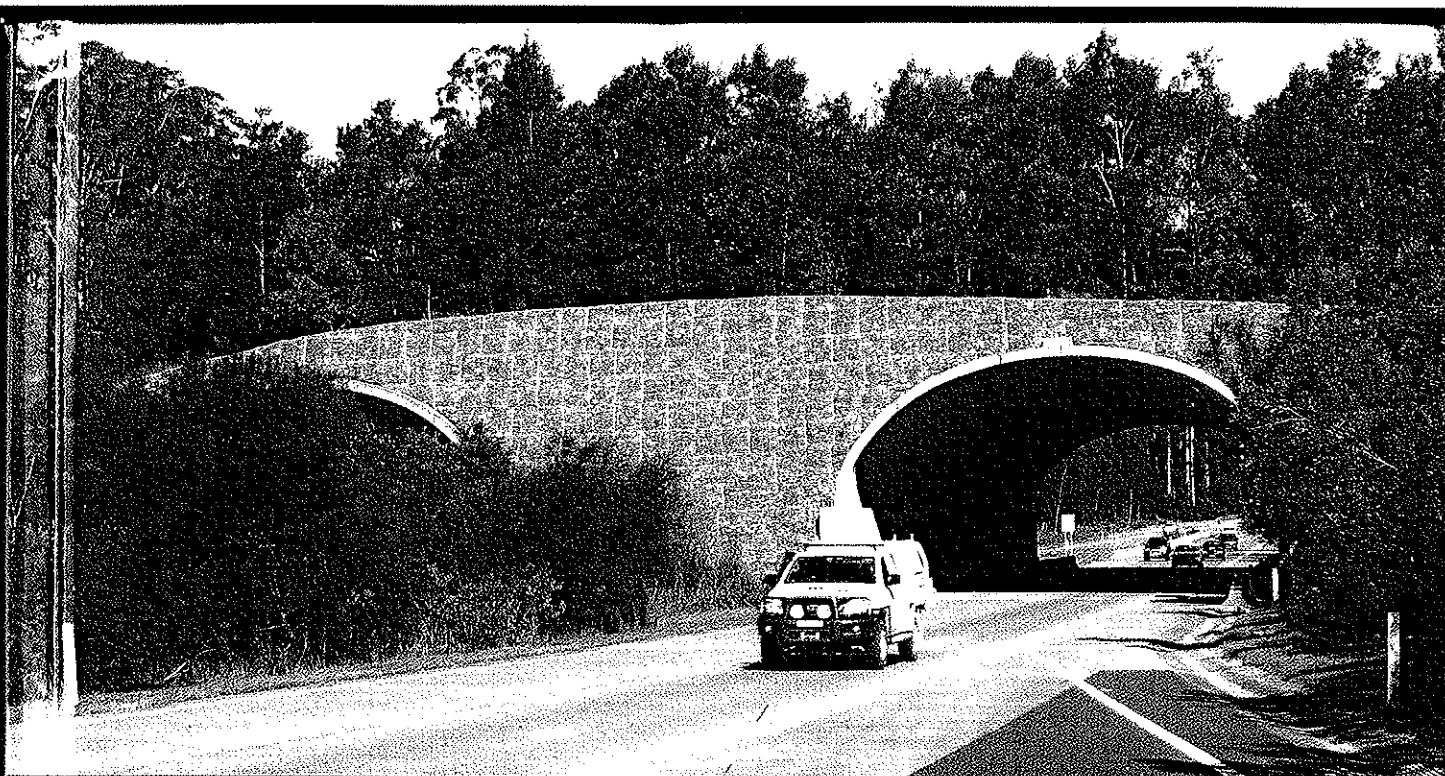

HANDBOOK OF ROAD ECOLOGY

Rodney van der Ree • Daniel J. Smith • Clara Grilo

WILEY Blackwell

Chapter 18

UNDERSTANDING AND MITIGATING THE NEGATIVE EFFECTS OF ROAD LIGHTING ON ECOSYSTEMS

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SUMMARY

Natural light plays an integral role in biological systems, one that can be disrupted by the intrusion of other light sources. Specifically, artificial lighting, including road lighting, poses negative effects on plant and animal physiology, animal behaviour and predation rates. These effects are cumulative as multiple, artificial light sources contribute.

18.1 Light functions as a natural stimulus.
18.2 Metrics used to quantify artificially produced light are generally not biologically relevant.
18.3 Species response to artificial light varies by visual system.
18.4 Light emitted varies relative to the type of lighting technology.
18.5 Planning for road lighting must include zoning relative to light levels and light-fixture placement.
18.6 Mitigating the negative effects of road lighting requires research collaboration.

Negative effects of artificial lighting, including road lighting, are manageable. By better understanding the ecosystems through which roads pass and how light affects resident organisms, we can adapt lighting fixtures, fixture design and zoning to minimise site-specific effects, as well as contributions to cumulative light pollution.

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INTRODUCTION

A critical aspect of road planning involves driver and pedestrian safety, and road lighting is a key component (IDA/IES 2011). However, decisions on how, where and when to use artificial lighting have immediate implications for the well-being of ecosystems through which roads pass. Specifically, light is a natural stimulus that affects the physiology, behaviour and movements of all organisms. Artificial lighting alters the length of natural photoperiod (duration of daily exposure to light) and contrasts in intensity and spectrum with natural, ambient light, thus unavoidably affecting the sensory ecology of organisms. Further, artificial light poses cumulative effects on ecosystems because multiple light sources are often present in a given area (Fig. 18.1). Cumulative effects are expressed differentially across species, because not all light sources are equal in their effects on physiology or behaviour.

To mitigate negative effects to natural systems by artificial lighting used on roads, planners must first consider whether lighting is necessary. If so, they must consider not only the varying sensitivity of the human eye to different light wavelengths relative to driver and pedestrian safety but also the biological relevance of lighting to the resident organisms. Our goal is to provide road practitioners, engineers and ecologists with a concise review of resources available to aid in the reduction of the negative effects of road lighting on ecosystems.

LESSONS

18.1 Light functions as a natural stimulus

Light exists as particles (photons) and waves and is described relative to wavelength (Fig. 18.2). Natural light plays a significant role in the sensory ecology of animals, particularly with regard to photoperiod, which stimulates (i) circadian rhythms important to the basic health and development of plants and animals (e.g. growth, reproduction and disease resistance) and (ii) daily and seasonal physiology and behaviour of animals (e.g. foraging, breeding, dispersal and migration). In addition, animals use light cues in predator detection, habitat selection and vehicle avoidance (Gaston et al. 2012, 2013).

18.2 Metrics used to quantify artificially produced light are generally not biologically relevant

Consideration given to design of light fixtures and emission spectra (i.e. the distribution of wavelengths emitted by a lamp; Fig. 18.2) generally fails to consider the

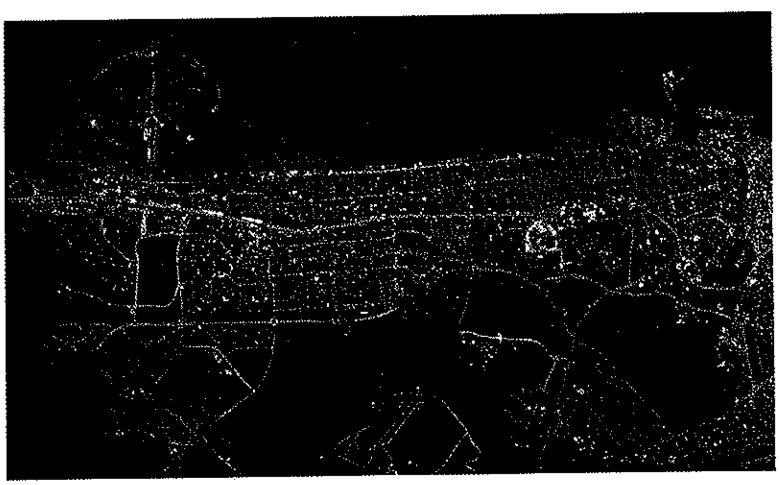

Figure 18.1 Multiple light sources, including road lighting, from Dubai, UAE, contributing to cumulative artificial light pollution. Photograph credit: Expedition 30 Crew to the International Space Station for the Earth Observations Experiment and Image Science & Analysis Laboratory, Johnson Space Center; U.S. National Aeronautics and Space Administration (http://earthobservatory.nasa.gov/IOTD/view.php?id=77360). Source: Photograph from Earth Observatory, NASA.

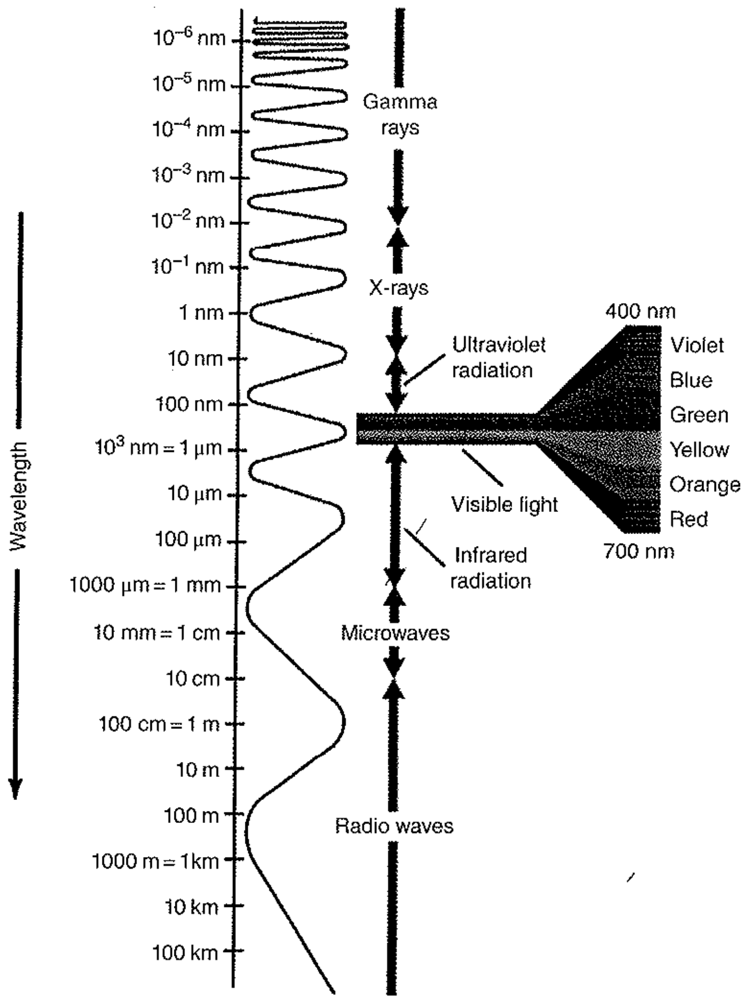

Figure 18.2 The electromagnetic spectrum and the portion of the spectrum visible to most animals, represented in nanometres (nm or 1×10^{-9} m) from 400 to 700 nm. Notably, many non-primate species of animals have the capability to detect wavelengths in the near ultraviolet (300–400 nm). Figure credit: U.S. National Aeronautics and Space Administration; http://science-edu.larc.nasa.gov/EDDOCS/Wavelengths_for_Colors.html. Source: NASA.

biological relevance of the light stimulus. For example, light emitted from artificial sources is typically not quantified relative to wavelength, but in lumens (i.e. the luminous flux or power from a light source) and illuminance (the total luminous flux incident on a surface per unit area). However, we cannot effectively understand animal response to light stimuli if the measurements (metrics) of fixture design and performance are in units of power.

Plants and animals respond directly to the intensity or number of photons per wavelength striking photoreceptors in their eyes (Endler 1990; Rich & Longcore 2006; Gaston et al. 2013). For example, 1 W of light at 400 nm (Fig. 18.2) has only 57% of the photon flux as 1 W of light at 700 nm (Endler 1990). In other words, the total energy reported is 1 W at both wavelengths, but the biologically relevant metric, photon flux by wavelength, differs by greater than 50%. As such, the lumen and luminous flux are inaccurate metrics for discerning biological effects because they do not take into account the density of photons striking photoreceptors. We suggest that light fixtures and potential effects on organisms be evaluated relative to emission spectra and biologically relevant light intensity within the area of incidence (i.e. the area illuminated). This task will require collaboration among planners, lighting engineers and ecologists (Lesson 18.5). As for actual measurements, these should be taken via spectroradiometer.

18.3 Species response to artificial light varies by visual system

Effective planning for road lighting should consider how light affects organisms in roadside habitats. Fortunately, recent research (e.g. Rich & Longcore 2006; Horváth et al. 2009; IDA 2010; Gaston et al. 2013) details the negative effects of artificial lighting on various species and ecosystems. In short, planning for road lighting relative to potential biotic effects must consider that relative brightness of artificial light and effects of emission spectra on organisms vary with the sensory (plants) and visual physiology of the animals affected.

For example, human vision is trichromatic, meaning that we possess three independent channels for detecting and processing colour. However, many non-primate animals perceive the world in a much different way. Birds are generally tetrachromatic and capable of detecting wavelengths within the ultraviolet portion of the electromagnetic spectrum (Hart 2001; Fig. 18.2), whereas few bird species rely on scotopic or rod-dominated vision (i.e. rod photoreceptors are primarily sensitive to light intensity, such as under dim-light conditions). Further, the ability to perceive colour is dependent on the number of different visual pigments present in cone photoreceptors.

The influence of natural light is evident with changes in photoperiod that influence the timing of seasonal events in birds (e.g. effects on breeding physiology) and even mate selection (Dawson et al. 2001; de Molenaar et al. 2006). The addition of artificial light can interfere with this natural stimulus (de Molenaar et al. 2006). Also, a light-sensitive 'magnetic compass' aids orientation during night-time migration (especially when cloud cover prevents the use of stars as visual cues); this innate navigational ability can be confounded by specific wavelengths from artificial lighting (e.g. >500 nm; Poot et al. 2008).

Perhaps the most well-known effect of artificial light on birds is the attraction to, and disorientation by, high-intensity glare from warning beacons on communication towers, offshore oil platforms and other structures (Gauthreaux & Belser 2006). Birds migrating at night and attracted to such lighting can become 'trapped by the beam' (Verheijen 1985) and subsequently die from direct collisions with structures or other birds or indirectly by depletion of energy reserves expended while flying towards or around artificial lights. Bird attraction to artificial lights is more pronounced on cloudy and misty nights than clear nights (Montevecchi 2006). Artificial lighting can also affect the quality of breeding habitat and timing of breeding (de Molenaar et al. 2006), prey availability (Negro et al. 2000), singing patterns (Miller 2006) and foraging and potentially increase exposure to predators by drawing birds to artificially lit areas (Santos et al. 2010). However, the primary negative effect of road lighting on birds is the contribution to cumulative light pollution of reflected or escaping light skywards from multiple light sources (Fig. 18.1) (light that interferes with detection of celestial migration cues), a problem that can be managed by fixture design (Lesson 18.4; Fig. 18.3) and zoning (Lesson 18.5).

In contrast, the visual capability of bats is primarily rod dominated, and species response to road lighting varies by level of illumination and area affected (Lesson 18.5). Foraging opportunities for bats can be enhanced due to insect attraction to light (Eisenbeis 2006; Lesson 34.3), but increased competition with other bat species and avoidance of lighting can also pose negative effects (Rydell 2006; Zurcher et al. 2010; Stone et al. 2012). Bats attracted to road lighting are also susceptible to vehicle collisions (Zurcher et al. 2010; Chapter 34). For the most part, however, effects of road lighting on bat species are manageable via attention to light-fixture location, lamp illuminance and shielding (Fig. 18.3; Lessons 18.4 and 18.5).

Similarly, other terrestrial mammal species (e.g. rodents) are also susceptible to disruption in photoperiod and migration, as well as enhanced predation associated with artificial lighting. As with bats, light-fixture location, lamp illuminance and shielding (Lessons 18.4 and 18.5) can be adapted to the particular species affected by road lighting (see Rich and Longcore (2006) for detailed discussion of artificial lighting effects on terrestrial mammals).

Few studies have examined the effects of road lighting on amphibians and reptiles or reported biologically relevant metrics of light intensity for these species or other taxa (Perry et al. 2008). An exception is the well-documented negative effect of artificial lighting on sea turtles (Salmon 2006). Also, as with birds, the magnetic compass in amphibians is affected by light wavelengths greater than 500 nm (Diego-Rasilla et al. 2010), a spectral range falling within that of sodium-vapour lamps often used along roads (Rydell 1992). An effective management approach to reduce negative effects of road

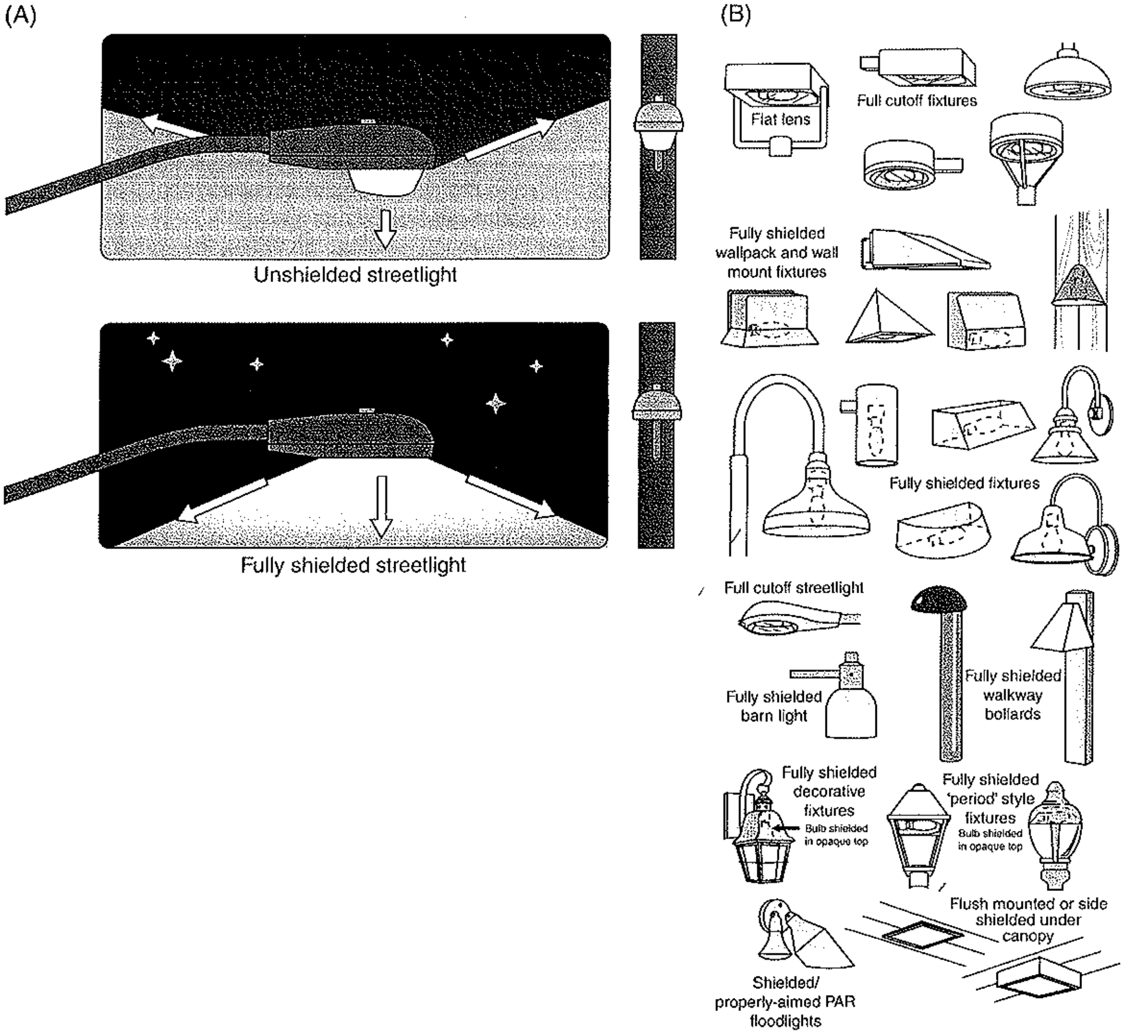

Figure 18.3 (A) Unshielded and shielded light showing light escaping. (B) Examples of fully shielded lamp fixtures intended for structures as well as road applications. Source: Reproduced with permission of R. Crelin (www.BobCrelin.com).

lighting on amphibians and reptiles includes species-specific considerations relative to light-fixture location, position above or in the road (i.e. road-embedded lighting), emission spectra and intensity, shielding (Fig. 18.3) and on/off schedules (Lessons 18.4, 18.5 and 18.6).

18.4 Light emitted varies relative to the type of lighting technology

Current options for selection of road lighting technology include standard high-intensity discharge sources (a lamp technology with emission from 550 to 650 nm; Rich & Longcore 2006; Fig. 18.2) and the more recently introduced solid-state light-emitting diodes (LEDs), often marketed as 'cool white' LEDs. Despite the name (associated with how humans perceive light from these devices), energy emitted by these LEDs commonly include wavelengths from 450 to 460 nm, thus falling into the blue range of the electromagnetic spectrum (IDA 2010; see also Gaston et al. 2012; Fig. 18.2). Advocates of these devices contend that they afford lower illumination levels because of the sensitivity of human rod cells to shorter wavelengths (IDA 2010; Falchi et al. 2011). However, caution is recommended when considering widespread use of this lighting.

Unnatural levels of exposure to wavelengths less than 500 nm can pose far greater deleterious effects on animals, including humans (e.g. disruption in circadian rhythms and metabolic function), than sources with emissions greater than 500 nm (IDA 2010; Falchi et al. 2011; Gaston et al. 2012).

In addition, lamp type also influences fixture temperature which, with emission spectra, contributes to insect attraction, as well as energy required for full illumination (Eisenbeis 2006). Attraction of invertebrate prey can influence foraging and imbalanced competition among bat species (Stone et al. 2012), as well as increased mortality to some insect species (Eisenbeis 2006).

18.5 Planning for road lighting must include zoning relative to light levels and light-fixture placement

Questions that should be asked during road planning include: What level of illumination is required, if any? How would planned lighting contribute to cumulative artificial light pollution within an ecosystem? What emission spectra would pose fewer direct negative consequences to species exposed to lighting? How might lighting indirectly affect animals by attracting and concentrating prey? How might light-fixture design, zoning and placement help reduce negative effects on organisms? Typically, recommended light-fixture type, area of effect and cumulative illumination by road lighting vary by human population density, level of human activity and the interspersion of protected natural areas.

The IDA/IES (2011) provides zoning guidance to balance illumination relative to the needs of people and ecosystems adjacent to the road, though guidance is not specific to biological light intensity. Within specified zones, and considering the type of site (e.g. road through residential or non-residential area), the IDA/IES recommends Total Initial Luminaire (TIL; lumens per site) and Maximum Allowable Backlight, Uplight and Glare (i.e. 'BUG') ratings. Essentially, each zone and associated TIL/BUG rating represents a broad approach to mitigating effects of light pollution. In addition, fixture orientation and shielding (also affecting the TIL/BUG rating) should limit upward incidental reflection or direct emission so as to reduce light escaping skywards (Fig. 18.3), which contributes to skyglow and attraction of insects or migrating birds (Eisenbeis 2006; Salmon 2006; Luginbuhl et al. 2009; Falchi et al. 2011; IDA/IES 2011). The IDA/IES (2011), in particular, provides a thorough summary of application type, fixture/lamp designs, associated metrics describing light properties and guidance on zoning and BUG ratings.

18.6 Mitigating the negative effects of road lighting requires research collaboration

Ultimately, effective mitigation of the effects of road lighting on ecosystems requires communication among road planners, lighting engineers and ecologists. An example of such collaboration is an advance in lighting technology that allows for complete elimination of traditional overhead road lighting where the intent is for driver orientation and not roadside illumination. Specifically, Bertolotti and Salmon (2005) and Salmon (2006) showed that road-embedded LEDs along Highway A1A in Boca Raton, Florida, United States, prevented stray light from reaching nearby beaches, thus reducing the nocturnal disorientation of dispersing sea turtle hatchlings. In addition, we suggest that future research in the development of lighting technology and application consider (i) light-fixture performance measured in terms of biologically relevant light intensity; (ii) lamp designs that are easily adaptable to wavelength and intensity requirements; and (iii) daily and seasonal scheduling for operation relative to the ecosystem affected.

CONCLUSIONS

Depending upon concerns for driver or pedestrian safety, an obvious solution to managing negative effects of road lighting in conservation areas is to avoid the use of road lighting altogether. However, where lighting is deemed necessary, it is also important to recognise that a 'one-size-fits-all' approach to road lighting will not minimise negative effects to ecosystems. Collaboration among planners, lighting engineers and ecologists will allow for the tailoring of lighting technology that maximises driver and pedestrian safety while reducing or eliminating the effects of artificial light on ecosystems. Where data on wavelength sensitivity of affected taxa are unavailable, we suggest that a conservative approach is to reference findings from taxonomically related species. These findings might include behavioural responses to biologically relevant measures of emission spectra or to light measured at levels of luminous flux (see Gaston et al. (2013)). Another option is to make conservative decisions on

lighting (e.g. avoiding emission spectra <500 nm; see Lesson 18.4). We also concur with Falchi et al. (2011) that where artificial lighting is necessary, these sources should (i) not release light directly at and above the horizontal; (ii) limit downward emission outside the area to which lighting is required; (iii) limit emission of short-wavelength spectra; (iv) be zoned and spaced to minimise unnecessary lighting; and (v) be operated via on/off scheduling where appropriate.

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FURTHER READING

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Forman et al. (2003): The first detailed and wide-ranging book on road ecology.

Gaston et al. (2013): Proposed a framework for consideration of how artificial lighting alters natural light regimens and influences biological systems.

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