviolet light is not visible to humans, yet is visible to other species. Insects are highly attracted to ultraviolet light and their attraction and mass death at lights would be dramatically reduced by eliminating ultraviolet light from general use (Frank 1988, Eisenbeis and Hassel 2000, Eisenbeis 2006, Frank 2006). Mercury vapor lamps are high in ultraviolet radiation, while other commonly used outdoor lamps (e.g., metal halide, fluorescent) have some ultraviolet as well. LEDs have no ultraviolet emissions and therefore attract fewer insects than lamps of comparable intensity and color temperature that do have some ultraviolet emissions (Poiani et al. 2015, Longcore et al. 2015).

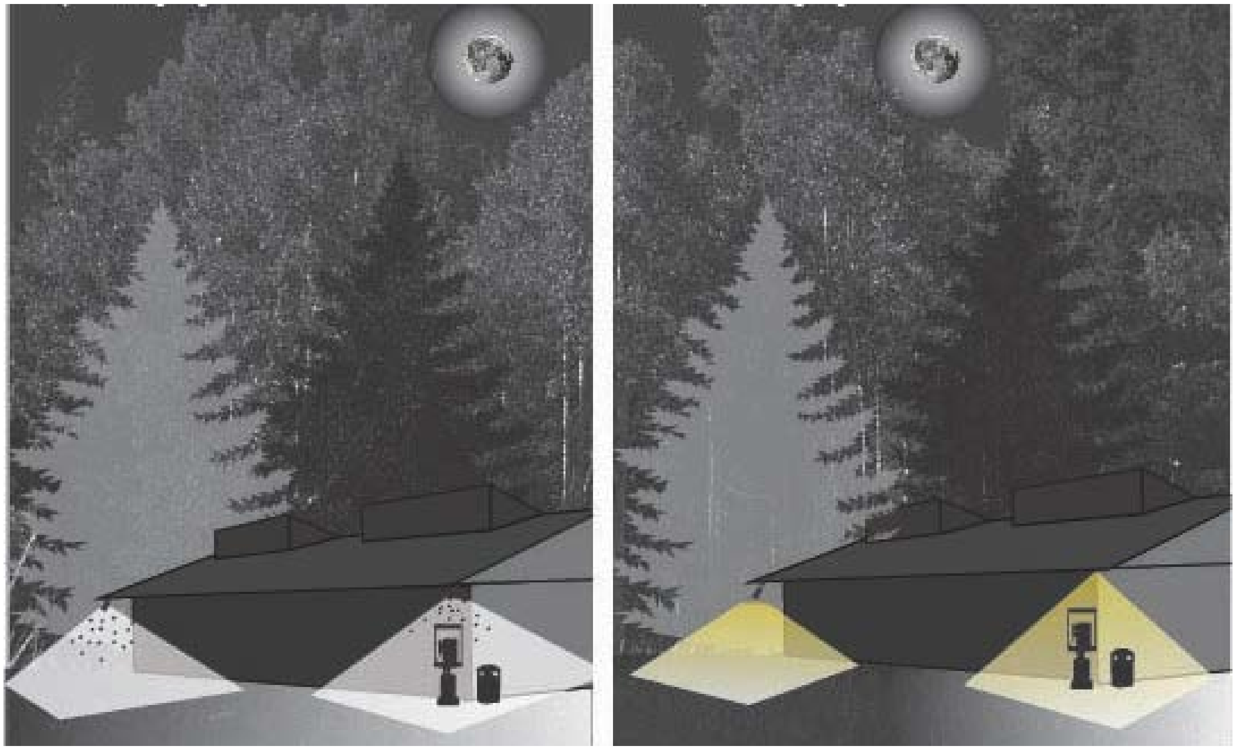


Figure 17. Yellow light that does not contain blue or ultraviolet wavelengths attracts far fewer insects.

Insects are also attracted to light in the short visible wavelengths (e.g., violet and blue) (**Figure 17**). Full-spectrum lighting that allows good color rendering for human vision is not advisable from the standpoint of ecological effects because it contains light in the blue spectrum (Eisenbeis and Eick 2011). All lights heavy in the blue portion of the spectrum, such as fluorescent lights, metal halide lights, and full-spectrum LED lights, will have greater impacts on insects than lights with longer wavelengths (e.g., low-pressure sodium vapor lamps or yellow/amber LEDs) (Eisenbeis and Eick 2011, Pawson and Bader 2014, Poiani et al. 2015, Longcore et al. 2015). If full-spectrum lighting is required, then the lowest possible color temperature is recommended (Longcore et al. 2015).

Blue light contains the most biologically active wavelengths for physiological processes such as the production of hormones and the timing of daily activities (Beier 2006, Brainard et al. 2015). This concern has been best expressed relative to human health (Pauley 2004, Brainard et al. 2015), but blue light also disrupts circadian rhythms in wildlife. To minimize disruption to circadian rhythms, shorter wavelengths such as blue and violet should be avoided. They might also be avoided to minimize influence on species that are phototactic to blue light, such as many frog species that have a blue light preference whereby they move toward blue light, presumably as an escape mechanism that leads them away from vegetation (and into water) in times of danger (Hailman and Jaeger 1974, Buchanan 2006); these preferences can vary depending on the intensity of illumination, however (Buchanan 2006).

Figure 18. Green lighting designed to minimize attraction of birds developed by Philips. Shell is using these lights on an oil platform in Alaska and Philips is adding the lights to its regular catalog. Photograph courtesy of Joop Marquenie.

Birds are able to orient to the Earth’s magnetic field under monochromatic blue or green light, but such navigational ability apparently does not function under lights that are only red or yellow. The molecular mechanism that allows detection of the Earth’s magnetic field requires light of a certain wavelength to be activated (Ritz et al. 2009), which presumably explains the inability of migratory birds to orient under light that lacks those wavelengths (Wiltschko et al. 1993, Wiltschko and Wiltschko 1995). Dutch researchers have experimented with the use of specially designed lamps that contain blue and green light at coastal locations and on offshore platforms to see if the number of attracted and disoriented birds is decreased (van de Laar 2007, Poot et al. 2008). Results show blue and green lights influence birds less than red and full-spectrum (white) light, although the effects on other species have not been documented in the scientific literature (**Figure 18**; **Figure 19**).

Figure 19. Green lights have been investigated for use on offshore structures and shown to be less attractive to birds.

In other situations, light that includes longer wavelengths appears to attract few insects and does not disrupt orientation of sea turtle hatchlings. For this reason, yellow lights are commonly identified as being wildlife-friendly (**Figure 17**). These same lights, however, reduce the foraging activity of native beach mice (some species of which are endangered) along the Florida coastlines where turtle-friendly lighting is recommended (Bird et al. 2004). Fireflies are vulnerable to impacts from yellow light because it is this part of the spectrum that is used by those species flying after dusk (Lloyd 2006).

Red light appears to disrupt the orientation capabilities of birds, but it seems to have the least effect on other species (**Figure 20**). Few insects are attracted to red light and dark-adapted eyes are not bleached by red light, making it the spectrum of choice for stargazers. In low-light environments in parks, red light might be preferable where lights are needed for safety reasons (**Figure 21**).

Figure 20. Red light does not disrupt dark-adapted vision and is therefore appropriate for campsites and locations used for astronomical observation.

Figure 21. Illumination of a stairway at a campground by two low-intensity red bulbs instead of by a bright white spotlight (Wagner et al*.* undated).

Through all the considerations for different taxa, a few general lessons emerge to guide use of spectrum: 1) the choice of color significantly affects the degree of biological disruption; 2) narrow-spectrum lights are preferable to broad-spectrum sources (i.e., white light); 3) ultraviolet light should be avoided; 4) blue and shorter wavelengths increase biological responses and generally should be avoided; and 5) concerns about individual species in an area may influence the choice of least disruptive color for lights.

Intensity

Land and facility managers have great latitude in selecting the intensity and quantity of lighting used. From a wildlife perspective, discretion should be exercised to use the minimum amount of light required. This can be accomplished by significantly decreasing the luminous output commonly specified by lighting designers. Land managers should not rely on standards promulgated by professional societies to guide lighting levels for natural areas because these are generally developed for urban/suburban areas with little to no regard for wildlife. Rather, every effort should be made to reduce the intensity of lights and still achieve the desired function.

Reduction in lighting intensity benefits species in the vicinity of lighting and also reduces the reflection of light in the atmosphere. The glow of lighted areas can thereby be reduced, decreasing impacts to natural systems and park visitor experience in wildlands. Often, illumination levels can be reduced without adverse consequence for human activity. In fact, reducing the contrast between light and dark areas increases the ability of humans to see. The human eye adapts to the brightest light in view. As the eye adapts to bright lights, acuity in darker areas is lost. Bright lights plunge the surrounding areas into dark shadows, while with dimmer lights the eye is able to retain some of its ability to see in darker areas.

Direction

Shielding lights is a common mitigation measure to reduce impacts to natural lands and species (**Figure 22**). Usually this involves shielding a fixture so that little or no light is emitted above the horizontal plane, and less than 10% of the light is emitted within ten degrees below the horizontal plane. This is the definition of a full cutoff lighting fixture. Shielding in this manner greatly reduces (but does not eliminate) sky glow. Light still reflects off the ground and scatters, so reduction in intensity should be combined with shielding. Downward-directed lights may still have adverse ecological consequences such as attracting insects and species that feed on the insects (e.g., bats, frogs, birds), or directing light into sensitive habitats such as wetlands and rivers.

Land managers should endeavor to shield lights beyond full cutoff to ensure that light falls only on the intended surfaces. Such mitigation will minimize direct glare, which can affect the orientation of organisms across distances (Reed et al. 1985, Telfer et al. 1987, Beier 1995, Longcore and Rich 2004); this will also minimize the area that is artificially illuminated. Design solutions to achieve these goals include the use of embedded lights to illuminate important surfaces (**Figure 23**) and simple retrofits to shield existing lights (**Figure 24**).

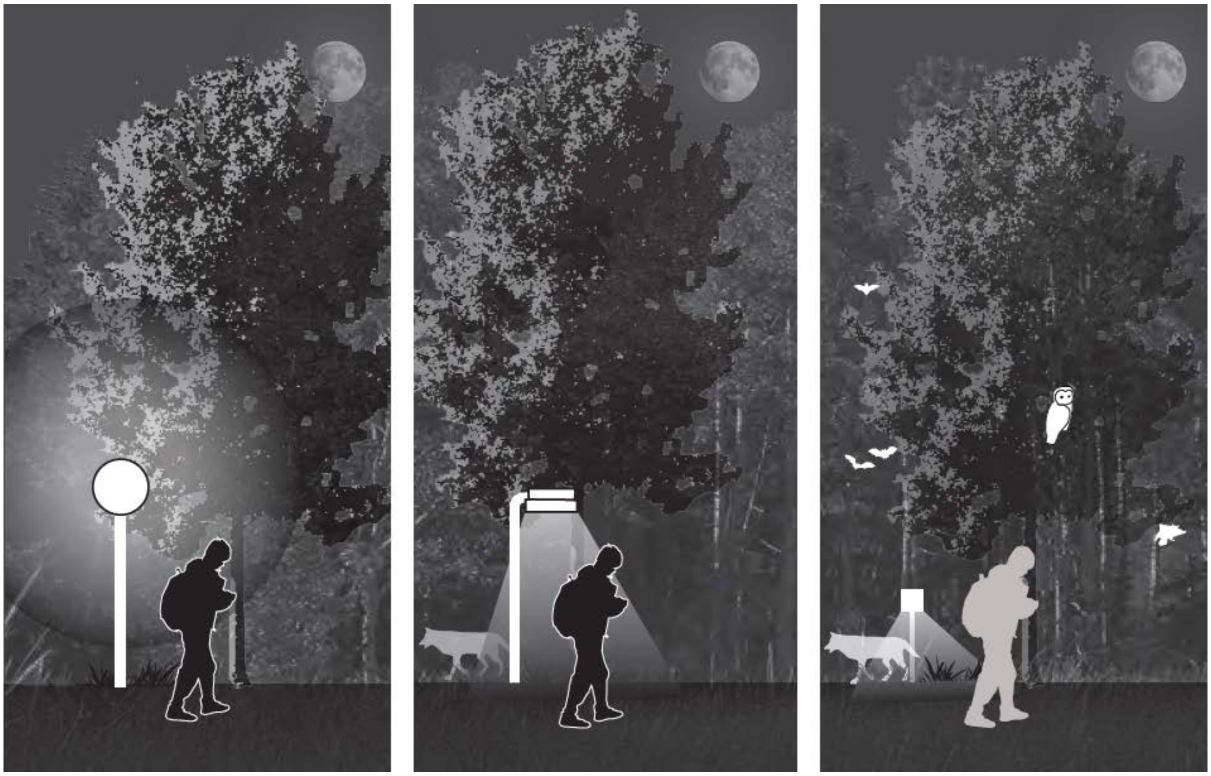


Figure 22. The more focused light can be on its target, the less it will affect other species.

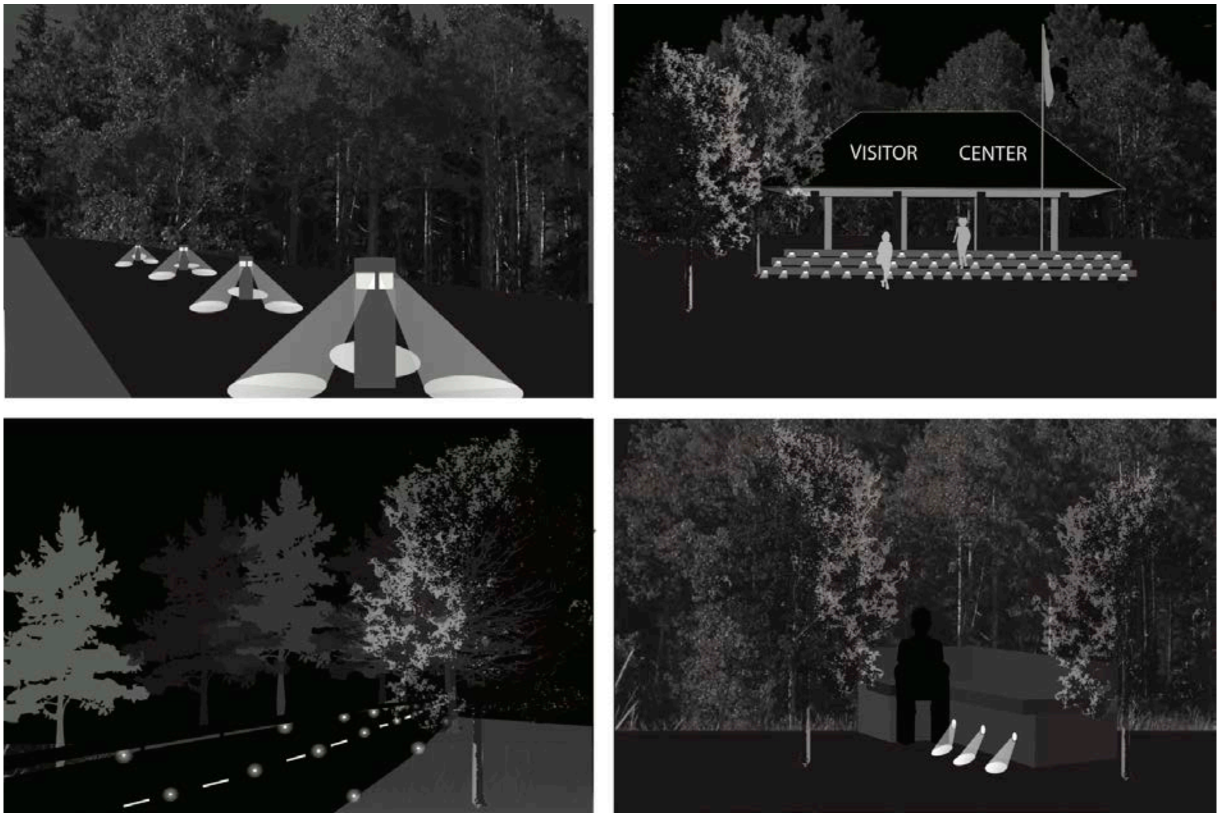


Figure 23. Embedded lights allow wayfinding with minimal intensity and good directional control.

Figure 24. A full cutoff shield being installed on an existing light on the lodge at Yellowstone National Park. This previously unshielded light was visible across the lake and from the backcountry. Photograph by Travis Longcore.

Duration

Impacts from lighting can be reduced by changing the duration of illumination. This approach reduces some impacts, but it may have some adverse consequences for those species sensitive to a changing light environment and so should be implemented with these limitations in mind. One common way to reduce the duration of illumination is to install a motion detector so that a light is only on when there is activity in a particular area (**Figure 25**). Although this limits the amount of time lights are on, lights that go on and off at irregular intervals may disrupt the nocturnal behavior of some species. For example, green frogs (*Rana clamitans*) reduce calling behavior and move away when a light is shined on them (Baker and Richardson 2006); return to a dark-adapted state can take hours (Buchanan 2006).

Figure 25. Motion- and heat-detecting lights provide illumination only when it is needed.

Another restriction on duration is setting a time for lights to be extinguished each night (**Figure 26**). For example, the lights that illuminate Mount Rushmore are only on for a few hours each night. This approach, known as part-night lighting, reduces impacts by allowing darkness during the late night and early morning hours. Depending on the timing of the lighting, darkness can be maintained for the majority of the activity period for a target species (Day et al. 2015). This approach, however, may still disrupt activities during the specific light conditions at dusk that are required by other species (Longcore et al. 2003, Day et al. 2015). Rather than a smooth range of illumination conditions occurring as the sun goes down and darkness falls, sites will experience a single illumination level until the lights are turned off. Many groups of species share resources across lighting levels; that is, one species may forage at dusk, another right after dusk, and another in the dark of night (Hailman 1984). Increased illumination, even on a temporary basis at dusk or dawn, reduces the time available for critical behaviors and could eliminate them altogether if a species prefers the transitional lighting levels of dusk when lights are illuminated. If artificial lighting eliminates a significant period of potential activity time for a species, the long-term consequences will be negative. In studies of bats, part-night lighting has been found to be ineffective in avoiding the activity periods of most species in the locations studied (Azam et al. 2015, Day et al. 2015).

Figure 26. Timed lights may affect species negatively during the transitional period of dusk, but may reduce impacts later at night.

There may be instances where avoiding lighting during a particular time when animals are active is an appropriate way to mitigate impacts. Many species are active during the crepuscular periods of dusk and dawn. If lighting can be avoided until after dark, or closer to dark, certain impacts on those species might be avoided. Setting photodetectors to activate lights only at very low levels of illumination will avoid the biologically active crepuscular period, reduce insect attraction, and limit light to after civil twilight when it is really needed.

Whenever lights are required, reducing their intensity or turning them off during periods they are not needed should always reduce impacts. For example, the Dutch government has mitigated lighting impacts on sensitive wet grassland habitats by turning off roadway lighting at 11 P.M. and replacing it with 7-watt incandescent bulbs halfway up the light standards (De Molenaar et al. 2006). These lights allow for wayfinding and have not changed the number of accidents occurring on the road.

Lighting situations

In addition to controlling for spectrum, intensity, direction, and duration, mitigation measures can be devised for many other situations in which lighting might be installed in parks. In the sections that follow, we discuss the issues involved with mitigating impacts from a series of different situations that might be faced by a park manager.

Communication towers

Each tower in the United States that is taller than 200 ft (61 m) must have obstruction lighting in accordance with Federal Aviation Administration (FAA) guidelines. Lighting is a primary factor resulting in the attraction to and mortality of birds at towers. An estimated 6.8 million birds per year are killed at tall towers (Longcore et al. 2012), including many species of conservation concern (Longcore et al. 2013). Reviews of previous work, and subsequent studies, have shown that mortality can be reduced by using a lighting system that has flashing lights only, whether these are strobe lights or red flashing lights (Gehring and Kerlinger 2007). White strobe lights have long been approved as lighting on towers and the FAA has updated its regulations to allow red flashing lights only (see FAA Advisory Circular 70/7460-1K). It is also important that towers do not have ground-level lighting around them because these lights can attract birds that then collide with tower guy wires (Longcore et al. 2008). Another option for tower lighting is an audio-visual warning system like OCAS (http://www.ocasinc.com). This approach uses radar to detect nearby aircraft, activating marker lights and emitting a verbal warning on aviation band radio. It is essentially a motion detector for tower lighting.

Night hiking and mountain biking

Night hiking and mountain biking have become popular activities in natural areas. The lights used in these activities, especially those used in mountain biking, have become brighter in recent years. For example, full-spectrum LED lights that emit 3,600 lumens (approximately the same as a 200-watt incandescent bulb) are advertised for use by bikers. Activities such as these expose wildlife to unnatural disturbance at night; this affects behaviors both because of the disturbance itself and because of the potential bleaching of eye pigments (“blinding”) from which recovery time can take minutes to hours.

Managers can mitigate the impacts of night hiking and biking by employing various strategies. These include:

1. Restrict the time of month when illuminated nocturnal recreation is allowed to the days before and after the full moon. In this manner animals are allowed the darkest part of the month as a refuge from disturbance.
2. Restrict the total luminous intensity of lights used in these activities.
3. Set curfews for illuminated nocturnal recreation.
4. Restrict nocturnal recreation activities to areas that are already disturbed by night lighting, leaving more remote wildland areas protected from nocturnal disturbance.

Campsite lighting

Although “traditional” camping with firelight and flashlights is certainly still a popular activity, more and brighter portable lights are being brought to campsites. Large arrays of lights are readily available and increasingly used by campers. Such lights can degrade the nighttime camping experience for other campers and will have greater impacts on wildlife than a campfire or small personal flashlight. Park managers might consider establishing guidelines for nighttime lighting at campsites, including limits on overall illumination, lighting curfews, and recommendations to use flashlights instead of area lighting. Lighting restrictions could be established in conjunction with quiet hours, and address portable lanterns and recreational vehicle lights. In especially dark areas, managers could recommend the use of red filters on flashlights. Such actions should be paired with minimizing lighting from the existing infrastructure (e.g., converting lights on bathrooms to low-intensity red lamps).

Off-road vehicles

Deserts and beaches often accommodate vehicular recreation. Vehicles commonly have 1,000–1,500 lumens of forward-facing light, and because this is concentrated in a fairly narrow cone, the light intensity can be very high, with low-beam headlights exceeding 4,000 candela on axis (candela is a unit measuring the brightness of a light emitted in a particular direction). For wildlife along the axis of the headlight, the intensity of a directional headlight is equivalent to an unrestricted 100,000-lumen light source (Schoettle et al. 2004). This disruption can be an intermittent impact or, in some situations, a chronic one. For example, vehicles on a beach will often park with the headlights kept on, in which case multiple headlights will be directed into the shoreline environment and have the effect of a much larger number of streetlights due to their concentrated and directed nature. The most effective mitigation would be to prohibit vehicles from these environments during sensitive times for wildlife. Additional mitigations may include restricting headlights to when the vehicle is moving or requiring low beams only.

Monuments

Parks must consider the need to preserve natural and cultural resources when making decisions related to lighting cultural monuments. For example, the Washington Monument is bathed in white light and is known to attract and kill migratory birds (Overing 1938). Because the Washington Monument has been illuminated at night since the 1930s and is so powerfully symbolic of Washington, D.C., it is not feasible to propose elimination of lighting altogether. Limitation on the hours of illumination is probably the best management action in such situations. Lighting for monuments should be designed to illuminate the monument only, and with the lowest intensity possible. Bright lighting that might have been required to accommodate photography in the past is no longer needed with current digital imaging technology.

Lighting schemes at monuments could also play a role in pest management. At the Lincoln Memorial, the lights are turned on at twilight when midges and gnats fly over from the Potomac River and onto the Memorial. This in turn attracts many spiders that weave webs on the monument and require extensive and frequent cleaning (C. Moore, pers. comm.). It might be possible to turn the lights on slightly later, after the crepuscular period, or to change the spectrum of light used to eliminate short blue and ultraviolet wavelengths. In such a manner the lighting scheme then becomes part of an Integrated Pest Management program.

Light-assisted fishing

Offshore lighting poses threats both to aquatic and terrestrial ecosystems. Light has a long history of use as a method to attract fishes for capture. In artisanal fisheries, dim lamps may be used on small human-powered boats. Current industrial-scale fisheries, however, use extremely bright lights (equivalent to 30,000 watts incandescent) to attract squid and other fishes. Even boats that do not use lights to attract their catch operate during the night and are highly illuminated. Illumination in this manner affects behavior of fishes (Nightingale et al. 2006) and other aquatic organisms (Forsythe et al. 2004). Lighting is also implicated in the mortality of seabirds in fisheries (Dick and Donaldson 1978, Carter et al. 2000). Spillover light on seabird nesting colonies has the potential to increase predation on vulnerable species (Keitt et al. 2004). Park managers should take action to reduce fishing activity with disruptive lighting near sensitive island habitats and in marine protected areas. A range of options is available to do so, including outright bans, limiting light-assisted fishing by phase of the moon (to dates around the full moon), and limiting total luminance allowed in protected waters.

Security lighting

Managers are often faced with pressure to install security lighting in hopes of decreasing illegal activity. The evidence that increased illumination reduces crime is unclear at best (Tien et al. 1977, Sherman et al. 1997), and dimming or shutting off lights may in fact reduce crime (Steinbach et al. 2015). Some schools use a “dark campus” approach, wherein all lights are extinguished at a certain hour. Lights seen after this time are then quickly recognized as indicative of unauthorized activity (Mizon 2012). Park managers should think very carefully about installation of any dusk-to-dawn security lighting. It has very little chance of being effective if staff members are not on site to observe activity. Complete darkness at night for areas in parks and protected areas that are off-limits and unoccupied should be considered in consultation with law enforcement.

Bridges

Bridges can introduce artificial lighting into natural areas through roadway lighting for safety or through architectural lighting. Both of these have the potential to disrupt natural habitats. For example, harbor seals used the lights on the Puntledge Bridge in British Columbia to form a “feeding line” and intercept outmigrating juvenile salmonid smolts (Yurk and Trites 2000). Extinguishing these lights led to a decrease in salmon mortality. Other studies document increased predation on fishes under illuminated bridges and docks (Nightingale et al. 2006). For bridges with tall structures, illumination of these towers may result in attraction of migratory birds. Such lighting should be avoided to the extent possible, such that obstruction lighting is limited to red flashing lights (if lighting is required by the FAA) and any roadway lighting is carefully directed onto the roadway with little or no spillover into the river. Furthermore, use of yellow light is preferable under most circumstances to minimize the attraction of insects, although selection of yellow lights alone will not eliminate the effects of lighting on foraging behavior of mammals (Bird et al. 2004). Other considerations with bridges include the synergistic effects of lighting and polarization that misleads insects and may even result in bridges being dispersal barriers along rivers (Horváth et al. 2009, Málnás et al. 2011).

Roadway lighting

Roadway lighting is a major source of outdoor illumination and contributes significantly to sky glow. In a study of lighting in Tucson, Arizona, roadway lighting accounted for 12% of upward directed lighting, following only commercial lights (36%) and sports fields (32%) as a proportion of total uplight (Luginbuhl et al. 2009). To maintain natural illumination conditions inside parks, managers must work with communities outside park boundaries to address these sources. Inside park boundaries, managers must make the decision whether roadway lighting is necessary in the first place, and if so, what characteristics it should have. To minimize impacts on wildlife, roadway lighting should be avoided to the extent possible, and where used should only be designed for the required intensity. The recommended lighting for a local road with low pedestrian conflict in the United States is 3–4 lux (ANSI/IES RP-8-14), which is more than 30 times brighter than the full moon's maximum intensity, so no roadway lighting is ecologically trivial. Recommended illumination for most roadways ranges from 6–15 lux (ANSI/IES RP-8-14).

One issue with reducing illumination for roadways is a concern that any reduction will increase traffic collisions. Studies of changes to roadway lighting in England and Wales, however, found no significant effect on number of traffic collisions from part-night lighting, switching off roadway lighting entirely, or changing the spectrum of roadway lighting (Steinbach et al. 2015).

Where light is essential, fixtures should be full cutoff and shielded to minimize glare from any non-road site, especially in areas with known sensitive species. The best overall choice for spectrum is probably yellow (e.g., low-pressure sodium or yellow/amber LED), but technical considerations may lead to use of a broader spectrum (e.g., high-pressure sodium). Yellow/amber LED streetlight fixtures are commercially available in response to demand for lighting with minimal impacts on bats (e.g., Innolumis bat lamp from the Netherlands) and other wildlife (e.g., Star Friendly® lights, C&W Energy Solutions).

Other alternatives are available to further reduce the impacts of street lighting. Embedded roadway lighting (**Figure 27**) has been investigated in Florida as a way to minimize impacts on nesting sea turtles (Bertolotti and Salmon 2005). Such lights may be useful in locations where snow plowing is not necessary. Another alternative is the use of dynamic lighting systems that decrease illumination based on the time of day or traffic volume so that lights are extinguished by a certain time at night or at a percentage of peak traffic (Collins et al. 2002).

Interested park managers can consult reviews on the impacts of light from street lighting systems, which recommend against full-spectrum lamps because of ecological, physiological, and dark-sky impacts (Falchi et al. 2011, Bierman 2012).

Vehicles along roads can cause the type of periodic changes in lighting levels that can affect animal behavior (Baker and Richardson 2006) and influence views of the night sky (Luginbuhl et al. 2009). Birds, especially migratory species and seabirds, can be attracted to vehicle headlights (Gauthreaux and Belser 2006). Although additional research on this topic would be welcome, managers can mitigate impacts from headlights by providing shielding of sensitive receptors using a range of physical barriers, including berms, dense shrubs, or even walls in particularly sensitive areas.

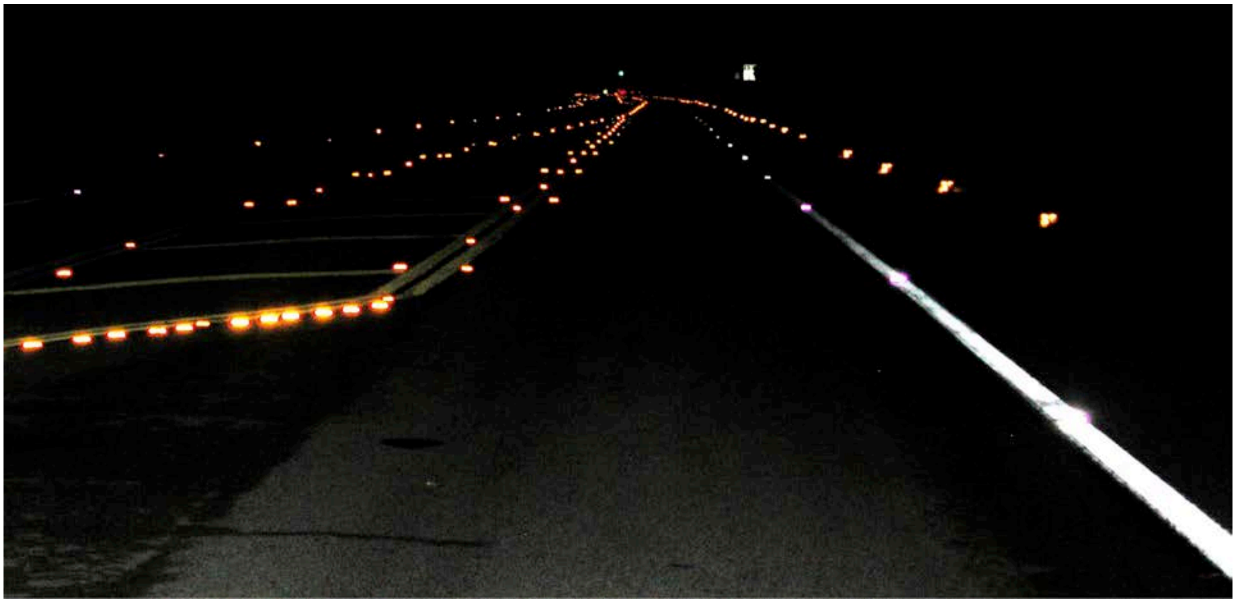


Figure 27. Embedded roadway lighting. These LED lights installed in the pavement are not visible to sea turtles nesting on the adjacent beach and are well received by motorists and pedestrians (Bertolotti and Salmon 2005). Photograph courtesy of Michael Salmon.

Energy production installations

Efforts to increase domestic energy production have resulted in pressure to explore and extract fossil fuels and develop industrial-scale facilities for wind and solar energy both on land and water. Energy production facilities have the potential to affect natural resources on park properties that may be found intermixed with other public and private lands approved for such activities. The direct impacts of such activities are of great conservation concern, but are not discussed here. In the event that such facilities are evaluated in the environmental review process, the following recommendations could be made to minimize the impacts of artificial night lighting.

Wind energy installations are generally illuminated with red flashing lights at the corners of arrays of turbines. Not all turbines have obstruction lighting. Researchers documenting mortality of animals (both bats and birds) at wind turbines have concluded that these flashing lights do not attract birds, but that constant illumination of ancillary structures on the ground is associated with increased bird mortality at nearby turbines (Kerlinger 2004, Kerlinger et al. 2010). Wind turbines currently are estimated to kill on the order of 100,000 (Kerlinger et al. 2011) and 573,000 (Smallwood 2013) birds per year, with this number likely to grow 30-fold in the next 20 years to meet federal goals for renewable energy. Ensuring that lighting is only red flashing with no steady-burning lights on any accessory structures would reduce mortality of nocturnal migrant birds, but would not mitigate the significant bat mortality that is associated with wind turbines (Kunz et al. 2007, Smallwood 2013).

Solar power plants are proposed and being built in open desert areas near parks and protected natural lands. Such facilities should not require dusk-to-dawn night lighting. If security lighting is desired, the recommendation should be made that it be fully shielded, low intensity, and on a motion detector.

Oil and natural gas facilities are often brightly illuminated at night. This light can have adverse consequences for any habitat in which it is found. For example, offshore oil platforms attract seabirds, usually to their detriment (Wiese et al. 2001, Montevecchi 2006). Terrestrial oil and gas facilities are often the only sources of light in remote open spaces. Parks can work with existing facilities to retrofit lights. For marine facilities, some initially positive data have been collected suggesting that using a green light on an offshore platform reduces the number of birds that are attracted to it (van de Laar 2007, Poot et al. 2008). By retrofitting the platform from white lights to green lights, Dutch researchers documented a reduction in the number of birds observed circling a platform (van de Laar 2007). The cause of this reduction could have been the wavelength of light used, or an overall decrease in lighting intensity that was a byproduct of the lighting change. The research shows that decreasing illumination and restricting the spectrum of light is a promising approach to reducing impacts to biological resources while still maintaining safe operations.

Indoor lighting

Although outdoor lighting is usually the focus of efforts to reduce impacts of night lighting on wildlife, indoor lighting should be considered as well. Indoor lighting may contribute substantially to ecological light pollution. In the extreme example of all-glass structures, greenhouses in Germany attract insects and migratory birds (Abt and Schultz 1995, Kolligs 2000). Furthermore, office buildings in urban cores can contribute as much to sky glow as billboards or roadway lighting (Oba et al. 2005). In darker environments, even the lights from a residence may have some effect on local wildlife behavior and degrade the experience of visitors in adjacent natural areas. Managers can be aware of these issues and seek to shield interior lights through use of curtains. This also gives an additional reason to cluster developments within parks. For urban areas and office buildings, guidelines are available to minimize the effects on birds, including through steps to reduce interior illumination (New York City Audubon Society 2007).

Lighthouses

The fatal attraction of birds to lighthouses has been observed for well over a century (Dutcher 1884, Miller 1897, Hansen 1954). In the United States, mortality of birds is more commonly reported on the East Coast than on the West Coast (Allen 1880, Merriam 1885), although mortality has been recorded on the West Coast as well (Squires and Hanson 1918). There has been some conflicting research on lighting color and flashing since the early 1900s (see review in Gauthreaux and Belser 2006), but the view has solidified that mortality can be decreased through the use of a flashing rather than constant light (Baldwin 1965, Jones and Francis 2003, Gauthreaux and Belser 2006). It is important that the light itself flashes, extinguishing completely between flashes, rather than the flashing effect being created by a rotating beam that remains illuminated. Reduction in lighting intensity also reduces bird mortality (Jones and Francis 2003).

Billboards

Billboards and other signage can affect wildlife behavior when illuminated. For example, light from a single billboard was sufficient to change the concealment behavior of juvenile salmon in a stream (Contor and Griffith 1995). While the significance of such behavioral changes is unknown, illumination of billboards and other signs should be controlled to minimize cumulative effects of lighting on wildlife, especially as digital billboards proliferate. Illumination from a typical digital billboard proposed for installation in endangered species habitat in southern California would have caused lighting levels to exceed 10^{-1} lux (equivalent to that of a full moon) up to 1,000 ft (305 m) from the sign, according to the lighting engineers for the applicant (Longcore 2015; the proposal was not approved). Such intense lighting has the potential to influence nearby sensitive resources and contribute to sky glow.

Conclusion

Light pollution within parks and protected lands can have a measurable impact upon the habitat quality of the park, even if the light itself originates outside of the park’s administrative boundary. Minimizing ecological impacts requires that land managers adopt an ethic of using only the minimum light necessary for human needs and being cautious when introducing light into or near a natural landscape. This report provides examples of the range of negative consequences that may arise from artificial night lighting. Though not a compendium of information for every species and every environment, it should provide adequate evidence for reasonable management of lighting in natural areas.

Park managers should first inventory their resources and determine if and where sensitive species or habitats exist. This information can then guide the development of the prescription of lighting zones within a park where different levels of lighting are allowed, depending on the uses and experiences desired for those zones. Lighting zones may be designed to minimize wildlife impacts only or also to integrate other aspects of a park experience. The most sensitive zone would have a prohibition on outdoor lighting or impose restrictions that define a narrow range of allowable artificial lighting. Looser restrictions that still provide adequate mitigation would be delineated for developed areas in parks and those with substantial human nighttime activity. In all instances, mitigation should address spectrum, intensity, direction, and duration. When all four aspects are addressed, mitigations can be effective at reducing ecological disruption from artificial night lighting.

Literature Cited

Abt, K. F., and G. Schultz. 1995. Auswirkungen der Lichtemissionen einer Großgewächshausanlage auf den nächtlichen Vogelzug [Impact of light emissions from a large illuminated greenhouse on nocturnal bird migration]. Corax **16**:17–29.

Allen, J. A. 1880. Destruction of birds by light-houses. Bulletin of the Nuttall Ornithological Club **5**:131–138.

Aubé, M., and J. Roby. 2014. Sky brightness levels before and after the creation of the first International Dark Sky Reserve, Mont-Mégantic Observatory, Québec, Canada. Journal of Quantitative Spectroscopy & Radiative Transfer **139**:52–63.

Aubé, M., J. Roby, and M. Kocifaj. 2013. Evaluating potential spectral imapcts of various artificial lights on melatonin suppression, photosynthesis, and star visibility. PLoS ONE **8**:e67798.

Aubrecht, C., C. D. Elvidge, T. Longcore, C. Rich, J. Safran, A. E. Strong, C. M. Eakin, K. E. Baugh, B. T. Tuttle, A. T. Howard, and E. H. Erwin. 2008. A global inventory of coral reef stressors based on satellite observed nighttime lights. Geocarto International **23**:467–479.

Azam, C., C. Kerbiriou, A. Vernet, J. F. Julien, Y. Bas, L. Plichard, J. Maratrat, and I. Le Viol. 2015. Is part-night lighting an effective measure to limit the impacts of artificial lighting on bats? Global Change Biology **21**:4333–4341.

Baker, B. J., and J. M. L. Richardson. 2006. The effect of artificial light on male breeding-season behaviour in green frogs, *Rana clamitans melanota*. Canadian Journal of Zoology **84**:1528–1532.

Baldwin, D. H. 1965. Enquiry into the mass mortality of nocturnal migrants in Ontario: final report. Ontario Naturalist **3**:3–11.

Barber-Meyer, S. M. 2007. Photopollution impacts on the nocturnal behaviour of the sugar glider (*Petaurus breviceps*). Pacific Conservation Biology **13**:171–176.

Becker, A., A. K. Whitfield, P. D. Cowley, J. Järnegren, and T. F. Næsje. 2013. Potential effects of artificial light associated with anthropogenic infrastructure on the abundance and foraging behaviour of estuary-associated fishes. Journal of Applied Ecology **50**:43–50.

Beier, P. 1995. Dispersal of juvenile cougars in fragmented habitat. Journal of Wildlife Management **59**:228–237.

Beier, P. 2006. Effects of artificial night lighting on terrestrial mammals. Pages 19–42 *in* C. Rich and T. Longcore, editors. Ecological consequences of artificial night lighting. Island Press, Washington, D.C.

Bennie, J., J. P. Duffy, T. W. Davies, M. E. Correa-Cano, and K. J. Gaston. 2015. Global trends in exposure to light pollution in natural terrestrial ecosystems. Remote Sensing **7**:2715–2730.

Bentley, M. G., P. J. W. Olive, and K. Last. 2001. Sexual satellites, moonlight and the nuptial dances of worms: the influence of the moon on the reproduction of marine animals. Earth, Moon and Planets **85–86**:67–84.

Bertolotti, L., and M. Salmon. 2005. Do embedded roadway lights protect sea turtles? Environmental Management **36**:702–710.

Bierman, A. 2012. Will switching to LED outdoor lighting increase sky glow? Lighting Research & Technology **44**:449–458.

Bird, B. L., L. C. Branch, and D. L. Miller. 2004. Effects of coastal lighting on foraging behavior of beach mice. Conservation Biology **18**:1435–1439.

Bird, S., and J. Parker. 2014. Low levels of light pollution may block the ability of male glow-worms (*Lampyris noctiluca* L.) to locate females. Journal of Insect Conservation **18**:737–743.

Boldogh, S., D. Dobrosi, and P. Samu. 2007. The effects of the illumination of buildings on house-dwelling bats and its conservation consequences. Acta Chiropterologica **9**:527–534.

Brainard, G. C., J. P. Hanifin, B. Warfield, M. K. Stone, M. E. James, M. Ayers, A. Kubey, B. Byrne, and M. Rollag. 2015. Short-wavelength enrichment of polychromatic light enhances human melatonin suppression potency. Journal of Pineal Research **58**:352–361.

Buchanan, B. W. 1993. Effects of enhanced lighting on the behaviour of nocturnal frogs. Animal Behaviour **45**:893–899.

Buchanan, B. W. 1998. Low-illumination prey detection by squirrel treefrogs. Journal of Herpetology **32**:270–274.

Buchanan, B. W. 2006. Observed and potential effects of artificial night lighting on anuran amphibians. Pages 192–220 *in* C. Rich and T. Longcore, editors. Ecological consequences of artificial night lighting. Island Press, Washington, D.C.

Burger, J., and M. Gochfeld. 1991. Human activity influence and diurnal and nocturnal foraging of sanderlings (*Calidris alba*). Condor **93**:259–265.

Carter, H. R., D. L. Whitworth, J. Y. Takekawa, T. W. Keeney, and P. R. Kelly. 2000. At-sea threats to Xantus' murrelets (*Synthliboramphus hypoleucus*) in the Southern California Bight. Pages 435–447 *in* D. R. Browne, K. L. Mitchell, and H. W. Chaney, editors. Proceedings of the fifth California Islands symposium. U.S. Minerals Management Service, Camarillo, California.

Christoffers, E. W., III. 1986. Ecology of the ghost crab *Ocypode quadrata* (Fabricius) on Assateague Island, Maryland and the impacts of various human uses of the beach on their distribution and abundance. Dissertation. Michigan State University, East Lansing, Michigan.

CIE. 1932. Commission Internationale de l'Éclairage Proceedings, 1931. Cambridge University Press, Cambridge.

Clarke, J. A. 1983. Moonlight's influence on predator/prey interactions between short-eared owls (*Asio flammeus*) and deermice (*Peromyscus maniculatus*). Behavioral Ecology and Sociobiology **13**:205–209.

Cleve, K. 1964. Der Anflug der Schmetterlinge an künstliche Lichtquellen [The flight of moths at artificial light sources]. Mitteilungen der dutschen Entomologischen Gesellschaft **23**:66–76.

Collins, A., T. Thurrell, R. Pink, and J. Feather. 2002. Dynamic dimming: the future of motorway lighting? Lighting Journal **67**:25–33.

Contor, C. R., and J. S. Griffith. 1995. Nocturnal emergence of juvenile rainbow trout from winter concealment relative to light intensity. Hydrobiologia **299**:179–183.

Daly, M., P. R. Behrends, M. I. Wilson, and L. F. Jacobs. 1992. Behavioural modulation of predation risk: moonlight avoidance and crespuscular compensation in a nocturnal desert rodent, *Dipodomys merriami*. Animal Behaviour **44**:1–9.

Davies, T. W., M. Coleman, K. M. Griffith, and S. R. Jenkins. 2015. Night-time lighting alters the composition of marine epifaunal communities. Biology Letters **11**:20150080.

Davies, T. W., J. P. Duffy, J. Bennie, and K. J. Gaston. 2014. The nature, extent, and ecological implications of marine light pollution. Frontiers in Ecology and the Environment **12**:347–355.

Day, J., J. Baker, H. Schofield, F. Mathews, and K. J. Gaston. 2015. Part-night lighting: implications for bat conservation. Animal Conservation **18**:512–516.

De Molenaar, J. G., R. J. H. G. Henkens, C. ter Braak, C. van Duyne, G. Hoefsloot, and D. A. Jonkers. 2003. Road illumination and nature, IV. Effects of road lights on the spatial behaivour of mammals. Alterra, Green World Research, Wageningen, The Netherlands.

De Molenaar, J. G., D. A. Jonkers, and M. E. Sanders. 2000. Road illumination and nature. III. Local influence of road lights on a black-tailed godwit (*Limosa l. limosa*) population. DWW Ontsnipperingsreeks deel 38A, Delft.

De Molenaar, J. G., M. E. Sanders, and D. A. Jonkers. 2006. Road lighting and grassland birds: local influence of road lighting on a black-tailed godwit population. Pages 114–136 *in* C. Rich and T. Longcore, editors. Ecological consequences of artificial night lighting. Island Press, Washington, D.C.

DeCoursey, P. J. 1986. Light-sampling behavior in photoentrainment of a rodent circadian rhythm. Journal of Comparative Physiology A **159**:161–169.

Dick, M. H., and W. Donaldson. 1978. Fishing vessel endangered by crested auklet landings. Condor **80**:235–236.

Duffy, J. P., J. Bennie, A. P. Durán, and K. J. Gaston. 2015. Mammalian ranges are experiencing erosion of natural darkness. Scientific Reports **5**:12042.

Dugan, P. J. 1981. The importance of nocturnal foraging in shorebirds: a consequence of increased invertebrate prey activity. Pages 251–260 *in* N. V. Jones and W. J. Wolff, editors. Feeding and survival strategies of estuarine organisms. Plenum Press, New York.

Dutcher, W. 1884. Bird notes from Long Island, N.Y. Auk **1**:174–179.

Eisenbeis, G. 2006. Artificial night lighting and insects: attraction of insects to streetlamps in a rural setting in Germany. Pages 281–304 *in* C. Rich and T. Longcore, editors. Ecological consequences of artificial night lighting. Island Press, Washington, D.C.

Eisenbeis, G., and K. Eick. 2011. Studie zur Anziehung nachtaktiver Insekten an die Straßenbeleuchtung unter Einbeziehung von LEDs [Attraction of nocturnal insects to street lights — a study of lighting systems, with consideration of LEDs]. Natur und Landschaft **86**:298–306.

Eisenbeis, G., and F. Hassel. 2000. [Attraction of nocturnal insects to street lights – a study of municipal lighting systems in a rural area of Rheinhessin (Germany)]. Natur und Landschaft **75**:145–156.

Evans, A. 1987. Relative availability of the prey of wading birds by day and by night. Marine Ecology – Progress Series **37**:103–107.

Falchi, F., P. Cinzano, C. D. Elvidge, D. M. Keith, and A. Haim. 2011. Limiting the impact of light pollution on human health, environment and stellar visibility. Journal of Environmental Management **92**:2714–2722.

Forsythe, J., N. Kangas, and R. T. Hanlon. 2004. Does the California market squid (*Loligo opalescens*) spawn naturally during the day or at night? A note on the successful use of ROVs to obtain basic fisheries biology data. Fishery Bulletin **102**:389–392.

Frank, K. D. 1988. Impact of outdoor lighting on moths: an assessment. Journal of the Lepidopterists' Society **42**:63–93.

Frank, K. D. 2006. Effects of artificial night lighting on moths. Pages 305–344 *in* C. Rich and T. Longcore, editors. Ecological consequences of artificial night lighting. Island Press, Washington, D.C.

Gal, G., E. R. Loew, L. G. Rudstam, and A. M. Mohammadian. 1999. Light and diel vertical migration: spectral sensitivity and light avoidance by *Mysis relicta*. Canadian Journal of Fisheries and Aquatic Science **56**:311–322.

Gastman, E. A. 1886. Birds killed by electric light towers at Decatur, Ill. American Naturalist **20**:981.

Gaston, K. J. 2013. A green light for efficiency. Nature **497**:560–561.

Gauthreaux, S. A., Jr., and C. G. Belser. 2006. Effects of artificial night lighting on migrating birds. Pages 67–93 *in* C. Rich and T. Longcore, editors. Ecological consequences of artificial night lighting. Island Press, Washington, D.C.

Gehring, J., and P. Kerlinger. 2007. Avian collisions at communications towers: II. The role of Federal Aviation Administration obstruction lighting systems. State of Michigan.

Gilbert, B. S., and S. Boutin. 1991. Effect of moonlight on winter activity of snowshoe hares. Arctic and Alpine Research **23**:61–65.

Gorbunov, M. Y., and P. G. Falkowski. 2002. Photoreceptors in the cnidarian hosts allow symbiotic corals to sense blue moonlight. Limnology and Oceanography **47**:309–315.

Gorenzel, W. P., and T. P. Salmon. 1995. Characteristics of American crow urban roosts in California. Journal of Wildlife Management **59**:638–645.

Griffin, P. C., S. C. Griffin, C. Waroquiers, and L. S. Mills. 2005. Mortality by moonlight: predation risk and the snowshoe hare. Behavioral Ecology **16**:938–944.

Grigione, M. M., and R. Mrykalo. 2004. Effects of artificial night lighting on endangered ocelots (*Leopardus paradalis*) and nocturnal prey along the United States-Mexico border: a literature review and hypotheses of potential impacts. Urban Ecosystems **7**:65–77.

Hagen, O., and V. R. Viviani. 2009. Investigation of the artificial night lighting influence in firefly (Coleoptera: Lampyridae) occurrence in the urban areas of Campinas and Sorocaba municipalities [extended abstract].*in* Anais do IX Congresso de Ecologia do Brasil, São Lourenço.

Hailman, J. P. 1984. Bimodal nocturnal activity of the western toad (*Bufo boreas*) in relation to ambient illumination. Copeia **1984**:283–290.

Hailman, J. P., and J. G. Jaeger. 1974. Phototactic responses to spectrally dominant stimuli and use of colour vision by adult anuran amphibians: a comparative survey. Animal Behaviour **22**:757–795.

Hailman, J. P., and J. G. Jaeger. 1976. A model of phototaxis and its evaluation with anuran populations. Behaviour **56**:289–296.

Hansen, L. 1954. Birds killed at lights in Denmark 1886–1939. Videnskabelige Meddelelser fra Dansk Naturhistorisk Forening **116**:269–368.

Henn, M., H. Nichols, Y. Zhang, and T. H. Bonner. 2014. Effect of artificial light on the drift of aquatic insects in urban central Texas streams. Journal of Freshwater Ecology **29**:302–318.

Hobson, E. S. 1965. Diurnal–nocturnal activity of some inshore fishes in the Gulf of California. Copeia **1965**:291–302.

Hobson, E. S., W. N. McFarland, and J. R. Chess. 1981. Crepuscular and nocturnal activities of Californian nearshore fishes, with consideration of their scotopic visual pigments and the photic environment. Fishery Bulletin **79**:1–30.

Hock, R. J. 1955. Photoperiod as stimulus for onset of hibernation. Federation Proceedings **14**:73–74.

Holzman, R., and A. Genin. 2003. Zooplanktivory by a nocturnal coral-reef fish: effects of light, flow, and prey density. Limnology and Oceanography **48**:1367–1375.

Holzman, R., and A. Genin. 2005. Mechanisms of selectivity in a nocturnal fish: a lack of active prey choice. Oecologia **146**:329–336.

Horváth, G., G. Kriska, P. Malik, and B. Robertson. 2009. Polarized light pollution: a new kind of ecological photopollution. Frontiers in Ecology and the Environment **7**:317–325.

Jaeger, R. G., and J. P. Hailman. 1976. Phototaxis in anurans: relation between intensity and spectral preferences. Copeia **1976**:92–98.

Johnsen, S. 2012. The optics of life: a biologist’s guide to light in nature. Princeton University Press, Princeton.

Jokiel, P. L., R. Y. Ito, and P. M. Liu. 1985. Night irradiance and synchronization of lunar release of planula larvae in the reef coral *Pocillopora damicornis*. Marine Biology **88**:167–174.

Jones, J., and C. M. Francis. 2003. The effects of light characteristics on avian mortality at lighthouses. Journal of Avian Biology **34**:328–333.

Keitt, B. S., B. R. Tershy, and D. A. Croll. 2004. Nocturnal behavior reduces predation pressure on black-vented shearwaters *Puffinus opisthomelas*. Marine Ornithology **32**:173–178.

Kerlinger, P. 2004. Attraction of night migrating birds to FAA and other types of lights. Curry & Kerlinger, LLC, Cape May, New Jersey.

Kerlinger, P., J. Gehring, and R. Curry. 2011. Understanding bird collisions at communication towers and wind turbines: status of impacts and research. Birding **43**:44–51.

Kerlinger, P., J. L. Gehring, W. P. Erickson, R. Curry, A. Jain, and J. Guarnaccia. 2010. Night migrant fatalities and obstruction lighting at wind turbines in North America. Wilson Journal of Ornithology **122**:744–754.

Kolligs, D. 2000. Ökologische Auswirkungen künstlicher Lichtquellen auf nachtaktive Insekten, insbesondere Schmetterlinge (Lepidoptera) [Ecological effects of artificial light sources on nocturnally active insects, in particular on moths (Lepidoptera)]. Faunistisch-Oekologische Mitteilungen Supplement **28**:1–136.

Kotler, B. P. 1984. Risk of predation and the structure of desert rodent communities. Ecology **65**:689–701.

Kotler, B. P. 1985. Owl predation on desert rodents which differ in morphology and behavior. Journal of Mammalogy **66**:824–828.

Kramer, K. M., and E. C. Birney. 2001. Effect of light intensity on activity patterns of Patagonian leaf-eared mice, *Phyllotis xanthopygus*. Journal of Mammalogy **82**:535–544.

Kronfeld-Schor, N., and T. Dayan. 2008. Activity patterns of rodents: the physiological ecology of biological rhythms. Biological Rhythm Research **39**:193–211.

Kumlien, L. 1888. Observations on bird migration at Milwaukee. Auk **5**:325–328.

Kunz, T. H., E. B. Arnett, W. P. Erickson, A. R. Hoar, G. D. Johnson, R. P. Larkin, M. D. Strickland, R. W. Thresher, and M. D. Tuttle. 2007. Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses. Frontiers in Ecology and the Environment **5**:315–324.

Kyba, C. C. M., T. Ruhtz, J. Fischer, and F. Hölker. 2011. Cloud coverage acts as an amplifier for ecological light pollution in urban ecosystems. PLoS ONE **6**:e17307.

Leis, J. M. 1986. Vertical and horizontal distribution of fish larvae near coral reeefs at Lizard Island, Great Barrier Reef. Marine Biology **90**:505–516.

Levy, O., L. Mizrahi, N. E. Chadwick-Furman, and Y. Achituv. 2001. Factors controlling the expansion behavior of *Favia favus* (Cnidaria: Scleractinia): effects of light, flow, and planktonic prey. Biological Bulletin **200**:118–126.

Lima, S. L. 1998. Stress and decision making under the risk of predation: recent developments from behavioral, reproductive, and ecological perspectives. Advances in the Study of Behavior **27**:215–290.

Lloyd, J. E. 2006. Stray light, fireflies, and fireflyers. Pages 345–364 *in* C. Rich and T. Longcore, editors. Ecological consequences of artificial night lighting. Island Press, Washington, D.C.

Longcore, T. 2015. Review of biological impacts analysis in Mitigated Negative Declaration for State Route 78 Digital Sign, City of Oceanside, California. Land Protection Partners, Los Angeles.

Longcore, T., H. L. Aldern, J. F. Eggers, S. Flores, L. Franco, E. Hirshfield-Yamanishi, L. N. Petrinec, W. A. Yan, and A. M. Barroso. 2015. Tuning the white light spectrum of light emitting diode lamps to reduce attraction of nocturnal arthropods. Philosophical Transactions of the Royal Society B: Biological Sciences **370**:20140125.

Longcore, T., and C. Rich. 2004. Ecological light pollution. Frontiers in Ecology and the Environment **2**:191–198.

Longcore, T., C. Rich, and S. A. Gauthreaux, Jr. 2008. Height, guy wires, and steady-burning lights increase hazard of communication towers to nocturnal migrants: a review and meta-analysis. Auk **125**:485–492.

Longcore, T., C. Rich, J. M. Marzluff, and B. Nightingale. 2003. Peer review of artificial light and noise impact analysis in Sand Point Magnuson Park Drainage, Wetland/Habitat Complex and Sports Fields/Courts Project Final Environmental Impact Statement. Land Protection Partners, Los Angeles.

Longcore, T., C. Rich, P. Mineau, B. MacDonald, D. G. Bert, L. M. Sullivan, E. Mutrie, S. A. Gauthreaux, Jr., M. L. Avery, R. L. Crawford, A. M. Manville, II, E. R. Travis, and D. Drake. 2012. An estimate of avian mortality at communication towers in the United States and Canada. PLoS ONE **7**:e34025.

Longcore, T., C. Rich, P. Mineau, B. MacDonald, D. G. Bert, L. M. Sullivan, E. Mutrie, S. A. Gauthreaux, Jr., M. L. Avery, R. L. Crawford, A. M. Manville, II, E. R. Travis, and D. Drake. 2013. Avian mortality at communication towers in the United States and Canada: which species, how many, and where? Biological Conservation **158**:410–419.

Luginbuhl, C. B., G. W. Lockwood, D. R. Davis, K. Pick, and J. Selders. 2009. From the ground up I: light pollution sources in Flagstaff, Arizona. Publications of the Astronomical Society of the Pacific **121**:185–203.

Málnás, K., L. Polyák, É. Prill, R. Hegedüs, G. Kriska, G. Dévai, G. Horváth, and S. Lengyel. 2011. Bridges as optical barriers and population disruptors for the mayfly *Palingenia longicauda*: an overlooked threat to freshwater biodiversity? Journal of Insect Conservation **15**:823–832.

Marcantonio, M., S. Pareeth, D. Rocchini, M. Metz, C. X. Garzon-Lopez, and M. Neteler. 2015. The integration of artificial night-time lights in landscape ecology: a remote sensing approach. Ecological Complexity **22**:109–120.

McFarlane, R. W. 1963. Disorientation of loggerhead hatchlings by artificial road lighting. Copeia **1963**:153.

McNeil, R., P. Drapeau, and J. D. Goss-Custard. 1992. The occurrence and adaptive significance of nocturnal habits in waterfowl. Biological Reviews **67**:381–419.

Menzel, R., and U. Greggers. 1985. Natural phototaxis and its relationship to colour vision in honeybees. Journal of Comparative Physiology A **157**:311–321.

Merriam, C. H. 1885. Preliminary report of the committee on bird migration. Auk **2**:53–65.

Miller, G. S., Jr. 1897. Winge on birds at the Danish lighthouses. Auk **14**:415–417.

Mizon, B. 2012. Light pollution: responses and remedies. Springer-Verlag, London.

Montevecchi, W. A. 2006. Influences of artificial light on marine birds. Pages 94–113 *in* C. Rich and T. Longcore, editors. Ecological consequences of artificial night lighting. Island Press, Washington, D.C.

Moore, M. V., S. J. Kohler, and M. S. Cheers. 2006. Artificial light at night in freshwater habitats and its potential ecological effects. Pages 365–384 *in* C. Rich and T. Longcore, editors. Ecological consequences of artificial night lighting. Island Press, Washington, D.C.

Moore, M. V., S. M. Pierce, H. M. Walsh, S. K. Kvalvik, and J. D. Lim. 2000. Urban light pollution alters the diel vertical migration of *Daphnia*. Verhandlungen der Internationalen Vereinigung fur Theoretische und Angewandte Limnologie **27**:779–782.

Moser, J. C., J. D. Reeve, J. M. S. Bento, T. M. C. Della Lucia, R. S. Cameron, and N. M. Heck. 2004. Eye size and behaviour of day- and night-flying leafcutting ant alates. Journal of Zoology, London **264**:69–75.

Mouritsen, K. N. 1992. Predator avoidance in night-feeding dunlins *Calidris alpina*: a matter of concealment. Ornis Scandinavica **23**:195–198.

New York City Audubon Society. 2007. Bird-safe building guidelines. New York City Audubon Society, New York.

Nightingale, B., T. Longcore, and C. A. Simenstad. 2006. Artificial night lighting and fishes. Pages 257–276 *in* C. Rich and T. Longcore, editors. Ecological consequences of artificial night lighting. Island Press, Washington, D.C.

Nørgaard, T., J. R. Henschel, and R. Wehner. 2006. The night-time temporal window of locomotor activity in the Namib Desert long-distance wandering spider, *Leucorchestris arenicola*. Journal of Comparative Physiology A **192**:365–372.

Oba, N., K. Kawakami, T. Iwata, T. Uozumi, and S. Kohko. 2005. Sky glow caused by the spill light from office buildings. Journal of Light & Visual Environment **29**:19–24.

Outen, A. R. 1998. The possible ecological implications of artificial lighting. Hertfordshire Biological Records Centre, Hertfordshire.

Overing, R. 1938. High mortality at the Washington Monument. Auk **55**:679.

Pauley, S. M. 2004. Lighting for the human circadian clock: recent research indicates that lighting has become a public health issue. Medical Hypotheses **63**:588–596.

Pawson, S. M., and M. K.-F. Bader. 2014. LED lighting increases the ecological impact of light pollution irrespective of color temperature. Ecological Applications **24**:1561–1568.

Perkin, E. K., F. Hölker, J. S. Richardson, J. P. Sadler, C. Wolter, and K. Tockner. 2011. The influence of artificial light on stream and riparian ecosystems: questions, challenges, and perspectives. Ecosphere **2**:122.

Perry, G., B. W. Buchanan, R. N. Fisher, M. Salmon, and S. E. Wise. 2008. Effects of artificial night lighting on amphibians and reptiles in urban environments. Herpetological Conservation **3**:239–256.

Perry, G., and R. N. Fisher. 2006. Night lights and reptiles: observed and potential effects. Pages 169–191 *in* C. Rich and T. Longcore, editors. Ecological consequences of artificial night lighting. Island Press, Washington, D.C.

Poiani, S., C. Dietrich, A. Barroso, and A. M. Costa-Leonardo. 2015. Effects of residential energy-saving lamps on the attraction of nocturnal insects. Lighting Research & Technology **47**:338–348.

Poot, H., B. J. Ens, H. de Vries, M. A. H. Donners, M. R. Wernand, and J. M. Marquenie. 2008. Green light for nocturnally migrating birds. Ecology and Society **13**:47.

Price, M. V., N. M. Waser, and T. A. Bass. 1984. Effects of moonlight on microhabitat use by desert rodents. Journal of Mammalogy **65**:353–356.

Reed, J. R., J. L. Sincock, and J. P. Hailman. 1985. Light attraction in endangered procellariiform birds: reduction by shielding upward radiation. Auk **102**:377–383.

Rich, C., and T. Longcore, editors. 2006. Ecological consequences of artificial night lighting. Island Press, Washington, D.C.

Riley, W. D., P. I. Davison, D. L. Maxwell, and B. Bendall. 2013. Street lighting delays and disrupts the dispersal of Atlantic salmon (*Salmo salar*) fry. Biological Conservation **158**:140–146.

Riou, S., and K. C. Hamer. 2008. Predation risk and reproductive effort: impacts of moonlight on food provisioning and chick growth in Manx shearwaters. Animal Behaviour **76**:1743–1748.

Ritz, T., R. Wiltschko, P. J. Hore, C. T. Rodgers, K. Stapput, P. Thalau, C. R. Timmel, and W. Wiltschko. 2009. Magnetic compass of birds is based on a molecule with optimal directional sensitivity. Biophysical Journal **96**:3451–3457.

Robert, M., R. McNeil, and A. Leduc. 1989. Conditions and significance of night feeding in shorebirds and other water birds in a tropical lagoon. Auk **106**:94–101.

Rodrigues, P., C. Aubrecht, A. Gil, T. Longcore, and C. Elvidge. 2012. Remote sensing to map influence of light pollution on Cory's shearwater in São Miguel Island, Azores Archipelago. European Journal of Wildlife Research **58**:147–155.

Rodríguez, A., and B. Rodríguez. 2009. Attraction of petrels to artificial lights in the Canary Islands: effects of the moon phase and age class. Ibis **151**:299–310.

Rohweder, D. A., and P. R. Baverstock. 1996. Preliminary investigation of nocturnal habitat use by migratory waders (Order Charadriiformes) in northern New South Wales. Wildlife Research **23**:169–183.

Salmon, M. 2003. Artificial night lighting and sea turtles. Biologist **50**:163–168.

Salmon, M. 2006. Protecting sea turtles from artificial night lighting at Florida's oceanic beaches. Pages 141–168 *in* C. Rich and T. Longcore, editors. Ecological consequences of artificial night lighting. Island Press, Washington, D.C.

Schlacher, T. A., J. Dugan, D. S. Schoeman, M. Lastra, A. Jones, F. Scapini, A. McLachlan, and O. Defeo. 2007a. Sandy beaches at the brink. Diversity and Distributions **13**:556–560.

Schlacher, T. A., L. Thompson, and S. Price. 2007b. Vehicles *versus* conservation of invertebrates on sandy beaches: mortalities inflicted by off-road vehicles on ghost crabs. Marine Ecology **28**:354–367.

Schmiedel, J. 2001. Auswirkungen künstlicher Beleuchtung auf die Tierwelt – ein Überblick [Effects of artificial lighting on the animal world – an overview]. Schriftenreihe für Landschaftspflege und Naturschutz **67**:19–51.

Schoettle, B., M. Sivak, M. J. Flannagan, and W. J. Kosmatka. 2004. A market-weighted description of low-beam headlighting patterns in the U.S.: 2004. UMTRI-2004-23. University of Michigan Transportation Research Institute, Ann Arbor, Michigan.

Sebens, K. P., and K. DeRiemer. 1977. Diel cycles of expansion and contraction in coral reef anthozoans. Marine Biology **43**:247–256.

Seligmann, H., S. C. Anderson, K. Autumn, A. Bouskila, R. Saf, B. S. Tuniyev, and Y. L. Werner. 2007. Analysis of the locomotor activity of a nocturnal desert lizard (Reptilia: Gekkonidae: *Teratoscincus scincus*) under varying moonlight. Zoology **110**:104–117.

Sherman, L. W., D. Gottfredson, D. MacKenzie, J. Eck, P. Reuter, and S. Bushway. 1997. Preventing crime: what works, what doesn't, what's promising. A report to the United States Congress. University of Maryland at College Park, Department of Criminology and Criminal Justice, College Park, Maryland.

Skutelsky, O. 1996. Predation risk and state-dependent foraging in scorpions: effects of moonlight on foraging in the scorpion *Buthus occitanus*. Animal Behaviour **52**:49–57.

Smallwood, K. S. 2013. Comparing bird and bat fatality-rate estimates among North American wind-energy projects. Wildlife Society Bulletin **37**:19–33.

Squires, W. A., and H. E. Hanson. 1918. The destruction of birds at the lighthouses on the coast of California. Condor **20**:6–10.

Steinbach, R., C. Perkins, L. Tompson, S. Johnson, B. Armstrong, J. Green, C. Grundy, P. Wilkinson, and P. Edwards. 2015. The effect of reduced street lighting on road casualties and crime in England and Wales: controlled interrupted time series analysis. Journal of Epidemiology and Community Health **69**:1118–1124.

Stokkan, K.-A., L. Folkow, J. Dukes, M. Neveu, C. Hogg, S. Siefken, S. C. Dakin, and G. Jeffery. 2013. Shifting mirrors: adaptive changes in retinal reflections to winter darkness in Arctic reindeer. Proceedings of the Royal Society B: Biological Sciences **280**:20132451.

Stone, E. L., S. Harris, and G. Jones. 2015. Impacts of artificial lighting on bats: a review of challenges and solutions. Mammalian Biology-Zeitschrift für Säugetierkunde **80**:213–219.

Stone, E. L., G. Jones, and S. Harris. 2012. Conserving energy at a cost to biodiversity? Impacts of LED lighting on bats. Global Change Biology **18**:2458–2465.

Sweeney, A. M., C. A. Boch, S. Johnsen, and D. E. Morse. 2011. Twilight spectral dynamics and the coral reef invertebrate spawning response. Journal of Experimental Biology **214**:770–777.

Telfer, T. C., J. L. Sincock, G. V. Byrd, and J. R. Reed. 1987. Attraction of Hawaiian seabirds to lights: conservation efforts and effects of moon phase. Wildlife Society Bulletin **15**:406–413.

Thibault, M., and R. McNeil. 1994. Day/night variation in habitat use by Wilson's plovers in northeastern Venezuela. Wilson Bulletin **106**:299–310.

Tien, J. M., V. F. O'Donnell, A. Barnett, and P. B. Mirchandani. 1977. National evaluation program, phase 1 report. Street lighting projects. National Institute of Law Enforcement and Criminal Justice, Washington, D.C.

Tigar, B. J., and P. E. Osborne. 1999. The influence of the lunar cycle on ground-dwelling invertebrates in an Arabian desert. Journal of Arid Environments **43**:171–182.

Upham, N. S., and J. C. Hafner. 2013. Do nocturnal rodents in the Great Basin Desert avoid moonlight? Journal of Mammalogy **94**:59–72.

van de Laar, F. J. T. 2007. Green light to birds: investigation into the effect of bird-friendly lighting. NAM Locatie L15-FA-1, Assen, The Netherlands.

Vásquez, R. A. 1994. Assessment of predation risk via illumination level: facultative central place foraging in the cricetid rodent *Phyllotis darwini*. Behavioral Ecology and Sociobiology **34**:375–381.

Verheijen, F. J. 1985. Photopollution: artificial light optic spatial control systems fail to cope with. Incidents, causations, remedies. Experimental Biology **1985**:1–18.

Wagner, R., C. Moore, and L. Smith. undated. Dark-sky camping: best practices in illumination for the Boy Scouts.

Walmsley, L., L. Hanna, J. Mouland, F. Martial, A. West, A. R. Smedley, D. A. Bechtold, A. R. Webb, R. J. Lucas, and T. M. Brown. 2015. Colour as a signal for entraining the mammalian circadian clock. PLoS Biology **13**:e1002127.

Wiese, F. K., W. A. Montevecchi, G. K. Davoren, F. Huettmann, A. W. Diamond, and J. Linke. 2001. Seabirds at risk around offshore oil platforms in the North-west Atlantic. Marine Pollution Bulletin **42**:1285–1290.

Wilhelm, S. I., J. J. Schau, E. Schau, S. M. Dooley, D. L. Wiseman, and H. A. Hogan. 2013. Atlantic puffins are attracted to coastal communities in Eastern Newfoundland. Northeastern Naturalist **20**:624–630.

Wiltschko, W., U. Munro, H. Ford, and R. Wiltschko. 1993. Red light disrupts magnetic orientation of migratory birds. Nature **364**:525–527.

Wiltschko, W., and R. Wiltschko. 1995. Migratory orientation of European robins is affected by the wavelength of light as well as by a magnetic pulse. Journal of Comparative Physiology A **177**:363–369.

Wise, S. 2007. Studying the ecological impacts of light pollution on wildlife: amphibians as models. Pages 107–116 *in* C. Marín and J. Jafari, editors. StarLight: a common heritage. StarLight Initiative La Palma Biosphere Reserve, Instituto De Astrofísica De Canarias, Government of The Canary Islands, Spanish Ministry of The Environment, UNESCO - MaB., Canary Islands, Spain.

Wise, S. E., and B. W. Buchanan. 2006. The influence of artificial illumination on the nocturnal behavior and physiology of salamanders. Pages 221–251 *in* C. Rich and T. Longcore, editors. Ecological consequences of artificial night lighting. Island Press, Washington, D.C.

Witherington, B. E. 1992. Behavioral responses of nesting sea turtles to artificial lighting. Herpetologica **48**:31–39.

Yahel, R., G. Yahel, T. Berman, J. S. Jaffe, and A. Genin. 2005. Diel pattern with abrupt crepuscular changes of zooplankton over a coral reef. Limnology and Oceanography **50**:930–944.

Yong, E. 2013. Why are reindeer eyes golden in summer but blue in winter? Phenomena. National Geographic (online).

Yurk, H., and A. W. Trites. 2000. Experimental attempts to reduce predation by harbor seals on out-migrating juvenile salmonids. Transactions of the American Fisheries Society **129**:1360–1366.

NPS 999/132629, May 2016

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov

EXPERIENCE YOUR AMERICA ™