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Reducing the ecological consequences of night-time light pollution: options and developments

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Summary

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.

Key-words: light pollution, lightscape, night-time, nocturnal, spectra, urbanization, vision

Introduction

Much concern has been expressed about the ecological consequences of growth in the distribution and density of electric lighting (Fig. 1; Longcore & Rich 2004; Rich & Longcore 2006; The Royal Commission on Environmental Pollution 2009; Hölker *et al.* 2010a). Globally light pollution is increasing rapidly (estimated at 6% per annum; Hölker *et al.* 2010b), both with marked regional expansion of electric lighting to previously unlit communities in the economically developing world, but also a greater density of lighting in many already heavily developed areas (e.g. Cinzano 2003; The Royal Commission on Environmental Pollution 2009). It takes several forms which, from an anthropocentric perspective, have been characterized as glare– undue brightness of a light source; over-illumination– lighting areas at levels beyond those at which human vision is able to differentiate; light clutter–

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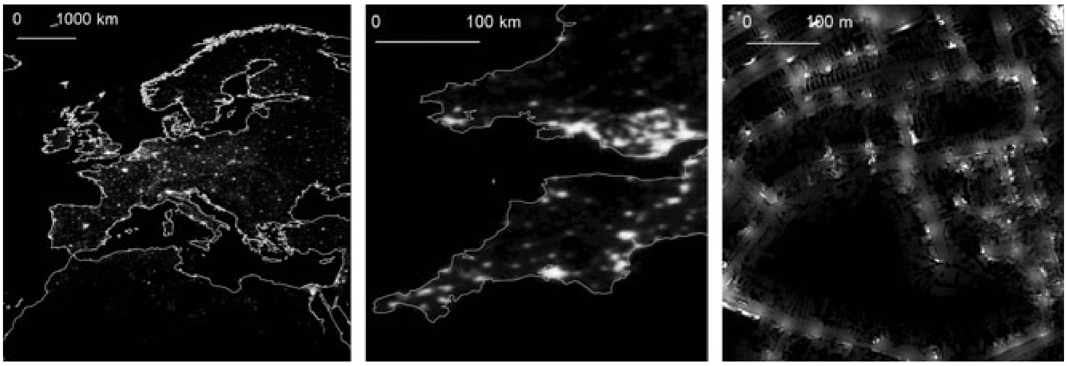

Fig. 1. Spatial heterogeneity in night-time lighting across (a) Europe, (b) south Wales and southwest England, and (c) a suburban area of Falmouth, England. Relative upwelling light intensity for (a) and (b) taken from satellite images for 2009 from the National Geophysical Data Center (USA; http://www.ngdc.noaa.gov/dmsp/downloadV4composites.html). Relative downwelling light intensity from street lighting for (c) was calculated using the locations of street lights, a 1-m resolution LiDAR digital surface model obtained from the Channel Coast Observatory (http://www.channelcoast.org/), and a shading algorithm assuming lights approximate point sources and intensity decays with distance according to the inverse-sine law, and validated using field measurements of light intensity.

excessive grouping of light sources; light trespass– unwanted direct lighting of an area; and skyglow– the increased night sky brightness that is produced by upwardly emitted and reflected electric light being scattered by water, dust and gas molecules in the atmosphere (The Royal Commission on Environmental Pollution 2009).

A wide variety of lighting devices contribute to night-time light pollution, including public street lighting, and light from advertising, architecture, domestic sources and vehicles. Of these, street lighting is a major concern and the focus of the majority of attention, as it is often the most persistent, aggregated and intense source of lighting in urban areas. Street lighting alone uses about 114 TWh of energy globally (International Energy Agency 2006). However, other sources of light, such as architectural, advertising and vehicle lights may be locally significant and have a disproportionate effect on the environment when they emit light horizontally.

The spatial pattern of light pollution is heterogeneous across scales (Fig. 1). In the vicinity of lit localities, skyglow extends the effects into otherwise unlit areas, particularly during periods of low cloud cover and when sources emit significant proportions of light at or above the horizontal, causing long path lengths through the atmosphere (Falchi *et al.* 2011). Conversely, vertical shading, creating discrete areas of darkness, occurs due to natural physiographic features such as hills and depressions; hedgerows, trees and other vegetation; and human-made structures such as quarries, walls and buildings. Horizontal shading occurs beneath vegetation canopies. Whilst most lighting devices are operated throughout the night, others are intermittent or operated for only parts thereof.

Recent decades have seen changes in the street lighting (and other lighting) technologies deployed, often with narrow spectrum light sources such as low-pressure sodium (LPS) and high-pressure sodium (HPS) lamps, which emit primarily yellow or amber light, being replaced with broader spectrum 'white' sources that enable better colour rendering for human vision (Table 1); although broad-spectrum fluorescent lighting has been used locally in street lighting since the 1930s. The development of central management systems (CMS) allows lighting operators to adjust times of operation remotely as required. Broader spectrum lighting technologies such as metal halide and light emitting diode (LED) lamps are becoming increasingly cost-effective to use, and the perceived amenity value of 'whiter' light is resulting in increasing numbers of these being introduced. Meanwhile, reductions in the duration and intensity of lighting, along with reducing the trespass of light into unwanted areas, are additional options currently being explored to cut street lighting costs, carbon emissions and light pollution. LED lamps are particularly suited to operating at variable brightness and/or being switched off at times of low demand, as they operate at full efficiency with no 'warm-up' time. One consequence of these changes is likely to be that in the future artificially lit environments will exhibit more complex patterns of spatial and temporal variation at both local and regional scales. This includes potentially ecologically significant heterogeneity in light intensity, duration and spectra.

Table 1. Selected major outdoor electrical lighting types, and some of their characteristics, based on data from Elvidge *et al.* (2010; see also Fig. 3). CCT – Correlated Colour Temperature (Kelvin) – colour appearance of light emitted by a lamp, with lower values being regarded as 'warm' and higher as 'cool' in appearance; CRI – Colour Rendering Index – ability of a lamp to reproduce colours compared with a natural source (assigned a value of 100); LE – Luminous Efficacy (dimensionless) – efficiency with which a lamp produces visible light. Values (and ranges) reflect representative examples of the different types

	CCT	CRI	LE
Low-pressure sodium	1807		87
High-pressure sodium	2005–2108	7–32	90–126
Fluorescent	2766–5193	5–82	61–92
Metal halide	2874–4160	64–100	62–100
Light emitting diodes	1739–8357	65–100	28–66

The key role of light in organismal biology raises the potential for significant impacts of night-time light pollution on the environment. Light is important to organisms as both an energy resource and an information source. As an energy resource, sunlight is the basis of photosynthesis in plants. Reflected light is used by animals with vision to infer a wide range of information from their surroundings. This includes many nocturnal animals that use moonlight and starlight to forage. Also as a source of information, patterns of light and darkness are used to regulate circadian cycles of activity; to control the behaviour and niche partitioning of diurnal, nocturnal and crepuscular animals; to determine daylength (and thus trigger seasonal phenological events such as bud burst, flowering and senescence); to infer the position of leaves within a canopy; and as a directional cue for navigation.

The extent to which artificial light influences any of these processes in an organism depends on several factors: the wavelengths of the light emitted with respect to the spectral sensitivity pigments and/or visual receptors (and in the case of vision, the spectral reflectance of objects of interest and of their background); the intensity of light that reaches the organism; and the directionality of light (e.g. direct radiation from a point source versus diffuse radiation from skyglow; polarized vs. non-polarized light). As organisms vary widely in their sensitivities to these properties of light (Land & Nilsson 2002), human perceptions are often an inadequate basis for an ecological understanding of the light environment.

Evidence exists of a wide diversity of ecological impacts of night-time light pollution (for reviews see Longcore & Rich 2004; Rich & Longcore 2006; Navara & Nelson 2007; Bruce-White & Shardlow 2011). These include influences on organismal movements (Peters & Verhoeven 1994; Moore *et al.* 2000; Lorne & Salmon 2007; Stone, Jones & Harris 2009), foraging (Rydell 1991; Buchanan 1993; Negro *et al.* 2000; Bird, Branch & Miller 2004; Santos *et al.* 2010), interspecific interactions (Svensson & Rydell 1998), communication (Baker & Richardson 2006; Miller 2006), reproduction (Boldogh, Dobrosi & Samu 2007) and mortality (Dick & Donaldson 1978; Peters & Verhoeven 1994; Le Corre *et al.* 2002; Black 2005). It is thus timely to consider the range of possible measures to prevent or reduce the ecological effects of night-time light pollution, current knowledge about their likely outcomes, and the research required to support favourable outcomes.

In this article, we explore five management options to reduce night-time light pollution. We examine their potential ecological benefits, adverse effects and their potential role in mitigation strategies. Several of these options are already being trialled for their cost- and energy-saving benefits. The five options are to (i) prevent areas from being artificially lit; (ii) limit the duration of lighting; (iii) reduce the trespass of lighting; (iv) change the intensity of lighting; and (v) change the spectrum of lighting.

Maintaining natural unlit areas

BACKGROUND

Arguably the simplest approach to managing night-time light pollution is to prevent areas from being lit in the first place, limit the installation of lighting devices or remove lighting devices where these are already in place. When carried out over very large areas, this will prevent or localize the problem of night-time light pollution, at least for those organisms that do not disperse or migrate over longer distances (and hence do not encounter light pollution elsewhere). However, diffuse illumination from artificial skyglow may remain an issue, even tens (and possibly hundreds) of kilometres from urban light sources.

The ecological consequences of excluding direct illumination from smaller areas will be strongly context dependent. Trespass of lighting can occur from beyond the boundaries of an unlit area (tending to penetrate a greater proportion of an area as the size of that area declines) and the effects of skyglow in illuminating areas where direct lighting is absent can be substantial, if at a much lower level than direct illumination. Nonetheless, towns and cities comprise heterogeneous lightscapes, with patches of low or no direct night-time lighting. This is particularly the case where natural structures, including vegetation, and artificial structures that cause shading are interspersed amongst more brightly lit areas (e.g. roads, buildings). Few studies have attempted to quantify the thresholds in terms of size of unlit area and light intensity below which an area is effectively unlit in ecological terms – indeed, these thresholds are likely to vary with the mobility and individual sensitivity of species. On the precautionary principle, it would seem sensible to maintain unlit areas of all sizes within the urban landscape wherever this is possible, whilst also determining just how important such dark refuges are, and their adequacy, for the maintenance of organisms in urban environments.

DEVELOPMENTS

At large spatial extents, the protection or creation of natural unlit areas has received most attention in the context of establishing International Dark Sky Places (including parks, reserves and communities; www.darksky.org/), with a particular goal of limiting skyglow, and preventing loss of visibility of stars and other celestial bodies. This is non-trivial, because globally many areas that are otherwise protected for the purposes of biological conservation still suffer from light pollution (Aubrecht, Jaiteh & de Sherbinin 2010). Indeed, monitoring programs have been put in place in US National Parks to determine the severity of the problem (e.g. National Park Service 2007).

On a more *ad hoc* basis, many protected areas have policies and regulations to limit the use of lighting devices within their bounds (e.g. see Hampshire County Council

2010). Artificial night-time lighting has also been excluded, or removed from, many smaller areas, usually with a view to addressing concerns with regard to individual species (or species groups). These include in the proximity of turtle nesting beaches to prevent the disorientation of hatchlings (Tuxbury & Salmon 2005), and on ships and oceanic islands to prevent bird strikes (Le Corre *et al.* 2002; Black 2005; de Villiers *et al.* 2005).

There is clearly potential for applying such an 'exclusion, reduction and removal' management approach much more widely. First, the proposed introduction of night-time light pollution to an area could become a routine component of Environmental Impact Assessments (Bruce-White & Shardlow 2011), and a consideration in decisions about whether and how developments should proceed, although a formal methodology for doing so is currently lacking. Second, a much more proactive approach could be developed to switching off or removing lighting devices, where they are no longer required, or never were. In addition to the ecological implications, there are obvious associated energy and carbon emissions savings, which has acted as a driver for switching off street lighting in a growing number of locations (Lockwood 2011). Worldwide, grid-based electric lighting has been estimated to account for 19% of electrical power production, the energy consumed to supply lighting to generate 1900 Mt.CO_2.annum, and annual lighting to cost $360 billion (including energy, equipment and labour; International Energy Agency 2006).

Bruce-White & Shardlow (2011) propose that particular targets for prevention, removal or reduction of lighting devices should include water bodies and areas of high conservation value (including those with species of conservation significance, and particularly where such species are known to be especially light sensitive). However, while the evidence base for the ecological effects of lighting is increasing for freshwater and marine habitats (Depledge, Godard-Codding & Bowen 2010; Perkin *et al.* 2011), and for a range of terrestrial organisms (Rich & Longcore 2006), to place such decisions on a firmer footing, a much better understanding is required of the relative vulnerability of different habitats and species to night-time light pollution, particularly outside the temperate northern hemisphere where the natural histories of species are typically more poorly studied.

Changing duration of lighting

BACKGROUND

In many areas, the complete or even partial removal of lighting devices may be neither practical nor desirable for reasons, whether real or perceived, of human use, comfort and safety (The Royal Commission on Environmental Pollution 2009). Ecological management considerations must then shift to how the form of night-time light pollution can be altered to reduce its potential impacts. The simplest option here is to change the period for which lighting occurs (so-called part-night lighting). In economically developed regions, night-time lighting tends to persist year-round between dusk and dawn. However, in less developed regions electric light switch offs may be more erratic, and/or from late at night until early morning, and associated with the availability of power or dependent on local generators.

The ecological consequences of changing the duration of night-time lighting are not well understood and constitute an important future research topic. However, given current knowledge, lighting could be switched off or dimmed during particularly critical times when biological activity is especially high or significant, such as when foraging, breeding or dispersal/migratory activities are occurring. Alongside more carefully tailored approaches (likely to be most relevant to particular species or species groups), the two obvious strategies are to switch off lighting during particular seasonal or nightly periods.

Seasonal changes in lighting strategy are most likely to be practical at mid- to high latitudes, where the need for artificial lighting in areas used primarily in evenings and mornings may be much reduced during the summer months with long hours of daylight. Conversely, in areas used during the night-time, demand for lighting may be higher in warmer summer evenings, and there may be opportunities for switching off during the colder winter months.

With regard to switching off during particular hours of the night, unfortunately it seems likely that those when lighting is most important to humans, the hours immediately after dusk and immediately before dawn, are also those at which it has the most significant impact on many other organisms. The majority of activity by nocturnal and crepuscular organisms tends to occur during these hours (e.g. Knight, Weiss & Weissling 1994; Svensson, Rydell & Brown 1999; Jetz, Steffen & Linsenmair 2003; Moser *et al.* 2004). Many species time the stages of their life cycle through the detection of daylength, including bud burst, flowering, dormancy and leaf abscission in plants, and reproduction, migration and diapause in animals, or require alternating light and darkness to maintain their circadian clock. Such physiological impacts may continue to be disrupted by light curfews, although this might be mitigated by lighting periodicity attuned to critical minimum periods of darkness for impacted taxa. As a general principle, steps toward reducing the duration of lighting seem likely to have positive or neutral ecological benefits.

In some limited circumstances, changing their duration on substantially shorter time-scales might usefully reduce the impacts of night-time lights. Thus, for example, it has been shown that avian collisions with communication towers tend to be much lower when using flashing than non-flashing (steady-burning) lights (Gehring, Kerlinger & Manville 2009).

DEVELOPMENTS

Reductions in the duration of night-time lighting seem likely to become increasingly widespread in regions with a developed lighting infrastructure as energy prices and concerns about carbon dioxide emissions increase. Energy costs and economic incentives are already driving a shift towards more energy efficient lighting, of which night-time switch offs are one option being explored. For example, in Devon, UK, many rural towns will have no lights on between the times of 00:30 and 05:30 (Devon County Council 2011), and such changes are becoming widespread (Lockwood 2011). Likewise, lighting is being switched off in the middle of the night on a growing number of motorways in the UK (Highways Agency 2011). Such part-night switch offs are, however, being evaluated with caution, due to concerns about (perceived and actual) rising crime levels and road traffic safety. The introduction of 'adaptive' lighting has also been much discussed, in which the occurrence and the level of light is determined in response to the movements of people and/or vehicles (e.g. E-Street 2007), or lighting may be requested for short periods by phone call, text message or via the internet, as in the town of Dörentrup in Germany. Such technology may become increasingly widespread. However, in economically developing regions, transition from non-electric lighting and small-scale generator-based or erratically available electric power to more reliable grid-based electricity supplies are likely to lead to marked increases in the duration of electric lighting unless similar technologies are made available at low cost.

Reducing trespass of lighting

BACKGROUND

Night-time light pollution is exacerbated by poor lighting design, installation and maintenance providing illumination outside the area of benefit. This results in light emitted in unnecessary or unwanted directions. Street lighting is usually required to illuminate the road surface and objects below the level of the light source, but poor lighting design can lead to significant proportions of light emitted upwards or at the horizontal. Commercial lighting (such as illuminated advertisements) and architectural lighting may be specifically designed to emit horizontal or vertical light, as do most emissions from road vehicles. Horizontal and near-horizontal light emittance increases the visibility of light sources from a distance, increasing the potential to disrupt animal navigation, and significantly increases the illuminated area, in turn increasing the encroachment of light into adjacent unlit areas. Moreover, due to the long path lengths of near-horizontal light through the atmosphere, light emitted in this direction produces more skyglow than that emitted upward, and much more than light emitted downward.

Changes in the wavelengths of light emitted in urban areas will also affect the intensity of, and area impacted by, skyglow. Due to increased atmospheric Rayleigh scattering at short wavelengths, blue-rich light sources produce more skyglow in the vicinity of light sources than an equivalent intensity of yellow-rich lighting, although beyond around 10 km from the light source this order is reversed and long wavelengths produce more skyglow (International Dark-Sky Association 2010; Falchi *et al.* 2011). While blue light is also critical for many other physiological processes, including melatonin suppression and control of the circadian clock in many species, specific ecological effects may be affected unequally by diffuse atmospheric light pollution at different wavelengths.

Reducing light trespass may not only reduce the ecological impacts of artificial light, but also has economic cost-saving benefits in that more focused lighting means a lower luminous flux is necessary to illuminate a given area to a required intensity. There is thus considerable potential to reduce ecological light pollution by reducing light trespass and upward or horizontally directed lighting, with little impact, and possibly improvement, on the functionality of lighting for human purposes. Construction of walls and other structures and planting of vegetation to shield sensitive areas against light, as well as replacing reflective surfaces with light absorbent ones, are further options for reduction of light trespass. The establishment of semi-natural barriers to artificial light (Salmon *et al.* 1995) and embedding of street lights in roads (Bertolotti & Salmon 2005) have been suggested as possible ways in which to mitigate against hatchling turtle disorientation on beaches in close proximity to road lighting. Greater use, and more efficient design, of light-focusing reflectors can also help to direct light where it is required.

DEVELOPMENTS

In economically developing regions, particularly the Newly Industrialized Countries (NICs) including China and India, electric lighting is likely to continue to increase in extent, significantly increasing the incursion of artificial light into previously unlit areas. However, in both currently lit and unlit areas, greater attention seems likely to be paid in coming years to reducing light trespass on the grounds that it represents a costly loss of lighting to areas in which it is not wanted. This will require changes in the design of the luminaires that physically house lamps and serve to distribute, direct and diffuse lighting. Different designs can vary dramatically in these regards (International Energy Agency 2006).

In an ecological context, changes in luminaires have particularly been championed in situations in which light trespass causes problems for given species of conservation concern (e.g. Reed, Sincock & Hailman 1985; Le Corre *et al.* 2002; Raine *et al.* 2007). Narrowing of light beams has also been proposed as one potentially valuable measure for reducing bird strikes at lighthouses (Jones & Francis 2003).

Changing intensity of lighting

BACKGROUND

Night-time lighting devices have been designed to facilitate human activities, usually with little or no consideration for other impacts (and often not optimized even for human use). There is thus considerable potential for modifying the lighting that they produce to provide a better compromise. Arguably the simplest way in which this could be carried out would be to reduce the intensity of night-time lighting. In the absence of artificial light, full moonlight under clear skies gives an illumination of *c.* 0·1–0·3 lux, a clear starry sky *c.* 0·001 lux, and an overcast night sky *c.* 0·00003–0·0001 lux (Rich & Longcore 2006). Typical incandescent, fluorescent or high-intensity discharge (HID) street lighting gives rise to street-level illumination of between 10 and 60 lux, with intensity steeply declining with distance to the light source (Fig. 2a). This produces a highly heterogeneous light environment, in which the roadside is characterized by steep gradients in light intensity. With careful planning, the development of directional LED lighting has the potential to provide a much more uniform, intermediate level of illumination (Fig. 2b). However, while peak light levels are much lower directly beneath these lamps, there is a loss of dark refuges between street lights (Fig. 2). The potential importance of such dark patches between lights, for example, in allowing light-avoiding animals to cross linear lit features such as roads or footpaths, has not been well studied.

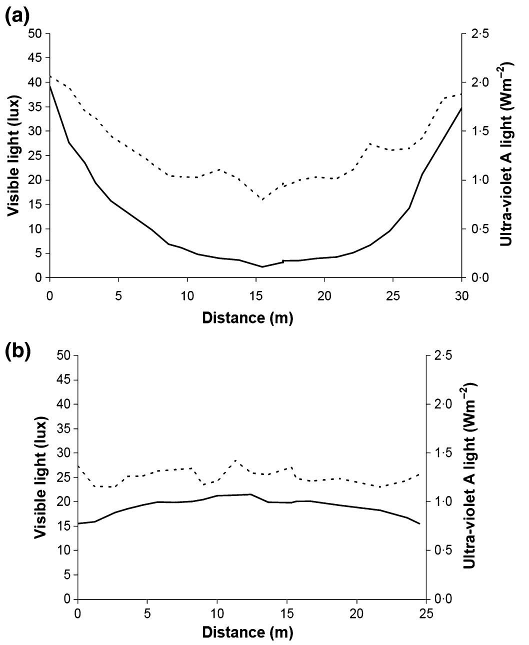

Fig. 2. Variation in visible (lux; solid line) and ultra-violet (UVA; dashed line) light flux measured in the horizontal plane at ground level in grassy road verges lit by two contrasting street lighting designs – (a) Metal Halide lamps (8 m high and 30 m between lamps) and (b) directional light emitting diode lamps (10 m high and 25 m between lamps).

Artificial night-time lighting has been shown to have ecological effects across a wide range of intensities. For example, flowering has been observed to be delayed and promoted, and vegetative growth enhanced amongst a wide range of ornamental plant species at *c.* 10 lux (Cathey & Campbell 1975a,b) and earlier initiation of morning song by American robins *Turdus migratorius* at <4 lux (Miller 2006). The benefit of reducing light intensity for the ecology of animals in the local environment rests largely on their sensitivity to light (and that of the species with which they interact), and this is dependent to a marked extent (although not exclusively) on the design of their eye, and its size. For example, insects that possess refracting superposition compound eyes can, in general, see better in lower light than can those with focal apposition eyes (Table 2).

Table 2 indicates that human vision can be up to four orders of magnitude less sensitive than that of other species in the environment. Human vision, particularly foveal colour vision, is one of the least sensitive (but most accurate) visual systems known amongst animals (Land & Nilsson 2002). Conversely, many nocturnal animals have visual systems designed to operate at light levels at which humans rely on less accurate, monochromatic rod vision, and even this system is poorly effective in comparison with many species active in low light conditions (Table 2). For example, the hawkmoth *Deiliphila elpenor* can discriminate colour, including UV, at light levels equivalent to starlight intensity, and the nocturnal gecko *Tarentola chezaliae* can discriminate colour at levels equivalent to dim moonlight (Kelber & Roth 2006). Dimming artificial light within the range at which humans can still retain sufficient visual acuity is unlikely to eliminate any effect on the vision of nocturnal animals. However, reducing light intensities will decrease the areas affected by light trespass, including edge effects on dark refuges in urban areas. In addition, reducing intensities will reduce the impact of street lighting on skyglow.

DEVELOPMENTS

The option of dimming lights in areas (e.g. alongside roads) that are less heavily used has been actively discussed and implemented in some regions (e.g. Gloucestershire County Council 2011; Leicester County Council 2011). However, this may often require a switch in the form of lighting technology that is being employed (International Energy Agency 2006). LPS lighting, while relatively energy efficient, operates most efficiently when illuminated at high levels throughout the entire period of darkness (The Royal Commission on Environmental Pollution 2009). Reducing the intensity or duration of light while maintaining adequate conditions for human vision may only be possible where a switch to LED or other solid-state lighting has occurred.

Table 2. The sensitivity (*S*) of animal eyes compared to light habitat and eye type. Compiled from tables in Land & Nilsson (2002), Somanathan *et al.* (2009) and Warrant (2006)

Species	Common name	Light habitat*	Eye design†	Sensitivity (μm^2 sr)	References
Dinopsis sp.	Spider	LLA	Cam	101	Blest & Land (1977)
Onitis aygulus	Dung beetle	LLA	Sup	58·9	McIntyre & Caveney (1998)
Ephestia sp.	Moth	LLA	Sup	38·4	Cleary, Deichsel & Kunze (1977)
Macroglossum sp.	Hawkmoth	HLA	Sup	37·9	Warrant, Bartsch & Nther (1999)
Homo sapiens (scotopic)	Man	LLA	Cam	18	Land (1981)
Bufo sp.	Toad	HLA	Cam	4	Warrant & Nilsson (1998)
Megalopta sp.	Sweat Bee	LLA	App	2·7	Greiner, Ribi & Warrant (2004)
Onitis belial	Dung beetle	HLA	Sup	1·9	McIntyre & Caveney (1998)
Onitis ion	Dung beetle	HLA	Sup	0·35	McIntyre & Caveney (1998)
Apis dorsata	Honey Bee	LLA	App	0·21	Somanathan *et al.* (2009)
Apis mellifera	Honey Bee	HLA	App	0·11	Greiner, Ribi & Warrant (2004)
Apis cerana	Honey Bee	HLA	App	0·07	Somanathan *et al.* (2009)
Phiddipus sp.	Spider	HLA	Cam	0·038	Land (1969)
Apis florea	Honey Bee	HLA	App	0·03	Somanathan *et al.* (2009)
Homo sapiens (photopic)	Man	HLA	Cam	0·01	Land (1981)

*Light habit is classified as either High Light Active (HLA) (i.e. diurnal species) or Low Light Active (LLA) (i.e. nocturnal and crepuscular species).
†Eye design is classified as either CAM (Camera Eye), Sup (Superposition Eye) or App (Apposition Eye).

Changing spectrum of lighting

BACKGROUND

Intensity is obviously only one important component of night-time light pollution; another is its spectral composition. Different lighting systems can give rise to an artificial light environment with contrasting spectral properties. Lamps producing light through heat (e.g. incandescent, quartz halogen) emit with peaks in the near infrared and higher in the red than green and blue. Gas discharge lamps (fluorescent, metal halide, high- and LPS) emit different series of narrow emission lines, while LEDs typically have one or more symmetrical emission curves with the peak varying greatly amongst models (Fig. 3; Elvidge *et al.* 2010). Changing the prevailing lighting types can thus influence the spectral composition of night-time light pollution and hence its ecological consequences; the spectral quality of light can be further altered by the use of filters incorporated into lighting design.

Changes in the spectral properties of night-time lighting could potentially have important ramifications for organism behaviour, species interactions and consequently community structure. This is because species differ in the wavelengths to which their visual systems are most sensitive and responsive (Peitsch *et al.* 1992; Briscoe & Chittka 2001), and organism behaviour can be dependent on the presence of certain wavelengths of light (Brunton & Majerus 1995; Hunt *et al.* 2001; Paul & Gwynn-Jones 2003; Lim & Li 2006a,b). For example, the jumping spider *Cupiennius salei* possesses trichomatic colour vision with receptor sensitivity maxima in the UV, green and blue (Walla, Barth & Eguchi 1996).

Spectral composition is also critical for a range of physiological mechanisms that control the light responses of plants and animals. In plants, the phytochrome system is sensitive to the ratio of red to far-red light (with peak absorbances at 660 and 720 nm respectively), while phototropins in plants and cryptochromes in plants and animals have peak absorbances in the blue and ultraviolet portion of the spectrum (Cashmore *et al.* 1999; Smith 2000). These pigments are involved in detecting daylength (photoperiodism) and constraining the circadian clock in a broad range of organisms.

Light sources with different spectral properties could have widely contrasting effects on different groups of organisms. Lighting technologies that emit a narrow spectrum of light, such as LPS lighting, are likely to have less ecological impact compared with broader spectrum or 'whiter' light sources (LEDs and metal halide lamps). In Fig. 3, the narrow spectrum of LPS lights corresponds only with the visual pigment absorbance curves of long wave photoreceptors. However, light sources that emit broader spectra overlap with the absorbance range of more visual pigments, which enables organisms to perceive a greater range of the colours in their environment. The selection of locations for nesting by both loggerhead *Caretta caretta* and green *Chelonia mydas* sea turtles was significantly reduced when these were lit using white mercury-vapour lamps, but not affected by narrow spectrum LPS lamps (Witherington 1992). Many animals possess a peak sensitivity maximum in the UV (Tovée 1995; Briscoe & Chittka 2001) and evidence from reflectance and behavioural studies suggests that this is important for flower recognition in pollinators (Chittka *et al.* 1994), sexual recognition in spiders (Lim & Li 2006a,b), mate selection in butterflies (Brunton & Majerus 1995), mate choice and foraging behaviour in birds (Hunt *et al.* 1999, 2001; Cuthill *et al.* 2000), prey location in owlflies (Kral 2002) and navigation in a number of arthropods and birds (Philipsborn & Labhart 1990; Bennett & Cuthill 1994; Dacke *et al.* 2003; Barta & Horváth 2004; Mappes &

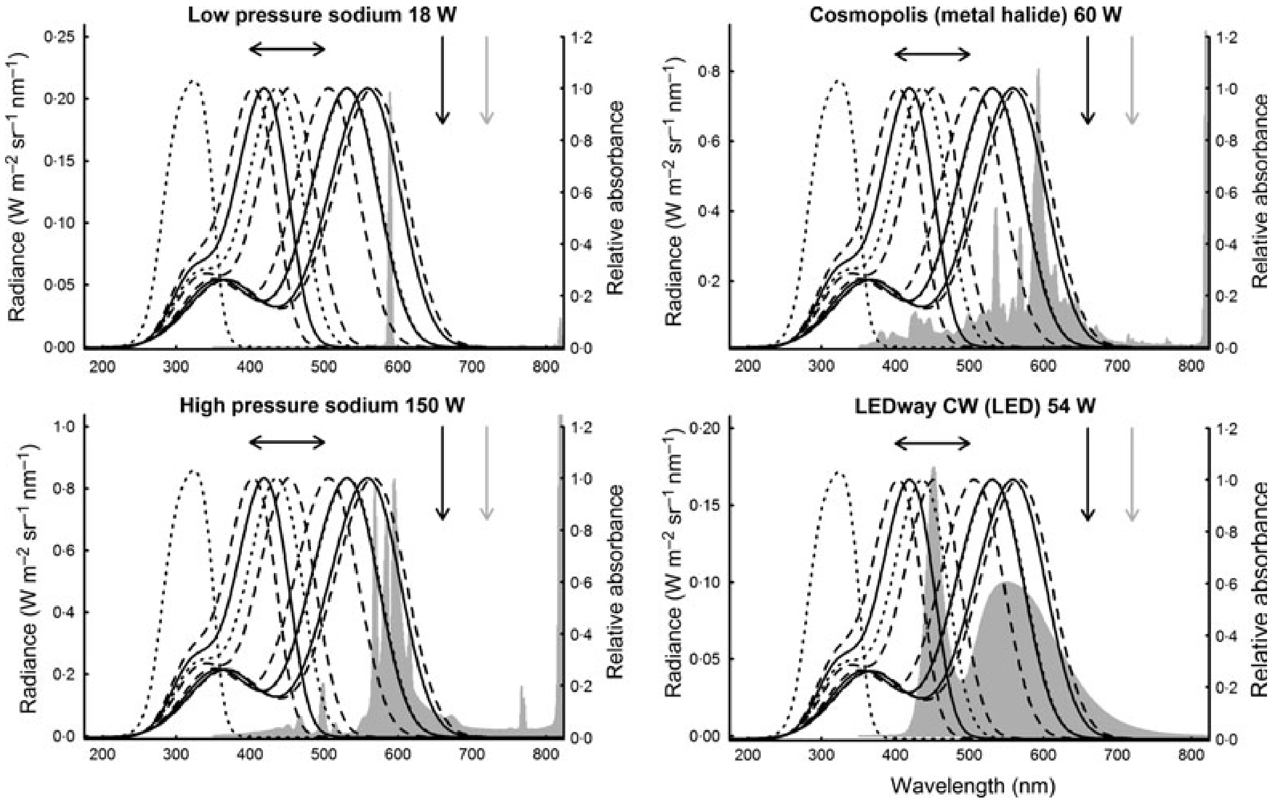

Fig. 3. The visual pigment absorbance curves of three animals compared to four potential street lighting technologies. The emission spectra of lights (Radiance) are presented in grey. Visual pigment absorbance curves are presented in black: solid lines – humans *Homo sapiens*, dashed lines – rock pigeon *Columba livia*, dotted lines – European honey bee *Apis mellifera*. Absorbance curves were calculated using the alpha and beta band A1 visual pigment templates of Govardovskii *et al.* (2000) using previously published pigment sensitivity maxima (λ_{max}) from Dartnall, Bowmaker & Mollon (1983; humans), Bowmaker *et al.* (1997; pigeons) and Peitsch *et al.* (1992; honey bees). Vertical arrows represent the absorbance peaks of phytochrome a (black) and b (grey) in plants. Horizontal arrows represent the absorbance range of cryptochrome in plants and animals. Light spectra were obtained from http://www.ngdc.noaa.gov/dmsp/nightsat.html (see Elvidge *et al.* 2010).

Homberg 2004). For example, moths are attracted to lights that emit wavelengths that correspond with the peak sensitivities of their visual systems (Cowan & Gries 2009), and light of shorter wavelengths (i.e. UV) can attract more individuals, species and larger individuals compared to longer wavelengths of light (Wallner *et al.* 1995; van Langevelde *et al.* 2011).

DEVELOPMENTS

There are likely to be substantial shifts in the composition of the global lighting stock in coming years, again predominantly associated with drives towards greater energy efficiency. If recent trends continue in the developed world, there is likely to be a widespread shift towards whiter light sources that provide superior colour rendering for human vision, such as metal halide and LED (The Royal Commission on Environmental Pollution 2009; Williams 2009). These changes are often perceived to improve public safety through crime and road traffic accident reduction, although the evidence behind such claims is debated (Marchant 2004). It can be assumed that the introduction of lighting with better colour rendering for human vision is also likely to increase the impact on the visual systems of other organisms at night, and the probability of interference with physiological systems sensitive to light at specific wavelengths (e.g. red/far-red sensitivity of phytochrome system in plants; blue sensitivity of pineal melatonin production). Striking the correct balance between energy efficiency, socio-political benefit and organism ecology is thus essential. Where such compromises are required this could potentially be achieved by retaining LPS lamps in ecologically sensitive areas, or by ensuring that white lights that minimise impact on organism ecology are selected where such sources are to be used. For example, metal halide lamps emit more in the UV than LEDs, increasing the potential for them to affect insects and birds that utilize this region of the light spectrum. Current white LED street lighting technologies use a yellow phosphor coating to convert light from a monochromatic blue to broad-spectrum lighting, but there is potential for the future development of LED lights that create white light with good colour rendition by mixing coloured light from three or more monochromatic LED sources (Schubert & Kim 2005). Technological challenges limit the current use of such combined monochromatic

Table 3. Proposed impacts of different options for changing artificial night-time lighting, relative to recent practice

Option	Biodiversity impact	Cost and carbon saving impact	Human security and amenity	Dark skies impact
Maintain natural unlit areas	0	0	0	0
Remove lighting to extend natural unlit areas	+	+	0/-	+
Reduce duration of lighting	0/+	+	0/-	+
Reduce trespass of light	+	+	+/0	+
Reduce intensity of light	+	+	+/0/-	+
Broaden spectrum of light	-	+	+	-

0: no change; +: positive impact; −: negative impact.

LED lighting for street lighting, but if overcome, this could give a high degree of control over the wavelengths emitted, and allow critical regions of the spectrum to be avoided. Understanding the ecological consequences of the increasing shift towards a 'white light night' in urban environments requires an understanding of the potential impact of these and possibly other light sources.

Conclusion

The artificial lightscape will change considerably over coming decades with the drive for more cost-effective low-carbon street lighting solutions and likely growth in the artificially lit area. Balancing the benefits of energy saving and carbon emissions reduction against the potential ecological consequences of changing lighting strategy and developing lighting strategies for newly lit areas that minimize ecological impact constitute significant future challenges (Table 3). In this review, we have identified several broad options that may be adopted by planners and lighting engineers to mitigate adverse ecological effects of light pollution, which often have clear additional benefits in terms of energy consumption, carbon emissions and aesthetics. From both aesthetic and ecological perspectives, maintaining and increasing natural unlit areas is likely to be the most effective change. However, this approach will often conflict with other social and economic objectives. Limiting the duration of lighting during the night is one way to reduce energy costs; however, it may have a limited effect on ecological processes, as peak times of demand coincide with the peak activities of many nocturnal and crepuscular animals, and even short periods of light during the night may be sufficient to disrupt circadian clocks and photoperiodism. However, flexible control systems, including on-demand street lighting, may be useful tools for mitigating ecological impacts of light by providing dark periods sufficient for normal ecological function. Reducing the trespass of lighting into areas in which it is not required is likely to provide valuable cost benefits, and help maintain heterogeneity of lighting even in otherwise well-lit areas, thus providing a dark resource that mobile animals can exploit. Reducing the intensity of lighting where possible will reduce energy consumption and carbon emissions and may help to localize the ecological effects of light pollution by reducing the trespass of direct and reflected light into unlit areas and reducing skyglow. The switch away from sodium lighting to 'whiter' light technologies is likely to have adverse effects on the environment by increasing the spectral range over which impacts occur, and increasing skyglow in the vicinity of urban areas due to greater Rayleigh scattering at short wavelengths. However, technological developments in LED lighting also present significant opportunities for greater control of the light environment in terms of the wavelengths emitted, as well as their timing and intensity in the future – if coupled with an enhanced understanding of the ecological impacts of light pollution, there is considerable potential to mitigate against many adverse effects.

The success of planners in successfully reducing the ecological impacts of light pollution will ultimately depend on matching the options outlined above with an assessment of the critical mechanisms and thresholds that determine those impacts in a particular environment. To date, however, ecological research on the impact of artificial light has been disparate and leaves many important questions unanswered. We suggest future research should aim primarily to support methodologies for environmental impact assessment of artificial light. To do this, we need better understanding of the intensity, spectra and periodicity of artificial light, along with tools that allow us to model lighting options. Equally importantly, we need more systematic ecological research that can interpret the impact of such complex potential variation in lighting options on organisms. Wherever possible, studies on the ecological effects of light pollution should seek to identify critical wavelengths, and thresholds in terms of timing and duration (season and lit period during the night) and spatial extent, that trigger effects. Finally, tools are needed for better interpreting the social and economic requirements for artificial light at night, so these are addressed at minimum ecological cost.

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