Assessing the Impacts of LED Lighting to Wildlife

Requested by
Scott Quinnell, Caltrans District 8

January 23, 2019

The Caltrans Division of Research, Innovation and System Information (DRISI) receives and evaluates numerous research problem statements for funding every year. DRISI conducts Preliminary Investigations on these problem statements to better scope and prioritize the proposed research in light of existing credible work on the topics nationally and internationally. Online and print sources for Preliminary Investigations include the National Cooperative Highway Research Program (NCHRP) and other Transportation Research Board (TRB) programs, the American Association of State Highway and Transportation Officials (AASHTO), the research and practices of other transportation agencies, and related academic and industry research. The views and conclusions in cited works, while generally peer reviewed or published by authoritative sources, may not be accepted without qualification by all experts in the field. The contents of this document reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the California Department of Transportation, the State of California, or the Federal Highway Administration. This document does not constitute a standard, specification, or regulation. No part of this publication should be construed as an endorsement for a commercial product, manufacturer, contractor, or consultant. Any trade names or photos of commercial products appearing in this publication are for clarity only.

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Executive Summary

Background

Caltrans lacks the critical information necessary to assess the potential impacts of proposed light-emitting diode (LED) lighting projects to endangered, threatened and other sensitive wildlife species. Without consensus on appropriate metrics for assessing impacts to these animals, Caltrans districts will likely produce nonstandard impact analyses and also lack standardized measures to avoid or minimize lighting impacts in sensitive species areas.

Information that assesses the impacts, describes exemplary practices and identifies effective, readily available commercial products in connection with the use of LED lighting in sensitive species areas will help Caltrans develop a set of standard measures that could be incorporated into safety lighting projects where a protected species habitat is present.

To inform Caltrans' inquiry, CTC & Associates conducted two surveys. An initial nine-question survey sought information from a broad range of potential respondents in state departments of transportation (DOTs) and participants in the Wildlife, Fisheries and Transportation Listserv managed by the Center for Transportation and the Environment at North Carolina State University, which includes participants from domestic and international agencies. A follow-up survey sought additional information from selected agencies responding to the first survey that indicated active engagement with LED lighting. Consultations with researchers and a targeted examination of relevant literature supplemented survey findings.

Summary of Findings

This Preliminary Investigation gathered information in three areas:

- Survey of practice.
- Consultation with researchers.
- Related research and resources.

Survey of Practice

Fourteen state DOTs and a representative from a South African agency responded to an initial online survey. Two agencies provided additional information about agency practices in a follow-up survey. Key findings from respondents' feedback to both surveys are highlighted below.

Use of Commercial Wildlife-Friendly LED Lighting

Several agencies reported on the wildlife-friendly LED lighting their agencies use or are preparing to use. Florida DOT is developing wildlife-friendly lighting specifications that will include a list of accepted fixtures. Backlight, uplight and glare (BUG)-rated lighting is used by Georgia DOT. Minnesota DOT considers LED lighting to be wildlife-friendly when it is used with shrouds that have 0 uplight (full cutoff) or when the LEDs have a color temperature of 4000K or less.

Use of LED Lighting in Protected Wildlife Species Habitat

Nine of the responding DOTs—Connecticut, Florida, Illinois, Massachusetts, Minnesota, North Dakota, Tennessee, Utah and Wisconsin—reported the use of LED lighting in areas where protected wildlife species habitat is present. Respondents from Connecticut, Florida and Minnesota indicated that LED lighting has impacted wildlife. Only three respondents—Montana, Oklahoma and Oregon—do not use LEDs in areas where protected wildlife species habitat is present.

Wildlife-Friendly Lighting Specifications

While none of the responding agencies has current specifications for LED or other lighting for use in sensitive species areas, the Florida DOT respondent reported on efforts underway to develop wildlife-friendly lighting specifications. Consultations with other divisions within the DOT, U.S. Fish and Wildlife Service, and Florida Fish and Wildlife Conservation Commission continue and are expected to result in a final specification available for use by June 2019. See page 7 for further details.

Case Studies

The brief case studies that begin on page 9 summarize feedback provided by respondents from Florida and Minnesota to a follow-up survey that gathered additional details about agency practices. The Florida DOT respondent provided a significant level of detail with regard to the lighting used, impact locations, species affected, and results of environmental reviews and consultations.

Other Agency Practices

Other agencies reported limited or no experience with wildlife-friendly lighting:

- Connecticut DOT's experience with wildlife-friendly lighting has been limited to project-specific issues, which include collaborating with the state's Wildlife Division in the Bureau of Natural Resources in connection with lighting for the Pearl Harbor Memorial Bridge in New Haven to mitigate impacts to avian migration patterns. Recently, the agency addressed concerns associated with LED lighting under a bridge near a ferry service and its potential impact to peregrine falcons nesting on the bridge.
- The Massachusetts DOT respondent noted the existence of federal lighting-related guidance in connection with the northern long-eared bat, but indicated that the agency does not use these provisions for "clearing" agency projects "as they are too restrictive on our construction activities."
- The Wisconsin DOT respondent is not aware of concerns about wildlife-friendly LED lighting, and the DOT has not investigated potential impacts to wildlife as a result of different lighting options.

Topic Areas Not Addressed by Respondents

None of the respondents offered information about completed research related to LED lighting and its impacts to wildlife, lighting alternatives, or conflicts among stakeholders.

Consultation With Researchers

The results of our contacts with researchers affiliated with four educational institutions that have experience investigating the impact of artificial light at night on wildlife and humans are summarized below.

- Brett Seymoure, a National Park Service postdoctoral fellow affiliated with Colorado State University, noted in a brief interview that spectrum and flicker are important issues to consider with regard to lighting and its impacts to humans and animals, as are the other components of light that contribute to animal health—brightness, color and polarization.

  Seymoure provided a collection of publications he describes as "foundational" that address lighting impacts across disciplines, with an emphasis on biology. These publications have been provided to Caltrans separately, along with preliminary drafts of articles that are being prepared for publication.

- Kamiel Spoelstra, a researcher affiliated with the Netherlands Institute of Ecology, pointed us to a web site containing the most recent publicly available research he has completed that addresses the effects of artificial light on nature (see page 15). He noted that a fact sheet on ecology and lighting will be published on this web site soon.

- Kevin Gaston, professor of biodiversity and conservation at University of Exeter (United Kingdom), directed us to a web site (see page 15) and provided a recent journal article. A citation for that article appears in the **Related Research and Resources** section of this report, along with other publications authored by Gaston.

- Travis Longcore, a University of Southern California researcher, reported that his research group will soon begin a project, with University of California, Davis in the lead, which will examine light conditions around underpasses and overpasses for wildlife to try to assess its influence. See page 24 for information about Longcore's recent research that produced "the first publicly available database showing how about two dozen different types of artificial lighting affect wildlife."

Related Research and Resources

An in-depth literature search identified a wealth of published research that addresses the biological impacts of artificial light at night to humans and animals. The relatively recent publications (typically published in the last 10 years) presented in this report do not represent a comprehensive examination of that primary topic, and instead provide a sampling of recent research examining LED lighting and its ecological and biological impacts, primarily to animals. The citations also examine, in a limited manner, lighting alternatives and other aspects of assessing the impact of artificial lighting (flickering light, light spectrum and measuring artificial light).

The citations that begin on page 17 are organized into eight categories:

- National guidance.
- State activities and guidance.
- Color temperature.
- Flickering artificial light.
- Impacts to animals and animal classes.
- Light spectrum.
- Lighting alternatives.
- Measuring artificial light.

Gaps in Findings

The initial survey received a limited response from state DOTs and from the larger community participating in the Wildlife, Fisheries and Transportation Listserv. Many of the responding agencies reported limited experience with wildlife-friendly lighting.

As previously noted, Florida DOT is actively engaged in the development of wildlife-friendly lighting specifications (expected to be completed by June 2019).

There is significant research interest in the biological impacts of artificial light at night to humans and animals, and specific interest in the impacts of LED lighting. As this report indicates, journal articles and other guidance are in progress and research efforts are just beginning that may be of interest to Caltrans. Checking back with researchers and conducting periodic future examinations of relevant literature may uncover additional findings.

Next Steps

Moving forward, Caltrans could consider:

- Consulting with the Florida DOT survey respondent to learn more about the agency's efforts to develop wildlife-friendly lighting specifications and how that experience could inform a similar Caltrans effort.
- Consulting with other survey respondents to learn more about agency practices, including:
    - Connecticut DOT's project-specific efforts to address wildlife impacts.
    - Georgia and Minnesota DOTs' use of BUG-rated lighting. The Minnesota DOT respondent provided a 5 rating for this type of lighting on a scale of 1 to 5 (where 1 = not at all successful and 5 = extremely successful).
- Contacting the agencies that reported use of LED lighting in protected wildlife species habitat to learn more about the lighting fixtures used and why they were selected.
- Reviewing the new database developed by a research team led by Travis Longcore that shows how different types of artificial lighting affect wildlife.
- Conducting an in-depth review of the publications cited in the **Related Research and Resources** section of this report to identify common themes and key findings that could inform Caltrans' efforts to develop a set of standard lighting-related measures.

Detailed Findings

Survey of Practice

Survey Approach

Caltrans is seeking information from other state transportation agencies about the transition to light-emitting diode (LED) lighting and its impacts to wildlife, including species with federal and/or state protections, or other species of special concern. The topic areas below are of particular interest:

- Assessment of the impacts of LED lighting to wildlife.
- Lighting alternatives and modifications, and other measures to protect wildlife.
- Use of LED lighting in sensitive wildlife habitat.
- Feedback related to wildlife-friendly LED lighting.

To inform Caltrans' inquiry, CTC & Associates conducted two surveys. An initial nine-question survey sought information from a broad range of potential respondents:

- State department of transportation (DOT) members of the AASHTO Committee on Environment and Sustainability.
- Participants in the Wildlife, Fisheries and Transportation Listserv managed by the Center for Transportation and the Environment at North Carolina State University. Listserv managers note that the list "is intended to facilitate discussion among transportation and environmental professionals about emerging issues and best practices that improve the way ecological issues are addressed in surface transportation." At the time of survey distribution, the listserv had more than 350 subscribers.

A follow-up survey sought additional information from selected agencies responding to the first survey that indicated active engagement with LED lighting. The questions for both surveys are provided in Appendix A. The full text of survey responses is presented in a supplement to this report.

Survey results are supplemented by:

- Results of consultations with researchers. Summaries of email exchanges or brief interviews with four experts with regard to the impacts of artificial light begin on page 14.
- Findings from a literature search, which are provided in **Related Research and Resources** beginning on page 17.

Summary of Survey Results

Fourteen state DOTs responded to the first online survey:

- Connecticut.
- Florida.
- Georgia.
- Illinois.
- Massachusetts.
- Minnesota.
- Montana.
- North Dakota.
- Oklahoma.
- Oregon.
- Tennessee.
- Utah.
- Washington.
- Wisconsin.

A representative from the South African Trans African Concessions (Pty) Limited (TRAC) also responded to the first survey. Respondents from Florida and Minnesota responded to the follow-up survey that gathered additional information about agency practices.

Respondents' feedback to both surveys is presented below in six topic areas:

- Use of commercial wildlife-friendly LED lighting.
- Use of LED lighting in protected wildlife species habitat.
- Wildlife-friendly lighting specifications.
- Case studies.
- Other agency practices.
- Topic areas not addressed by respondents.

Use of Commercial Wildlife-Friendly LED Lighting

Four respondents reported on the wildlife-friendly LED lighting their agencies use:

- Florida DOT is "currently looking to incorporate these fixtures." See below for more information about wildlife-friendly lighting specifications in development.
- Georgia DOT uses backlight, uplight and glare (BUG)-rated lighting.
- Minnesota DOT generally considers LED lighting to be wildlife-friendly when it is used with shrouds that have 0 uplight (full cutoff) or when the LEDs have a color temperature of 4000K or less.
- The TRAC respondent from South Africa reported on complaints from a neighboring farm owner near a toll plaza about the color change of the streetlights, which led to owls in the area being killed by traveling vehicles. The agency "amended the lights" in an unspecified manner and "the problem seems to have been solved."

Use of LED Lighting in Protected Wildlife Species Habitat

Nine of the responding DOTs—Connecticut, Florida, Illinois, Massachusetts, Minnesota, North Dakota, Tennessee, Utah and Wisconsin—reported the use of LED lighting in areas where protected wildlife species habitat is present. Respondents from Connecticut, Florida and Minnesota indicated that LED lighting has impacted wildlife. Only three respondents—Montana, Oklahoma and Oregon—do not use LEDs in areas where protected wildlife species habitat is present.

Wildlife-Friendly Lighting Specifications

While none of the responding agencies has current specifications for LED or other lighting for use in sensitive species areas, the Florida DOT respondent reported on efforts underway to develop wildlife-friendly lighting specifications. These efforts are summarized below.

Florida DOT is working in coordination with the U.S. Fish and Wildlife Service (USFWS) and the Florida Fish and Wildlife Conservation Commission to address lighting concerns associated with nesting sea turtles. The criteria and specifications in development are anticipated to be applicable for projects that may need to consider wildlife-friendly lighting for other species. The specifications in process will add new or revise existing content in two manuals:

Section 231, Lighting, FDOT Design Manual, Florida Department of Transportation, January 2019.
http://fdot.gov/roadway/FDM/current/2019FDM231Lighting.pdf
This section of Florida DOT's Design Manual is now under revision to include wildlife-friendly lighting criteria.

Section 992, Highway Lighting Materials, Standard Specifications for Road and Bridge Construction, Florida Department of Transportation, January 2019.
http://www.fdot.gov/programmanagement/Implemented/SpecBooks/January2019/Files/119eBook.pdf
See page 1203 of the manual (page 1211 of the PDF) for the section that will be revised to include specifications for luminaires for wildlife-friendly conventional lighting.

The respondent reported that the draft specifications and special provisions are being developed in collaboration with the agency's design, standards, specifications, construction and safety offices. Florida DOT continues to hold meetings with USFWS and the state wildlife commission, and expects that the process for official review and approval will result in a final form of the specifications that are available for use by June 2019.

Cited below are previously published research and other resources related to Florida DOT's evaluation of the impacts of lighting on nesting sea turtles:

Understanding, Assessing and Resolving Light-Pollution Problems on Sea Turtle Nesting Beaches, Version 2, Blair E. Witherington, R. Erik Martin and Robbin N. Trindell, Florida Fish and Wildlife Conservation Commission, 2014.
http://f50006a.eos-intl.net/ELIBSQL12_F50006A_Documents/TR-2Rev2.pdf
From the executive summary:

> The Solutions section underscores the use of BAT [best available technology] to manage lights from indoor and outdoor sources. Amber light emitting diodes (LEDs), red neon, and low-pressure sodium-vapor luminaires are good substitutes for more disruptive lighting near sea turtle nesting beaches. Effective Methods for Managing Light includes an overview of the current status and lessons learned. Solutions are provided for several categories of common light-pollution problems: swimming pools, parks, piers, sidewalks, walkways, bikeways, streetlights, parking facilities, decorative lights, and illuminated signs.
>
> ….
>
> Appendices provide additional information on appropriate lamp types, lamp colors, fixture designs, and fixture mounting for various applications near sea turtle nesting beaches. They also provide information for contacting lighting companies that offer appropriate lighting fixtures and governmental and nongovernmental organizations that can help with sea turtle conservation. Last, they suggest responses to commonly encountered questions and comments regarding sea turtles and artificial lighting.

"Installing Turtle-Friendly Lighting on Florida's Coastal Roadways," *Successes in Stewardship*, Federal Highway Administration, May 2012.
https://www.environment.fhwa.dot.gov/Pubs_resources_tools/publications/newsletters/may12nl.pdf
From the newsletter: …FDOT sought to identify a lighting design that would provide safety for pedestrians and vehicular traffic without affecting sea turtle nesting areas. In 2001, FDOT undertook a demonstration project that turned off existing roadway lighting and installed embedded LED lights along State Road A1A (SR A1A) in Boca Raton. In addition to the embedded LED lighting, FDOT installed low lighting along the bike path adjacent to the road to improve safety for cyclists. The project spanned the entire nesting season of 2001.

Related Resource:

Impacts of Coastal Roadway Lighting on Endangered and Threatened Sea Turtles, Michael Salmon, Jeanette Wyneken and Jerris Foote, Florida Department of Transportation, April 2003.
Citation at https://trid.trb.org/View/702625
This is the research study referenced in the newsletter article cited above.

Case Studies

The brief case studies below summarize feedback provided by respondents from Florida and Minnesota to a follow-up survey that gathered additional details of agency practices.

Case Study: Florida Department of Transportation

Location of Impacts	In Florida, lighting impacts are most often seen along coastal areas where nesting sea turtles are encountered. The agency has also had at least one interstate interchange project in Florida panther habitat that required additional consideration for impacts due to proposed lighting.
Lighting Type Used	The Florida Fish and Wildlife Conservation Commission recommends wildlife-certified light fixtures and bulbs that include pole-mounted luminaires (see **Related Resource** on page 11). This list includes LEDs (the respondent describes some of the LED products as having "dubious intensity"). Florida DOT intends to create a similar list of standard LED products that may be used without extensive coordination with other agencies.
Species Impacted	Florida panther (*Puma concolor coryi*) Green turtle (sea turtle) (*Chelonia mydas*) Hawksbill (sea turtle) (*Eretmochelys imbricata*) Kemp's ridley sea turtle (*Lepidochelys kempii*) Leatherback (sea turtle) (*Dermochelys coriacea*) Loggerhead (sea turtle) (*Caretta caretta*)

Extent of Impact

For the panther reserve described above, where an interstate runs through the reserve, the impact area is adjacent to the right of way. This means that the impact area is within 50 feet of the luminaires. The agency encouraged designers to orient luminaires away from the impact area.

Environmental Review or Consultation

Typically, Florida DOT consults with USFWS on coastal projects regarding effects of lighting on sea turtles. The consultations typically result in commitments to various actions depending on the nature of the project, including:

- Limiting sky glow.
- Avoiding nighttime lighting during nesting season.
- Ensuring nighttime lighting does not trespass onto nesting areas.
- Providing sea turtle-friendly lighting through use of downward directed, full cutoff, well-shielded fixtures with low-pressure sodium or amber LED lamps that allow no emission of light above the horizontal plane of the fixture.

Lighting designs are typically reviewed by both agencies.

The DOT has completed consultation for one project with lighting adjacent to the panther reserve previously described.

Lighting Alternatives and Modifications

Lighting filter. Filters have been used in the past but not on a standardized basis; the DOT has no plans to pursue continued use.

Shielding. This is a common practice for Florida DOT but is insufficient by itself. The respondent noted that it is difficult to determine the success of this practice because it is not typically used individually, though did provide a 3 rating on a scale of 1 to 5 (where 1 = not at all successful and 5 = extremely successful).

Luminaires with low backlight, uplight and glare (BUG) ratings. Agency use of BUG-rated fixtures is a common practice, even outside wildlife impact areas. The respondent gave this lighting option a 3 rating.

Other modifications:

- In Florida, there are sections of roadway where the lighting is disconnected during sea turtle hatching season. The agency does not consider this to be a successful mitigation.
- Florida DOT does not use adjustments based on the presence of vehicles on the roadway, ambient nighttime light or timers.

Nonlighting Measures

Florida DOT has used the following practices to supplement its lighting-related measures:

- Posted signs about possible wildlife in the area (bear, panther).
- Provided fencing to discourage wildlife from coming onto limited access facilities.

Nonlighting Measures (continued)

- Provided wildlife crossings in various forms (box or elliptical culverts, "dry shelves" adjacent to bridges or culverts where the original structure is intended for drainage purposes, and wildlife-specific structures where a drainage feature doesn't exist.

Public Comments

The respondent noted that any public comments received in response to implementation of wildlife-friendly LED lighting would be directed to DOT districts. Lacking a central repository for these comments, additional investigation would be required to determine if public comments have been received by the agency.

Related Resource

Fixtures and Bulbs: Certified Wildlife Lighting, Florida Fish and Wildlife Conservation Commission, 2018.
http://myfwc.com/conservation/you-conserve/lighting/certified/
From the web site: The fixtures and bulbs on the pages listed below have all been reviewed through the Wildlife Lighting Certification Process. To be Wildlife Lighting Certified, the required options and bulleted recommendations for each fixture or bulb must also be met. They are categorized by use.

Case Study: Minnesota Department of Transportation

Location of Impacts

Various and unspecified.

Lighting Type Used

Various and unspecified. The agency generally considers LED lighting to be wildlife-friendly when it is used with shrouds that have 0 uplight (full cutoff) or when the LEDs have a color temperature of 4000K or less.

Species Impacted

Northern long-eared bat (*Myotis septentrionalis*)

Western prairie fringed orchid (*Platanthera praeclara*)

Unspecified birds

Environmental Review or Consultation

In some cases, USFWS has identified areas where LEDs should not be used to avoid impacting the species of moth that pollinates the western prairie fringed orchid.

USFWS has also identified avoidance and minimization measures (AMMs) for lighting used on projects that may affect northern long-eared bats. (See page 12 for more information about the AMMs associated with the northern long-eared bat.)

Lighting Alternatives and Modifications

Luminaires with low BUG ratings are used as a common practice. The respondent provided a 5 rating on a scale of 1 to 5 (where 1 = not at all successful and 5 = extremely successful).

Lighting Alternatives and Modifications (continued)	Other modifications: • In rare cases, the agency may opt not to use LEDs. The respondent did not indicate the type of lighting used in their place. • Minnesota DOT does not use adjustments based on the presence of vehicles on the roadway, ambient nighttime light or timers.
Nonlighting Measures	None reported.
Public Comments	Some members of the public have commented that lighting is still too bright.

Related Resource

Roadway Lighting Products, Approved/Qualified Products, Minnesota Department of Transportation, 2018.
http://www.dot.state.mn.us/products/roadwaylighting/index.html
This web site provides access to a hyperlinked site map of approved lighting products and lists of approved products for light foundations, lighting hardware, luminaires, rodent intrusion barrier, service cabinets, bridge navigation lanterns and air obstruction lights.

Other Agency Practices

Three respondents offered information about current agency practices:

- *Connecticut*. The DOT's experience has been limited to project-specific issues, which include collaborating with the state's Wildlife Division in the Bureau of Natural Resources in connection with lighting for the Pearl Harbor Memorial Bridge (more commonly known as the Q Bridge) in New Haven to address concerns about impacts to avian migration patterns. Recently, the agency addressed concerns associated with LED lighting under a bridge near a ferry service and its potential impact to peregrine falcons nesting on the bridge.
- *Massachusetts*. The respondent noted the existence of federal lighting-related guidance in connection with the northern long-eared bat, but indicated that the agency does not use these provisions for "clearing" agency projects "as they are too restrictive on our construction activities." The citation below provides the guidance referenced by the respondent:

  Range-Wide Programmatic Consultation for Indiana Bat and Northern Long-Eared Bat: Avoidance and Minimization Measures, Endangered Species, U.S. Fish and Wildlife Service, January 2018.
  https://www.fws.gov/midwest/endangered/section7/fhwa/pdf/AppC_AMMsRevisedFeb2018.pdf
  From the document: For projects to be covered by the Programmatic Biological Opinion (BO), specific avoidance and minimization measures (AMMs) related to the Indiana bat and northern long-eared bat (NLEB) will be implemented where applicable. AMMs, if adopted under appropriate circumstances, are expected to reduce the potential impacts of the proposed action on both bat species.

….

The following AMMs are necessary to avoid and minimize impacts to the Indiana bat and NLEB, and where applicable, are required for projects using the range-wide programmatic consultation.

….

Lighting

Lighting AMM 1. Direct temporary lighting away from suitable habitat during the active season.

Lighting AMM 2. When installing new or replacing existing permanent lights, use downward-facing, full cut-off lens lights (with same intensity or less for replacement lighting); or for those transportation agencies using the BUG system developed by the Illuminating Engineering Society, the goal is to be as close to 0 for all three ratings with a priority of "uplight" of 0 and "backlight" as low as practicable.

- *Wisconsin*. To the respondent's knowledge, concerns about wildlife-friendly LED lighting have not been raised in Wisconsin, nor has the DOT investigated potential impacts to wildlife as a result of different lighting options.

Topic Areas Not Addressed by Respondents

None of the respondents offered information about three topic areas addressed in the survey:

- *Research*. None of the responding agencies reported on completed research that examines the effects of LED lighting and its impacts to wildlife.
- *Lighting alternatives*. Aside from LED lighting, none of the respondents have identified a cost-effective, energy-efficient lighting alternative that avoids or minimizes impacts to wildlife.
- *Conflicts among stakeholders*. None of the responding agencies reported on conflicts between competing stakeholders as a result of implementing wildlife-friendly LED lighting.

Consultation With Researchers

We contacted researchers affiliated with four educational institutions—Colorado State University, Netherlands Institute of Ecology, University of Exeter and University of Southern California—that have experience investigating the impact of artificial light at night on wildlife and humans. Below are summaries of email or phone queries posed to these researchers, and links or references to relevant resources.

Colorado State University

Brett Seymoure, a National Park Service postdoctoral fellow affiliated with Colorado State University, noted in a brief interview that spectrum and flicker are important issues to consider with regard to lighting and its impacts to humans and animals, as are the other components of light that contribute to animal health—brightness, color and polarization.

Seymoure provided a collection of publications he describes as "foundational" that address lighting impacts across disciplines, with an emphasis on biology. These publications have been provided to Caltrans separately, along with preliminary drafts of articles that are being prepared for publication.

Contact: Brett Seymoure, Postdoctoral Fellow, Department of Biology and Department of Fish, Wildlife and Conservation Biology, Colorado State University and National Park Service, brett.seymoure@colostate.edu.

Related Resources:

> **Brett M. Seymoure**, Behavioral and Sensory Ecology in the 21st Century, undated.
> http://www.brettseymoure.com
> *From the web site*: I study how animals have adapted to and are affected by their environment. How has the environment selected for different visual traits? Specifically, how does environmental lighting affect organisms' coloration and vision? How and why have different visual systems evolved? How does anthropogenic light affect visually guided behavior in animals? I approach these questions from a sensory and behavioral ecological perspective to shed light onto evolutionary and conservation biology.

Netherlands Institute of Ecology

Kamiel Spoelstra, a researcher affiliated with the Netherlands Institute of Ecology, pointed us to the web site cited below for the most recent publicly available research he has completed that addresses the effects of artificial light on nature. He noted that a fact sheet on ecology and lighting will be published on this web site soon.

Contact: Kamiel Spoelstra, Postdoctoral Researcher in Animal Ecology, Netherlands Institute of Ecology, 31-317-473454, k.spoelstra@nioo.knaw.nl.

Related Resource:

LichtOpNatuur: What Are the Effects of Artificial Light on Nature?, Kamiel Spoelstra and Roy van Grunsven, undated.
www.lichtopnatuur.org
This web site provides access to in-depth research and a description of monitoring efforts that address the impacts of artificial light on birds, moths, amphibians, mammals and plants. Links to publications, presentations and other media are also provided (some in Dutch).

University of Exeter (United Kingdom)

Kevin Gaston, professor of biodiversity and conservation at University of Exeter, directed us to the web site cited below and provided a recent journal article (see "Nature, Extent and Ecological Implications of Night-Time Light From Road Vehicles" on page 24).

Contact: Kevin Gaston, Professor of Biodiversity and Conservation, University of Exeter, 01-326-255810, k.j.gaston@exeter.ac.uk.

Related Resource:

Kevin J. Gaston, Professor of Biodiversity and Conservation at University of Exeter, 2018.
http://kevingaston.com/
This web site provides information about Gaston's research activities, which he describes as:

> … basic, strategic and applied research in ecology. This is presently centred around three main issues:
>
> - Common ecology – the study of common species, the determinants of commonness and its consequences.
> - Nighttime ecology – the study of the abundance, distribution and interactions of species during the night (including the consequences of anthropogenic pressures such as artificial nighttime lighting).
> - Personalised ecology – the study of the direct interactions between individual people and nature, their causes and consequences.

The web site also provides links to relevant publications.

University of Southern California

Travis Longcore, a University of Southern California researcher, reported that his research group will soon begin a project, with University of California, Davis in the lead, which will examine light conditions around underpasses and overpasses for wildlife to try to assess its influence. He noted that "[m]uch of my current research is about measuring light conditions properly for ecological studies and connect[ing] the ground-based measurements to satellite measurements." See page 24 for information about Longcore's recent research that produced "the first publicly available database showing how about two dozen different types of artificial lighting affect wildlife."

In addition to publications cited in the **Related Research and Resources** section of this report, Longcore provided a draft article planned for publication in *LED Professional Review*. The published article is cited in *Related Resources* below.

Contact: Travis Longcore, Assistant Professor of Architecture, Spatial Sciences and Biological Sciences, School of Architecture, University of Southern California, 213-821-1310, longcore@usc.edu.

Related Resources:

Longcore Landscape and Urban Nature Lab, USC School of Architecture and USC Spatial Sciences Institute, University of Southern California, undated.
https://www.travislongcore.net
From the web site:

> Formed in 2015, the Landscape & Urban Nature Lab is based on the premise that empirical analysis using a spatial framework can provide a common platform to address important issues of ecological management, stewardship, and design. The lab focuses on cities because they represent an increasing proportion of human settlements on the planet, where nature can either be incorporated and encouraged or polluted and excluded, with dramatically different outcomes for people, biodiversity, and the environment as a whole.
>
> Current research efforts focus on four themes: 1) light pollution and its impacts on species, ecosystems, and people; 2) historical ecology as a means to understand landscapes and inspire restoration and management; 3) spatial ecology and conservation at the intersection of cities and nature; and 4) urban bioresource management using spatial tools and approaches such as geodesign.
>
> The lab operates virtually, with personnel located in the USC School of Architecture and the USC Spatial Sciences Institute and with many off-campus collaborators.

Links to relevant publications are available at https://travislongcore.net/light-pollution/.

"Hazard or Hope? LEDs and Wildlife," Travis Longcore, *LED Professional Review*, Vol. 70, pages 52-57, November/December 2018.
https://www.researchgate.net/profile/Travis_Longcore/publication/329174799_Hazard_or_Hope_LEDs_and_Wildlife_LED_Professional_Review/links/5bfa21d3299bf1a0203140e3/Hazard-or-Hope-LEDs-and-Wildlife-LED-Professional-Review.pdf
From the abstract: The introduction and widespread uptake of LEDs as outdoor lighting has caused no small amount of concern amongst conservation biologists. The prevailing impression that LEDs are always blue-white is well founded as adoption of LEDs for streetlights were invariably high color temperatures and with the deterioration of phosphors the blue wavelengths penetrated even more. But LEDs do have characteristics that differentiate them from other light sources and may allow for the reduction of environmental effects of lighting on species and habitats: direction, duration, intensity and spectrum.

Related Research and Resources

An in-depth literature search identified a wealth of published research that addresses the biological impacts of artificial light at night to humans and animals. The relatively recent publications (typically, published in the last 10 years) presented below do not represent a comprehensive examination of that primary topic, and instead provide a sampling of recent research examining LED lighting and its ecological and biological impacts, primarily to animals. The citations below also examine, in a limited manner, lighting alternatives and other aspects of assessing the impact of artificial lighting (flickering light, light spectrum and measuring artificial light).

The citations below are organized into eight categories:

- National guidance.
- State activities and guidance.
- Color temperature.
- Flickering artificial light.
- Impacts to animals and animal classes.
- Light spectrum.
- Lighting alternatives.
- Measuring artificial light.

National Guidance

Wildlife Lighting, Florida Fish and Wildlife Conservation Commission and the U.S. Fish and Wildlife Service, undated.
http://myfwc.com/conservation/you-conserve/lighting/
From the web site: The Wildlife Lighting Certification Program is a cooperative effort between the Florida Fish and Wildlife Conservation Commission and the U.S. Fish and Wildlife Service designed to educate the members of the public, the building industry and government officials how to minimize adverse impacts to wildlife by using proper lighting methods.

Artificial Night Lighting and Protected Lands: Ecological Effects and Management Approaches, Travis Longcore and Catherine Rich, National Park Service, May 2016.
https://www.uv.es/salvemlanit/Documents/Longcore-Artificial-night-lighting-protected-lands.pdf
From the introduction: 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.

2016 Animal Responses to Light Meeting Report, Solid-State Lighting Program, U.S. Department of Energy, June 2016.
https://www.energy.gov/sites/prod/files/2016/06/f32/ssl_animalresponse_jun2016.pdf
From the introduction:

> On April 19th, 2016, ten experts in fields related to animal physiological responses to light gathered with light-emitting diode (LED) manufacturers and the DOE [Department of Energy] Solid-State Lighting (SSL) Program for a discussion of common research themes,

research challenges and paths forward to better understand the broad topic of animal responses to light. The meeting, hosted by the Midwest Energy Efficiency Alliance (MEEA) in Chicago, Illinois, commenced with “soapbox” presentations, where each participant was invited to give a short presentation describing their field of expertise and forward-looking research concepts. This was followed by a general discussion of research and development opportunities for SSL that potentially benefit productivity and wellbeing of livestock and minimize impacts of light on wildlife and landscape ecology. This report is a summary of the input provided at this meeting and the subsequent discussions.

State Activities and Guidance

Cited below are a Kansas DOT research report that provides information to assist with the agency’s transition to LED lighting, and research proposed by Ohio DOT that considers the use of LEDs in ecologically sensitive areas. See page 8 for publications associated with Florida DOT’s research efforts in this topic area.

Kansas

Kansas Highway LED Illumination Manual: A Guide for the Use of LED Lighting Systems, Hongyi Cai, Kansas Department of Transportation, December 2015.
http://www.ksdot.org/Assets/wwwksdotorg/bureaus/kdotlib/KU156.pdf
This research project designed to assist Kansas DOT with its implementation of LED roadway lighting describes the LED lighting specified for Lighting Zone 1 (dark ambient lighting used in state parks, recreation areas and wildlife preserves).

Ohio

Proposed Research: Ecological Design Rules for Roadway Lighting, RFP Solicitation Number 2019-07, Ohio Department of Transportation, posted January 15, 2018.
http://www.dot.state.oh.us/Divisions/Planning/SPR/Research/RFP/Documents/2019-RFPs/2019-07_EcologicalRoadwayLighting.pdf
This research proposal was part of Ohio DOT’s solicitation for proposals for fiscal year 2019, with responses due March 2, 2018. *From the proposal*:

> **Problem Statement**
> Currently, the Ohio Department of Transportation (ODOT) designs roadway lighting in agricultural areas to produce adequate pavement illumination per the Traffic Engineering Manual (TEM), which cites industry standard IES [Illuminating Engineering Society] RP-8. Typically, designers give little or no consideration to light trespass during roadway lighting design. All ODOT lighting installations run dusk-to-dawn with no programmed dimming or light curfews. An upcoming addition to the TEM will address light trespass in agricultural areas by recommending a light trespass illuminance limit of 0.1 foot-candle on agricultural fields.
> The proposed research will focus on the effects that LED lighting has on wildlife in ecologically sensitive urban and rural areas. Limited but ongoing academic research suggests that the quantity and spectra of LED lighting have negative (and occasionally positive) effects on terrestrial and aquatic ecosystems. These effects can influence individual species and the overall ecosystem health. Lighting that illuminates the roadway pavement is engineered lighting. Industry standards provide design pavement illuminance values, and it is difficult to deviate from these established engineering standards without

reasonable justification. Well-executed research targeting this issue can serve as such justification for ODOT roadway lighting design changes that relate to ecological effects.

Goals and Objectives

The goal of this research is to establish design rules for roadway lighting in ecologically sensitive urban and rural areas. Objectives include:

- Determining the effects of roadway lighting on various wildlife areas:
    - What type of animals are affected by light?
    - How do attributes of the site play a role in the effect?

Color Temperature

"Light at Night Disrupts Nocturnal Rest and Elevates Glucocorticoids at Cool Color Temperatures," Valentina J. Alaasam, Richard Duncan, Stefania Casagrande, Scott Davies, Abhijaat Sidher, Brett Seymoure, Yantao Shen, Yong Zhang and Jenny Q. Ouyang, *Journal of Experimental Zoology Part A,* May 2018 (epublication ahead of print).
Citation at https://doi.org/10.1002/jez.2168
From the abstract: Nighttime light pollution is quickly becoming a pervasive, global concern. Since the invention and proliferation of light-emitting diodes (LED), it has become common for consumers to select from a range of color temperatures of light with varying spectra. Yet, the biological impacts of these different spectra on organisms remain unclear. We tested if nighttime illumination of LEDs, at two commercially available color temperatures (3000 and 5000 K) and at ecologically relevant illumination levels affected body condition, food intake, locomotor activity, and glucocorticoid levels in zebra finches (*Taeniopygia guttata*). We found that individuals exposed to 5000 K light had higher rates of nighttime activity (peaking after 1 week of treatment) compared to 3000 K light and controls (no nighttime light). Birds in the 5000 K treatment group also had increased corticosterone levels from pretreatment levels compared to 3000 K and control groups but no changes in body condition or food intake. Individuals that were active during the night did not consequently decrease daytime activity. This study adds to the growing evidence that the spectrum of artificial light at night is important, and we advocate the use of nighttime lighting with warmer color temperatures of 3000 K instead of 5000 K to decrease energetic costs for avian taxa.

"LED Lighting Increases the Ecological Impact of Light Pollution Irrespective of Color Temperature," S. M. Pawson and M. K.-F. Bader, *Ecological Applications*, Vol. 24, No. 7, pages 1561-1568, October 2014.
https://esajournals.onlinelibrary.wiley.com/doi/full/10.1890/14-0468.1
From the abstract: Recognition of the extent and magnitude of night-time light pollution impacts on natural ecosystems is increasing, with pervasive effects observed in both nocturnal and diurnal species. Municipal and industrial lighting is on the cusp of a step change where energy-efficient lighting technology is driving a shift from "yellow" high-pressure sodium vapor lamps (HPS) to new "white" light-emitting diodes (LEDs). We hypothesized that white LEDs would be more attractive and thus have greater ecological impacts than HPS due to the peak UV-green-blue visual sensitivity of nocturnal invertebrates. Our results support this hypothesis; on average LED light traps captured 48% more insects than were captured with light traps fitted with HPS lamps, and this effect was dependent on air temperature (significant light × air temperature interaction). We found no evidence that manipulating the color temperature of white LEDs would minimize the ecological impacts of the adoption of white LED lights. As such, large-scale adoption of energy-efficient white LED lighting for municipal and industrial use may

exacerbate ecological impacts and potentially amplify phytosanitary pest infestations. Our findings highlight the urgent need for collaborative research between ecologists and electrical engineers to ensure that future developments in LED technology minimize their potential ecological effects.

Flickering Artificial Light

"Potential Biological and Ecological Effects of Flickering Artificial Light," Richard Inger, Jonathan Bennie, Thomas W. Davies and Kevin J. Gaston, *PLoS ONE*, Vol. 9, No. 5, May 2014.
https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0098631
From the abstract: Organisms have evolved under stable natural lighting regimes, employing cues from these to govern key ecological processes. However, the extent and density of artificial lighting within the environment has increased recently, causing widespread alteration of these regimes. Indeed, night-time electric lighting is known significantly to disrupt phenology, behaviour, and reproductive success, and thence community composition and ecosystem functioning. Until now, most attention has focussed on effects of the occurrence, timing, and spectral composition of artificial lighting. Little considered is that many types of lamp do not produce a constant stream of light but a series of pulses. This flickering light has been shown to have detrimental effects in humans and other species. Whether a species is likely to be affected will largely be determined by its visual temporal resolution, measured as the critical fusion frequency. That is the frequency at which a series of light pulses are perceived as a constant stream. Here we use the largest collation to date of critical fusion frequencies, across a broad range of taxa, to demonstrate that a significant proportion of species can detect such flicker in widely used lamps. Flickering artificial light thus has marked potential to produce ecological effects that have not previously been considered.

Impacts to Animals and Animal Classes

The publications below address the impacts of LED and other lighting types on arthropods, bats, birds, insects and mice.

Arthropods

"Tuning the White Light Spectrum of Light Emitting Diode Lamps to Reduce Attraction of Nocturnal Arthropods," Travis Longcore, Hannah L. Aldern, John F. Eggers, Steve Flores, Lesly Franco, Eric Hirshfield-Yamanishi, Laina N. Petrinec, Wilson A. Yan and André M. Barroso, *Philosophical Transactions of the Royal Society; Series B, Biological Sciences,* Vol. 370, No. 1667, May 2015.
http://rstb.royalsocietypublishing.org/content/royptb/370/1667/20140125.full.pdf
From the abstract: Artificial lighting allows humans to be active at night, but has many unintended consequences, including interference with ecological processes, disruption of circadian rhythms and increased exposure to insect vectors of diseases. Although ultraviolet and blue light are usually most attractive to arthropods, degree of attraction varies among orders. With a focus on future indoor lighting applications, we manipulated the spectrum of white lamps to investigate the influence of spectral composition on number of arthropods attracted. We compared numbers of arthropods captured at three customizable light-emitting diode (LED) lamps (3510, 2704 and 2728 K), two commercial LED lamps (2700 K), two commercial compact fluorescent lamps (CFLs; 2700 K) and a control. We configured the three custom LEDs to minimize invertebrate attraction based on published attraction curves for honeybees and moths. Lamps were placed with pan traps at an urban and two rural study sites in Los Angeles,

California. For all invertebrate orders combined, our custom LED configurations were less attractive than the commercial LED lamps or CFLs of similar colour temperatures. Thus, adjusting spectral composition of white light to minimize attracting nocturnal arthropods is feasible; not all lights with the same colour temperature are equally attractive to arthropods.

Bats

"Transition From Conventional to Light-Emitting Diode Street Lighting Changes Activity of Urban Bats," Daniel Lewanzik and Christian C. Voigt, *Journal of Applied Ecology,* Vol. 54, No. 1, pages 264-271, February 2017.
Citation at https://besjournals.onlinelibrary.wiley.com/doi/abs/10.1111/1365-2664.12758
From the summary:

1. Light pollution is rapidly increasing and can have deleterious effects on biodiversity, yet light types differ in their effect on wildlife. Among the light types used for street lamps, light-emitting diodes (LEDs) are expected to become globally predominant within the next few years.
2. In a large-scale field experiment, we recorded bat activity at 46 street lights for 12 nights each and investigated how the widespread replacement of conventional illuminants by LEDs affects urban bats: we compared bat activity at municipal mercury vapour (MV) street lamps that were replaced by LEDs with control sites that were not changed.
3. *Pipistrellus pipistrellus* was the most frequently recorded species; it was 45% less active at LEDs than at MV street lamps, but the activity did not depend on illuminance level. Light type did not affect the activity of *Pipistrellus nathusii*, *Pipistrellus pygmaeus* or bats in the *Nyctalus/Eptesicus/Vespertilio* (NEV) group, yet the activity of *P. nathusii* increased with illuminance level. Bats of the genus *Myotis* increased activity 4·5-fold at LEDs compared with MV lights, but illuminance level had no effect.
4. Decreased activity of *P. pipistrellus*, which are considered light tolerant, probably paralleled insect densities around lights. Further, our results suggest that LEDs may be less repelling for light-averse *Myotis* spp. than MV lights. Accordingly, the transition from conventional lighting techniques to LEDs may greatly alter the anthropogenic impact of artificial light on urban bats and might eventually affect the resilience of urban bat populations.
5. *Synthesis and applications*. At light-emitting diodes (LEDs), the competitive advantage—the exclusive ability to forage on insect aggregations at lights—is reduced for light-tolerant bats. Thus, the global spread of LED street lamps might lead to a more natural level of competition between light-tolerant and light-averse bats. This effect could be reinforced if the potential advantages of LEDs over conventional illuminants are applied in practice: choice of spectra with relatively little energy in the short wavelength range; reduced spillover by precisely directing light; dimming during low human activity times; and control by motion sensors. Yet, the potential benefits of LEDs could be negated if low costs foster an overall increase in artificial lighting.

"Dark Matters: The Effects of Artificial Lighting on Bats," E. G. Rowse, D. Lewanzik, E. L. Stone, S. Harris and G. Jones, *Bats in the Anthropocene: Conservation of Bats in a Changing World*, C. Voigt and T. Kingston (editors), Springer Nature, pages 187-213, 2016.
https://link.springer.com/chapter/10.1007/978-3-319-25220-9_7
From the abstract: While artificial lighting is a major component of global change, its biological impacts have only recently been recognised. Artificial lighting attracts and repels animals in

taxon-specific ways and affects physiological processes. Being nocturnal, bats are likely to be strongly affected by artificial lighting. Moreover, many species of bats are insectivorous, and insects are also strongly influenced by lighting. Lighting technologies are changing rapidly, with the use of light-emitting diode (LED) lamps increasing. Impacts on bats and their prey depend on the light spectra produced by street lights; ultraviolet (UV) wavelengths attract more insects and consequently insectivorous bats. Bat responses to lighting are species-specific and reflect differences in flight morphology and performance; fast-flying aerial hawking species frequently feed around street lights, whereas relatively slow-flying bats that forage in more confined spaces are often light-averse. Both high-pressure sodium and LED lights reduce commuting activity by clutter-tolerant bats of the genera *Myotis* and *Rhinolophus*, and these bats still avoided LED lights when dimmed. Light-induced reductions in the activity of frugivorous bats may affect ecosystem services by reducing dispersal of the seeds of pioneer plants and hence reforestation. Rapid changes in street lighting offer the potential to explore mitigation methods such as part-night lighting (PNL), dimming, directed lighting, and motion-sensitive lighting that may have beneficial consequences for light-averse bat species.

Bats and Lighting: Overview of Current Evidence and Mitigation, Emma L. Stone, Bats and Lighting Research Project, University of Bristol, 2013.
http://www.batsandlighting.co.uk/downloads/lightingdoc.pdf
From the foreword: These guidelines have been drafted with input from experts in lighting (Institute of Lighting Professionals), bat surveys, ecology and mitigation (Bat Conservation Trust), legislation (Natural England) and bat research and mitigation (University of Bristol) to provide the best current evidence and thinking in the field of mitigation of the impacts of lighting on bats. This document is aimed at ecologists, lighting engineers, architects, planners and ecologists in Local Authorities and Statutory Nature Conservation Organisations such as Natural England, Scottish Natural Heritage or Natural Resources Wales.

Birds

"Effects of Nocturnal Illumination on Life-History Decisions and Fitness in Two Wild Songbird Species," Maaike de Jong, Jenny Q. Ouyang, Arnaud Da Silva, Roy H. A. Van Grunsven, Bart Kempenaers, Marcel E. Visser and Kamiel Spoelstra, *Philosophical Transactions of the Royal Society; Series B, Biological Sciences,* Vol. 370, No. 1667, May 2015.
http://rstb.royalsocietypublishing.org/content/royptb/370/1667/20140128.full.pdf
From the abstract: The effects of artificial night lighting on animal behaviour and fitness are largely unknown. Most studies report short-term consequences in locations that are also exposed to other anthropogenic disturbance. We know little about how the effects of nocturnal illumination vary with different light colour compositions. This is increasingly relevant as the use of LED lights becomes more common, and LED light colour composition can be easily adjusted. We experimentally illuminated previously dark natural habitat with white, green and red light, and measured the effects on life-history decisions and fitness in two free-living songbird species, the great tit (*Parus major*) and pied flycatcher (*Ficedula hypoleuca*) in two consecutive years. In 2013, but not in 2014, we found an effect of light treatment on lay date, and of the interaction of treatment and distance to the nearest lamp post on chick mass in great tits but not in pied flycatchers. We did not find an effect in either species of light treatment on breeding densities, clutch size, probability of brood failure, number of fledglings and adult survival. The finding that light colour may have differential effects opens up the possibility to mitigate negative ecological effects of nocturnal illumination by using different light spectra.

Insects

"Quantifying the Attractiveness of Broad-Spectrum Street Lights to Aerial Nocturnal Insects," Andrew Wakefield, Moth Broyles, Emma L. Stone, Stephen Harris and Gareth Jones, *Journal of Applied Ecology*, Vol. 55, pages 714-722, 2018.
https://besjournals.onlinelibrary.wiley.com/doi/pdf/10.1111/1365-2664.13004
From the abstract:

1. Sodium street lights, dominated by long wavelengths of light, are being replaced by broad-spectrum, white lights globally, in particular light-emitting diodes (LEDs). These white lights typically require less energy to operate and are therefore considered "eco-friendly." However, little attention has been paid to the impacts white lights may have upon local wildlife populations.
2. We compared insect attraction to orange (high-pressure sodium, HPS) and white (metal halide, MH and LED) street lights experimentally using portable street lights and custom-made flight intercept traps.
3. Significantly more (greater than five times as many) insects were attracted to white MH street lights than white (4,250 K) LED and HPS lights. There was no statistical difference in the numbers of insects attracted to LED and HPS lights for most taxa caught. However, rarefaction shows a greater diversity of insects caught at LED than HPS lights.
4. *Policy implications*. With the current, large-scale conversion to white light-emitting diode (LED) lighting, our results give insight into how changes to street light technology may affect wildlife populations and communities. We recommend avoiding metal halide light installations as they attract many more insects than competing technologies. We highlight the need to tailor LED lighting to prevent disturbances across multiple insect taxa.

Mice

"The Influence of Low-Powered Family LED Lighting on Eyes in Mice Experimental Model," Mei-Ling Peng, Cheng-Yu Tsai, Chung-Liang Chien, John Ching-Jen Hsiao, Shuan-Yu Huang, Ching-Ju Lee, Hsiang-Yin Lin, Yang-Cheng Wen and Kuang-Wen Tseng, *Life Science Journal,* Vol. 9, No. 1, pages 477-482, 2012.
http://www.lifesciencesite.com/lsj/life0901/072_8366life0901_477_482.pdf
From the abstract: Ocular tissue damage because of exposure to visible light has been demonstrated by the results of human and animal studies. The short-wavelength visible light between 430 nm [nanometers] to 500 nm (blue light) is especially associated with retina damage. Recently, new powerful sources and relatively inexpensive blue energy of LED (light emitting diodes) family lamps in home illumination are available. The aim of this study is to investigate the effects of illumination source from the low-powered and the conscious spectrum source of LED family lamps on retina tissues. The illumination source of LED family lamps was analyzed from 300 nm to 800 nm using an UV-visible spectrophotometer. In animal experiments, young adult mice were assigned to expose to family LED light for 2h[ours] every day ranging 2 to 4 weeks or light environment using LED family lamps for 39 weeks. After LED light treatment, sections of eyes were stained with hematoxylin and examined using histopathology. The data clearly demonstrated irradiation of the white LED is above 400 nm and is not within the ultraviolet light region. However, the analysis of spectrum distribution demonstrated that the family LED lighting exhibited power-peak at 450 nm is within the blue light region. Histological results showed that the photoreceptor layer is significantly reduced in thickness after 4 weeks of LED exposure 2h every day or LED illuminated environment. This

study provides important data regarding the efficacy and safety of LED light in family illumination. It is impossible to consider these degenerative changes are related unavoidably part of their mechanism of action or an avoidable toxic effect.

Light Spectrum

"Nature, Extent and Ecological Implications of Night-Time Light From Road Vehicles," Kevin J. Gaston and Lauren A. Holt, *Journal of Applied Ecology*, Vol. 55, No. 5, pages 2296-2307, September 2018.
https://besjournals.onlinelibrary.wiley.com/doi/10.1111/1365-2664.13157
From the abstract:

1. The erosion of night-time by the introduction of artificial lighting constitutes a profound pressure on the natural environment. It has altered what had for millennia been reliable signals from natural light cycles used for regulating a host of biological processes, with impacts ranging from changes in gene expression to ecosystem processes.
2. Studies of these impacts have focused almost exclusively on those resulting from stationary sources of light emissions, and particularly streetlights. However, mobile sources, especially road vehicle headlights, contribute substantial additional emissions.
3. The ecological impacts of light emissions from vehicle headlights are likely to be especially high because these are (1) focused so as to light roadsides at higher intensities than commonly experienced from other sources, and well above activation thresholds for many biological processes; (2) projected largely in a horizontal plane and thus can carry over long distances; (3) introduced into much larger areas of the landscape than experience street lighting; (4) typically broad "white" spectrum, which substantially overlaps the action spectra of many biological processes and (5) often experienced at roadsides as series of pulses of light (produced by passage of vehicles), a dynamic known to have major biological impacts.
4. The ecological impacts of road vehicle headlights will markedly increase with projected global growth in numbers of vehicles and the road network, increasing the local severity of emissions (because vehicle numbers are increasing faster than growth in the road network) and introducing emissions into areas from which they were previously absent. The effects will be further exacerbated by technological developments that are increasing the intensity of headlight emissions and the amounts of blue light in emission spectra.
5. *Synthesis and applications*. Emissions from vehicle headlights need to be considered as a major, and growing, source of ecological impacts of artificial night-time lighting. It will be a significant challenge to minimise these impacts whilst balancing drivers' needs at night and avoiding risk and discomfort for other road users. Nonetheless, there is potential to identify solutions to these conflicts, both through the design of headlights and that of roads.

"Rapid Assessment of Lamp Spectrum to Quantify Ecological Effects of Light at Night," Travis Longcore, Airam Rodríguez, Blair Witherington, Jay F. Penniman, Lorna Herf and Michael Herf, *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, June 2018 (epublication ahead of print).
Citation at https://doi.org/10.1002/jez.2184
From the abstract: For many decades, the spectral composition of lighting was determined by the type of lamp, which also influenced potential effects of outdoor lights on species and

ecosystems. Light-emitting diode (LED) lamps have dramatically increased the range of spectral profiles of light that is economically viable for outdoor lighting. Because of the array of choices, it is necessary to develop methods to predict the effects of different spectral profiles without conducting field studies, especially because older lighting systems are being replaced rapidly. We describe an approach to predict responses of exemplar organisms and groups to lamps of different spectral output by calculating an index based on action spectra from behavioral or visual characteristics of organisms and lamp spectral irradiance. We calculate relative response indices for a range of lamp types and light sources and develop an index that identifies lamps that minimize predicted effects as measured by ecological, physiological, and astronomical indices. Using these assessment metrics, filtered yellow-green and amber LEDs are predicted to have lower effects on wildlife than high pressure sodium lamps, while blue-rich lighting (e.g., K ≥ 2200) would have greater effects. The approach can be updated with new information about behavioral or visual responses of organisms and used to test new lighting products based on spectrum. Together with control of intensity, direction, and duration, the approach can be used to predict and then minimize the adverse effects of lighting and can be tailored to individual species or taxonomic groups.

Related Resources:

Rapid Assessment of Lamp Spectrum to Quantify Ecological Effects of Light at Night, Travis Longcore, Airam Rodríguez, Blair Witherington, Jay F. Penniman, Lorna Herf and Michael Herf, 2018.
https://fluxometer.com/ecological/
This web site provides access to the database described in the June 2018 journal article cited above and the newsletter article cited below.

"Scientist's New Database Can Help Protect Wildlife From Harmful Hues of LED Lights," Gary Polakovic, *USC News*, June 12, 2018.
https://news.usc.edu/144389/usc-scientist-database-reduce-effects-of-led-light-on-animals/
From the article: The research is important for wildlife conservation. For example, loggerhead sea turtle hatchlings, an endangered species, leave beach nests at night and follow artificial light inland to danger instead of skittering to the ocean. Similarly, lights attract migrating juvenile salmon, exposing them to predators. Also, global declines in insects have been linked in part to light pollution, Longcore said. The new research will help people choose lighting to reduce wildlife impacts.

The researchers focused on only four groups of creatures, which have been studied for light responses previously. Future studies will incorporate more species worldwide.

A central component of the USC research includes the first publicly available database showing how about two dozen different types of artificial lighting affect wildlife. The matrix is called "Rapid Assessment of Lamp Spectrum to Quantify Ecological Effects of Light at Night." Developers, land-use planners and policymakers can use it to choose lighting that balances the needs of nature and people. Today, regulations to limit light direction or intensity typically don't account for the different hues of LED lights, Longcore said.

"If we don't provide advice and information to decisionmakers, they will go with the cheapest lighting or lighting that serves only one interest and does not balance other interests," Longcore said. "We provide a method to assess the probable consequences of new light sources to keep up with the changing technology and wildlife concerns."

“Experimental Illumination of Natural Habitat—An Experimental Set-Up to Assess the Direct and Indirect Ecological Consequences of Artificial Light of Different Spectral Composition,” Kamiel Spoelstra, Roy H. A. van Grunsven, Maurice Donners, Phillip Gienapp, Martinus E. Huigens, Roy Slaterus, Frank Berendse, Marcel E. Visser and Elmar Veenendaal, *Philosophical Transactions of the Royal Society; Series B, Biological Sciences,* Vol. 370, No. 1667, May 2015.
http://rstb.royalsocietypublishing.org/content/royptb/370/1667/20140129.full.pdf
From the abstract: Artificial night-time illumination of natural habitats has increased dramatically over the past few decades. Generally, studies that assess the impact of artificial light on various species in the wild make use of existing illumination and are therefore correlative. Moreover, studies mostly focus on short-term consequences at the individual level, rather than long-term consequences at the population and community level—thereby ignoring possible unknown cascading effects in ecosystems. The recent change to LED lighting has opened up the exciting possibility to use light with a custom spectral composition, thereby potentially reducing the negative impact of artificial light. We describe here a large-scale, ecosystem-wide study where we experimentally illuminate forest-edge habitat with different spectral composition, replicated eight times. Monitoring of species is being performed according to rigid protocols, in part using a citizen-science-based approach, and automated where possible. Simultaneously, we specifically look at alterations in behaviour, such as changes in activity, and daily and seasonal timing. In our set-up, we have so far observed that experimental lights facilitate foraging activity of pipistrelle bats, suppress activity of wood mice and have effects on birds at the community level, which vary with spectral composition. Thus far, we have not observed effects on moth populations, but these and many other effects may surface only after a longer period of time.

“Artificial Light Pollution: Are Shifting Spectral Signatures Changing the Balance of Species Interactions?” Thomas W. Davies, Jonathan Bennie, Richard Inger, Natalie Hempel De Ibarra and Kevin J. Gaston, *Global Change Biology,* Vol. 19, No. 5, pages 1417-1423, February 2013.
https://onlinelibrary.wiley.com/doi/epdf/10.1111/gcb.12166
From the abstract: Technological developments in municipal lighting are altering the spectral characteristics of artificially lit habitats. Little is yet known of the biological consequences of such changes, although a variety of animal behaviours are dependent on detecting the spectral signature of light reflected from objects. Using previously published wavelengths of peak visual pigment absorbance, we compared how four alternative street lamp technologies affect the visual abilities of 213 species of arachnid, insect, bird, reptile and mammal by producing different wavelength ranges of light to which they are visually sensitive. The proportion of the visually detectable region of the light spectrum emitted by each lamp was compared to provide an indication of how different technologies are likely to facilitate visually guided behaviours such as detecting objects in the environment. Compared to narrow spectrum lamps, broad spectrum technologies enable animals to detect objects that reflect light over more of the spectrum to which they are sensitive and, importantly, create greater disparities in this ability between major taxonomic groups. The introduction of broad spectrum street lamps could therefore alter the balance of species interactions in the artificially lit environment.

“Limiting the Impact of Light Pollution on Human Health, Environment and Stellar Visibility,” Fabio Falchi, Pierantonio Cinzano, Christopher D. Elvidge, David M. Keith and Abraham Haim, *Journal of Environmental Management*, Vol. 92, No. 10, pages 2714-2722, October 2011.
Citation at http://www.sciencedirect.com/science/article/pii/S030147971100226X
From the abstract: Light pollution is one of the most rapidly increasing types of environmental degradation. Its levels have been growing exponentially over the natural nocturnal lighting levels

provided by starlight and moonlight. To limit this pollution several effective practices have been defined: the use of shielding on lighting fixture to prevent direct upward light, particularly at low angles above the horizon; no over lighting, i.e., avoid using higher lighting levels than strictly needed for the task, constraining illumination to the area where it is needed and the time it will be used. Nevertheless, even after the best control of the light distribution is reached and when the proper quantity of light is used, some upward light emission remains, due to reflections from the lit surfaces and atmospheric scatter. The environmental impact of this "residual light pollution" cannot be neglected and should be limited too. Here we propose a new way to limit the effects of this residual light pollution on wildlife, human health and stellar visibility. We performed analysis of the spectra of common types of lamps for external use, including the new LEDs. We evaluated their emissions relative to the spectral response functions of human eye photoreceptors, in the photopic, scotopic and the 'meltopic' melatonin suppressing bands. We found that the amount of pollution is strongly dependent on the spectral characteristics of the lamps, with the more environmentally friendly lamps being low pressure sodium, followed by high pressure sodium. Most polluting are the lamps with a strong blue emission, like Metal Halide and white LEDs. Migration from the now widely used sodium lamps to white lamps (MH and LEDs) would produce an increase of pollution in the scotopic and melatonin suppression bands of more than five times the present levels, supposing the same photopic installed flux. This increase will exacerbate known and possible unknown effects of light pollution on human health, environment and on visual perception of the Universe by humans. We present quantitative criteria to evaluate the lamps based on their spectral emissions and we suggest regulatory limits for future lighting.

Lighting Alternatives

"New Framework of Sustainable Indicators for Outdoor LED (Light Emitting Diodes) Lighting and SSL (Solid State Lighting)," Annika K. Jägerbrand, *Sustainability*, Vol. 7, No. 1, pages 1028-1063, January 2015.
http://www.mdpi.com/2071-1050/7/1/1028/htm
From the abstract: Light emitting diodes (LEDs) and SSL (solid state lighting) are relatively new light sources, but are already widely applied for outdoor lighting. Despite this, there is little available information allowing planners and designers to evaluate and weigh different sustainability aspects of LED/SSL lighting when making decisions. Based on a literature review, this paper proposes a framework of sustainability indicators and/or measures that can be used for a general evaluation or to highlight certain objectives or aspects of special interest when choosing LED/SSL lighting. LED/SSL lighting is reviewed from a conventional sustainable development perspective, i.e., covering the three dimensions, including ecological, economic and social sustainability. The new framework of sustainable indicators allow prioritization when choosing LED/SSL products and can thereby help ensure that short-term decisions on LED/SSL lighting systems are in line with long-term sustainability goals established in society. The new framework can also be a beneficial tool for planners, decision-makers, developers and lighting designers, or for consumers wishing to use LED/SSL lighting in a sustainable manner. Moreover, since some aspects of LED/SSL lighting have not yet been thoroughly studied or developed, some possible future indicators are suggested.

Outdoor Lighting Retrofits: A Guide for the National Park Service and Other Federal Agencies, National Park Service and the California Lighting Technology Center, University of California, Davis, July 2014.
http://cltc.ucdavis.edu/sites/default/files/files/publication/nps-outdoor-lighting-retrofits-guide-july2014.pdf
From page 5 of the PDF:

> This guide provides an overview of outdoor lighting best practices as well as information on lighting technologies that can optimize energy, cost and maintenance savings. It offers guidance for evaluating light sources, performing a lighting audit, and pairing lamps with lighting controls. In many cases, following best practices allows facilities to exceed federal standards for outdoor lighting energy efficiency.

The guide also briefly addresses the "measures [that] can be taken to minimize the impact of nighttime lighting on any wildlife in the surrounding ecosystem."

"Reducing the Ecological Consequences of Night-Time Light Pollution: Options and Developments," Kevin J. Gaston, Thomas W. Davies, Jonathan Bennie and John Hopkins, *Journal of Applied Ecology*, Vol. 49, No. 6, pages 1256-1266, December 2012.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3546378/
From the abstract:

1. Much concern has been expressed about the ecological consequences of night-time light pollution. This concern is most often focused on the encroachment of artificial light into previously unlit areas of the night-time environment, but changes in the spectral composition, duration and spatial pattern of light are also recognized as having ecological effects.
2. Here, we examine the potential consequences for organisms of five management options to reduce night-time light pollution. These are to (i) prevent areas from being artificially lit; (ii) limit the duration of lighting; (iii) reduce the 'trespass' of lighting into areas that are not intended to be lit (including the night sky); (iv) change the intensity of lighting; and (v) change the spectral composition of lighting.
3. Maintaining and increasing natural unlit areas is likely to be the most effective option for reducing the ecological effects of lighting. However, this will often conflict with other social and economic objectives. Decreasing the duration of lighting will reduce energy costs and carbon emissions, but is unlikely to alleviate many impacts on nocturnal and crepuscular animals, as peak times of demand for lighting frequently coincide with those in the activities of these species. Reducing the trespass of lighting will maintain heterogeneity even in otherwise well-lit areas, providing dark refuges that mobile animals can exploit. Decreasing the intensity of lighting will reduce energy consumption and limit both skyglow and the area impacted by high-intensity direct light. Shifts towards 'whiter' light are likely to increase the potential range of environmental impacts as light is emitted across a broader range of wavelengths.
4. Synthesis and applications. The artificial lightscape will change considerably over coming decades with the drive for more cost-effective low-carbon street lighting solutions and growth in the artificially lit area. Developing lighting strategies that minimize adverse ecological impacts while balancing the often conflicting requirements of light for human utility, comfort and safety, aesthetic concerns, energy consumption and carbon emission reduction constitute significant future challenges. However, as both lighting technology and understanding of its ecological effects develop, there is potential to identify adaptive solutions that resolve these conflicts.

Measuring Artificial Light

"Quantifying Urban Light Pollution: A Comparison Between Field Measurements and EROS-B Imagery," Yali Katz and Noam Levin, *Remote Sensing of Environment*, Volume 177, pages 65-77, May 2016.
Citation at https://www.sciencedirect.com/science/article/pii/S0034425716300451
From the abstract: Artificial night lighting and its negative consequences are of interest in the fields of Astronomy, Human Geography, Ecology and Human Health. The majority of studies to date focused on the impacts light pollution has on our ability to view the night sky, as well as on biodiversity, ecosystems and humans. However, in recent years, with the emergence of new high spatial resolution sensors, providing detailed evaluation of night lights at the local level, more attention has been given for estimating and quantifying artificial light within cities. In this study, we evaluate urban night lights within the city of Jerusalem by combining data from two remote sensing tools: ground measurements using Sky Quality Meter (SQM) devices and space-borne measurements using EROS-B night light imagery. In addition, we examined the use of the SQM for evaluating artificial light in different view directions: upwards, downwards and horizontally. Differences in night lights were found between the three SQM view directions, with the brightest values measured in the horizontal direction (8.7–18.9 mag_{SQM} $arcsec^{-2}$, and darkest values in the downwards direction (11.2–19.5 mag_{SQM} $arcsec^{-2}$). The downwards SQM measurements were influenced by surface albedo, the horizontal direction was the most exposed to direct lights from buildings and cars, while in most locations the upwards direction represented skyglow. Using quantile regression we found strong correlations between the SQM and EROS-B brightness values. Statistically significant correlations (R^2 = 0.53) were found between the upwards and downwards devices to the EROS-B in the 0.95 quantile, as well as between the horizontal device to the EROS-B in the 0.90 quantile (R^2 = 0.44). In addition to local and external light sources, bright areas on the EROS-B image were associated with areas of low vegetation cover and high albedo. This study provides evidence for the correspondence between field and space-borne measurements of artificial lights and emphasizes the need for better understanding of light pollution at the local level and for taking into account of the three-dimensional nature of light pollution.

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Appendix A: Survey Questions

Two surveys, presented below, were conducted for this project:

- An initial nine-question survey sought information from a broad range of potential respondents:
  - State department of transportation (DOT) members of the AASHTO Committee on Environment and Sustainability.
  - Participants in the Wildlife, Fisheries and Transportation Listserv managed by the Center for Transportation and the Environment at North Carolina State University. Listserv managers note that the list "is intended to facilitate discussion among transportation and environmental professionals about emerging issues and best practices that improve the way ecological issues are addressed in surface transportation."
- A follow-up survey was distributed to selected respondents to gather additional information about agency practices with regard to LED lighting.

First Survey

Assessing the Impacts of LED Lighting to Wildlife

1. Has your agency identified impacts, or the potential for impacts (direct, indirect or cumulative), to wildlife from the use of LED lighting?
   - No.
   - Yes.
2. Has your agency completed research—published or unpublished—examining effects of LED lighting and its impacts to wildlife?
   - No.
   - Yes. Please describe this research and provide a link to the research report or send any files not available online to chris.kline@ctcandassociates.com.

Lighting Alternatives and Modifications

3. Has your agency identified commercial wildlife-friendly LED lighting that has been approved for use?
   - No.
   - Yes. Please describe this lighting and provide product details, including plans and drawings, if available. Send any files not available online to chris.kline@ctcandassociates.com.
4. Aside from LED lighting solutions, has your agency identified a cost-effective, energy-efficient lighting alternative that avoids or minimizes impacts to wildlife?
   - No.
   - Yes. Please describe the lighting alternative(s), including the vendor and product details.

Agency Use of LED Lighting in Sensitive Wildlife Habitat

5. Does your agency use LED lighting in areas where protected wildlife species habitat is present?
   - No.
   - Yes.
6. Has your agency adopted specifications for LED or other lighting for use in sensitive species areas?
   - No.
   - Yes. Please provide a link to these specifications or send any files not available online to chris.kline@ctcandassociates.com.

Feedback Related to Wildlife-Friendly LED Lighting

7. Has your agency identified any conflicts between competing stakeholders as a result of implementing wildlife-friendly LED lighting?
   - No.
   - Yes. Please describe your agency's response to these conflicts.

Wrap-Up

8. Please provide links to any other documentation associated with your agency's use of wildlife-friendly LED or other lighting that you have not already provided. Send any files not available online to chris.kline@ctcandassociates.com.
9. Please use this space to provide any comments or additional information about your previous responses.

Follow-Up Survey

Assessing the Impacts of LED Lighting to Wildlife

1. Please describe the impacts or potential for impacts to wildlife your agency has identified in each topic area below.

   Location:

   Species affected:

   Lighting type used:

   Metrics used to quantify impacts or effects:

   Extent of impact area (for example, feet from light source):
2. Has your agency completed any environmental review or consultation(s), such as with the U.S. Fish and Wildlife Service, on lighting projects?
   - No.
   - Yes. Please summarize the results of these consultations and include any discussions of indirect effects and resulting avoidance and minimization measures.

Lighting Alternatives

3. If your agency has attempted to modify commercial LED or other lighting installations to minimize impacts to wildlife, please describe below each modification technique your agency has used.
    - Lighting filter.
    - Shielding.
    - Selecting luminaires with low backlight, uplight and glare (BUG) ratings.
    - Adjustments based on presence of vehicles on the roadway.
    - Adjustments based on ambient nighttime light.
    - Adjustments based on timers.
    - Other technique 1 (please describe).
    - Other technique 2 (please describe).
    - Other technique 3 (please describe).
4. If your agency has attempted to modify commercial LED or other lighting installations to minimize impacts to wildlife, please describe the modifications' success by rating all the techniques below that apply using the rating scale of 1 = not at all successful to 5 = extremely successful.
    - Lighting filter.
    - Shielding.
    - Selecting luminaires with low backlight, uplight and glare (BUG) ratings.
    - Adjustments based on presence of vehicles on the roadway.
    - Adjustments based on ambient nighttime light.
    - Adjustments based on timers.
    - Other technique 1 (as described in Question 3).
    - Other technique 2 (as described in Question 3).
    - Other technique 3 (as described in Question 3).
5. Has your agency employed any nonlighting measures that meet safety requirements and avoid or minimize impacts to wildlife?
    - No.
    - Yes. Please describe these nonlighting measures.

Feedback Related to Wildlife-Friendly LED Lighting

6. Has your agency received public comments in response to implementation of wildlife-friendly LED lighting?
    - No.
    - Yes. Please summarize these public comments.

Wrap-Up

7. Please use this space to provide any comments or additional information about your previous responses.