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REVIEW

Benefits and costs of artificial nighttime lighting of the environment

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Abstract: Artificial lighting has transformed the outdoor nighttime environment over large areas, modifying natural cycles of light in terms of timing, wavelength, and distribution. This has had widespread benefits and costs to humankind, impacting on health and wellbeing, vehicle accidents, crime, energy consumption and carbon emissions, aesthetics, and wildlife and ecosystems. Here, we review these effects, particularly in the context of ongoing developments in the extent of artificial lighting and in the prevalent technologies being employed. The key issue that emerges is how best to maximize the benefits of artificial nighttime lighting whilst limiting the costs. To do so, three main strategies are required. First, important knowledge gaps need to be filled. Second, there is an urgent need to connect the research being conducted in different disciplines, which to date has been very disjointed. Third, it is imperative that much firmer and well-developed links are made between research, policy, and practice.

Key words: accidents, aesthetics, crime, ecosystems, health, light pollution, lighting, night, sky glow, wellbeing.

Résumé : L'éclairage artificiel a transformé l'environnement nocturne extérieur sur de grandes superficies, modifiant les cycles naturels de la lumière en terme de temps, de longueurs d'ondes et de distribution. Ceci s'est traduit par des coûts et bénéfices largement étendus pour l'humanité, affectant la santé et le bien-être, les accidents d'automobile, le crime, la consommation d'énergie et les émissions de carbones, l'esthétique ainsi que la faune et les écosystèmes. Les auteurs passent en revue ces effets, particulièrement dans le contexte de développement continu dans l'extension de l'éclairage artificiel et dans les technologies dominantes mises en oeuvre. La problématique clé qui en émerge consiste à savoir comment maximiser le mieux possible les bénéfices de l'éclairage nocturne artificiel tout en limitant les coûts. Pour atteindre cet objectif, trois stratégies principales s'imposent. Il faut d'abord combler des déficiences de connaissances. Deuxièmement, il existe un urgent besoin d'intégrer les travaux de recherche conduits dans diverses disciplines, lesquels ont été conduits de façon disparate jusqu'ici. Et troisièmement, il est impératif que des liens beaucoup plus solides et mieux développés se développent entre la recherche, les politiques et la pratique. [Traduit par la Redaction]

Mots-clés : accidents, esthétique, crime, écosystèmes, santé, pollution lumineuse, éclairage, nuit, luminosité nocturne, bien-être.

1. Introduction

Humans have dramatically transformed the outdoor nighttime light environment. The introduction of artificial lighting, and particularly electric lighting, has disrupted natural cycles of light and darkness that had previously been rather consistent over long periods of geological and evolutionary time. This disruption, which derives from public and private lighting sources (Fig. 1; including street lighting, advertising lighting, architectural lighting, security lighting, domestic lighting, and vehicle lighting) has a number of distinct components. First, it has introduced light sources at intensities that are substantially brighter than, or comparable to, those from natural nocturnal sources of nighttime light. A full moon on a cloudless night gives illuminance of the order of 0.1 lx, and on a moonless overcast night this reduces to about 0.0001 lx (Rich and Longcore 2006*a*). By contrast, direct lighting immediately under street lamps is commonly of the order of 10–40 lx (and substantially higher for some other sources), and remains above 1 lx several meters away, and sky glow (artificial light scattered in the lower atmosphere) under cloudy conditions in urban areas has alone been shown to be of an equivalent or greater magnitude than high-elevation summer moonlight (Kyba et al. 2011). Globally, there are more than 100 million street lights (International Energy Agency 2006), and already by the end of the last century around 23% of the land surface area of the United States, 37% of the European Union, and 5% of the world regularly experienced sky glow greater than that naturally expected (Cinzano et al. 2001).

Second, artificial sources have changed the spectrum of lighting compared with natural nighttime sources, with signatures that differ from those of direct and diffuse sunlight, twilight, and moonlight. For example, in the UK early electric street lighting relied on incandescent bulbs that emit primarily in yellow wavelengths, in the 1960s and 1970s low-pressure sodium lighting was widely adopted that emits a single narrow peak in the visible spectrum at 589.3 nm, and more recent technologies often emit over a broad range of wavelengths (high-pressure sodium lighting emits a yellow light allowing some colour discrimination; high intensity discharge lamps emit a whiter light, with significant peaks in blue and ultra-violet wavelengths; and LED-based white street lighting typically emits at all wavelengths between around 400 and 700 nm, with peaks in the blue and green; Elvidge et al. 2010). Such changes influence not only the spectra of direct lighting but also that of sky glow (Kyba et al. 2012; Luginbuhl et al. 2014).

Third, artificial sources have introduced pulsing or flickering light at frequencies (typically >100 Hz) that had previously been scarce, and much higher and acting over much wider areas than those of typical natural sources, such as wildfires and canopy sunflecks. Dependent on the controlling mechanisms, many lighting

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Fig. 1. Examples of artificial lighting at night. (*a*) Aesthetic lighting of buildings, Prague, Czech Republic; (*b*) city centre lights of Brisbane, Australia; (*c*) lights of the city of Plymouth, UK; (*d*) car park lighting, St Ives, UK; (*e*) beach-side lighting St Ives, UK; and (*f*) ships' lights in Falmouth Bay, UK. Photographs by J. Duffy and K.J. Gaston.

types can flicker at a rate that is a function of the frequency of the electrical source (Alliance for Solid-State Illumination Systems and Technologies 2012). Consciously imperceptible to the human vision system, although under some circumstances nonetheless capable of eliciting biological responses (e.g., Berman et al. 1991; Burns et al. 1992), this can be detected by the vision systems of a diversity of other organisms (Woo et al. 2009; Inger et al. 2014).

The present global artificial nighttime lighting pattern is produced by the interaction between topography, the distributions of built structures and vegetation, and a complex mosaic of lighting systems, giving rise to spatially and temporally heterogeneous patterns of emissions, in terms of their intensity, spectra, and flicker (e.g., Cinzano et al. 2001; Gaston et al. 2012, 2013; Hale et al. 2013; Small and Elvidge 2013). The situation has become especially dynamic in recent years, with reductions in nighttime lighting being undertaken in some developed regions to lower energy costs, and expansions in lighting in other developed regions, as well as many developing ones. These have been accompanied by widespread changes in lighting technologies, including changes to provision of whiter lights, and centrally managed lighting systems, and projects to introduce solar powered lighting to remote rural areas. Overall, however, existing lighting systems are often poorly designed and installed, in terms both of fulfilling human needs and limiting negative environmental impacts. This gives much scope for improvements in these regards, and the potential for policy and implementation that provide clear win-wins (Gaston 2013).

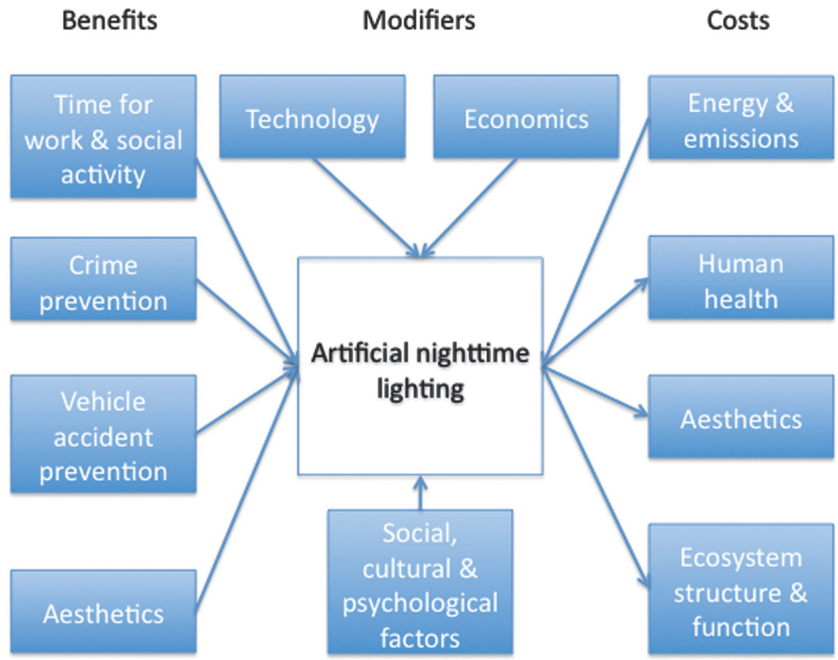
Here, we review the benefits and costs of anthropogenic changes to the nighttime light environment (Fig. 2), particularly in the context of ongoing developments in the extent of artificial lighting and in the prevalent technologies being employed. We focus in turn on the impacts on six issues, namely (*i*) human health and wellbeing; (*ii*) vehicle accidents; (*iii*) crime; (*iv*) energy consumption and carbon emissions; (*v*) aesthetics; and (*vi*) ecosystem structure. In each case, where relevant, we consider the separate effects of light intensity, light spectra, and light flicker. Following extensive searches, we draw on a wide range of published material, including peer-reviewed papers and governmental and non-governmental reports.

2. Human health and wellbeing

Foremost, artificial nighttime lighting has been introduced to areas to extend the period of any given day that is usable for a wide array of otherwise diurnally restricted human activities (we will highlight other purposes of lighting later). This doubtless has profound benefits for human wellbeing in increasing opportunities for economically productive activity, leisure and recreational activities, and social interaction and cohesion. However, whilst commonly asserted, robust empirical evidence demonstrating that this is actually the case, and under what circumstances, is largely wanting (Jakle 2001; Mills 2005; Koslofsky 2011). Clear opportunities to address this knowledge gap exist with ongoing schemes to introduce artificial nighttime lighting to communities in the developing world that have previously lacked such infrastructure.

Artificial light has also been used as a treatment in a variety of medical contexts, although given the high intensities typically involved (>2000 lx) whether there are implications here for understanding the consequences of more typical patterns of outdoor nighttime light exposure remain unclear. For example, light has been employed (often during the daytime) to treat seasonal affective disorder, depression in women with pre-menstrual disorder (Parry and Newton 2001), to regulate menstrual cycles (Lin et al. 1990), and to improve activity levels of patients with dementia (Holman 2010) by manipulating the onset of melatonin production.

Fig. 2. The benefits and costs of artificial nighttime lighting.



Less tangible is an apparent sense of wellbeing humans may instinctively feel in lit environments, even where their physical wellbeing may be unaffected or harmed, possibly a response evolved due to increased predation risk in dark areas in naturally lit environments (Packer et al. 2011). This apparently irrational response in developed societies is likely to frustrate implementation of more rational lighting policies.

Although widely discussed, the negative impacts of the introduction of artificial nighttime lighting on human health remain to be fully understood (but see Navara and Nelson 2007; Erren and Reiter 2009; Boyce 2010; Fonken and Nelson 2011). However, there is growing evidence that these impacts may be substantial and quite pervasive, foremost because of the effects of exposure to artificial light at night on melatonin suppression, and its downstream consequences (Lewy 1983; Zeitzer et al. 2000). A recent EU report reviewing the health implications of artificial light concluded that ill-timed exposure to light at night may be associated with an increased risk of breast cancer and gastrointestinal and cardiovascular disorders (Scientific Committee on Emerging and Newly Identified Health Risks 2012), and the WHO has identified shift work as a possible carcinogen because of chronobiological disruption (Straif et al. 2007). The effects were not linked to a particular lighting technology but due directly or indirectly to artificial nighttime light itself. Studies have variously documented geographic and chronological covariance between patterns of nighttime lighting and the incidence of breast cancer and obesity (Kloog et al. 2010; Wyse et al. 2011; Bauer et al. 2013). In the case of obesity, researchers concluded that chronic circadian desynchrony, defined as small daily changes in the 24 h light:dark cycle as induced by electric lighting, are associated with increasing weight gain and metabolic disorders such as diabetes in both experimental animals and in shift workers (Wyse et al. 2011).

Of course, correlation is not causation and patterns of electric lighting are typically closely associated with many other environmental changes that accompany the urbanization process (Gaston 2010). This said, there are mechanistic reasons to anticipate links between artificial nighttime lighting and human health. First, even brief exposure to nighttime lighting has been shown to influence patterns of melatonin production in humans (O'Leary et al. 2006; Chang et al. 2012), and more prolonged exposure to low intensity lighting has been found, or is strongly implied, to do so in other organisms (e.g., Cos et al. 2006; Evans et al. 2007; Bedrosian et al. 2011*a*, 2011*b*). Exposure to room light (<200 lx) before bedtime has been shown to have a profound suppressive effect on melatonin levels in humans and to shorten the body's internal representation of biological night, with the delay of melatonin onset but not offset reducing the duration of melatonin production by more than an hour (Gooley et al. 2011). It is currently unclear whether very low-level light can have a meaningful impact on nighttime melatonin production in humans as few studies have been undertaken and these are preliminary in nature (Hébert et al. 2002; O'Leary et al. 2006), but given the documented impact on other organisms more experimental studies to investigate this potential effect should be undertaken (Stevens 2009). That humans are sensitive to even short-term changes in light exposure is, however, clear and manipulating light exposure even for a short time (by one week in an experimental setting) can cause changes in melatonin production (Hébert et al. 2002).

Second, disruption of melatonin production has been shown to be associated with the development of cancer. Tests in vitro have demonstrated that melatonin has antioxidant properties, including "scavenging" free radicals that may be implicated in the development of cancer cells, and it has also been shown to enhance immune responses that may have protective features (Scientific Committee on Energy and Newly Identified Health Risks 2012). The disruption of the circadian rhythms that result from ill-timed exposure to light at night are directly implicated in the suppression of melatonin production (Gooley et al. 2011) and thus the loss of these beneficial effects. In relation to the influence of melatonin on breast cancer in humans it has been shown that in addition to the loss of the protective features associated with melatonin, the suppression of the hormone leads to increasing levels of oestrogen, which is a risk factor in developing this type of cancer (Cohen et al. 1978). The alteration of clock gene functioning is also believed to lead to negative effects on cell cycle regulation in mammary tissue (Sahar and Sassone-Corsi 2007). Shift workers have been documented as having the greatest exposure to ill-timed light at night, and this has led to the conclusion that shift work with its attendant circadian disruption is probably carcinogenic to humans (Kubo et al. 2006; IARC 2010).

Some attention has been paid to the human health implications of artificial nighttime lighting of different spectra. Light at shorter wavelengths of the visible range (blue) is more effective in suppressing melatonin (Duffy and Wright 2005; Falchi et al. 2011; Aubé et al. 2013; Wahnschaffe et al. 2013). Exposure to light of 40 lx at 6500 K (termed cold light) for 2 h in the evening induced melatonin suppression and enhanced subjective alertness, suggesting that sensitivity in cognitive response is blue-shifted relative to the three cone visual photopic system (Chellappa et al. 2011). It has also been shown that moderate exposures (5 h) at 100 lx with a relatively high amount of short wavelength LED light can evoke circadian, melatonin, and behavioural changes (as measured in alertness levels and cognitive performance; Cajochen et al. 2011). Although in some circumstances increased alertness may be of benefit, exposure to such light in late evening and at night will compromise human sleep patterns and circadian timing. Amongst healthy subjects exposure to blue light evokes a stronger emotional response to vocal stimuli relative to green light (Vanderwalle et al. 2010), indicating a general human emotional response to light spectral composition.

Finally, human health effects have been demonstrated caused by the flickering of artificial lights. These include headaches, seizures, and a variety of neurological impacts (IEE 2010). It is also possible that there is a link between exposure to flicker from fluorescent lighting and increased anxiety symptoms in patients with agoraphobia (Hazell and Wilkins 1990). Such research is, however, largely based on exposure to artificial light during the day and in particular fluorescent lighting in work-based environments such as classrooms (Winterbottom and Wilkins 2009). It is unlikely, for example, that the typically much briefer exposure to flicker from street lighting as encountered by most people could produce these neurological effects. Nonetheless, with an increasing switch to the use of LED technology in street lighting (which has increased potential for flicker in some instances, when phase-width modulation is used to control light intensity), this is an area that could usefully be explored further.

3. Vehicle accidents

There is a strongly held public perception that street lighting contributes directly to the safety with which vehicles can be used on roads at night, and it has been introduced widely for that explicit purpose. For example, until 2007 the UK Highways Agency installed lighting on motorways and major trunk roads on the assumption that this reduces nighttime accident rates by an average of 30%. This assessment has since been revised to 10% for motorways and dual carriageways and 12.5% for single carriageways (UK Highways Agency 2007). This new advice has been used by local authorities to support trials of reducing street lighting as a means of making energy efficiency savings without compromising public safety. A recent study combining visual coverage area analysis with statistical association between lighting and nighttime crashes has demonstrated that improvements in traffic safety changes in night to day crash ratios did not exceed 13% (Bullough et al. 2013).

The empirical evidence that street lighting improves road safety, and under what circumstances, remains limited. A comparison of road traffic casualties revealed that these tended to be greater at night than during the day and to be lower on lit roads than unlit ones (Plainis et al. 2006). A major review, considering controlled before-and-after studies, in which lighting was introduced to previously unlit areas or lighting levels were increased, concluded that street lighting may indeed prevent road traffic accidents (Beyer and Ker 2010). However, the small number of empirical studies conducted to date (17 reviewed) and their restricted geographic focus (10 from USA, 4 UK, 2 Australia, 1 Germany) pose obvious limitations on confidence in this finding. Moreover, and much more significantly, the lack of randomized control trials is a potentially severe constraint on what can be concluded (Marchant 2010). This is unlikely to change. Such trials are virtually impossible to conduct because, as a consequence of ethical and moral considerations, experimental removal or reduction of artificial nighttime lighting is not carried out in areas in which the risks of vehicle accidents are thought a priori to be high. The same problem surrounds more recent trials, for example, in some regions of the UK, in which local authorities have reduced lighting at night (part-night lighting and dimming) and have recorded no increase in road traffic accidents (Warwickshire County Council Final Report 2012). Indeed, when accidents have occurred in areas in which lighting has been altered, intense public pressure can quickly arise to abort these changes (Hansard 2013), arguably regardless of whether lighting may actually have had any role to play.

Understanding the influence of street lighting on vehicular accidents is further complicated by four other considerations. First, as demonstrated by an investigation conducted to determine the relationships between the presence of lighting and the frequency and severity of accidents on different road classes of the UK highways system, there are many interacting variables that make attributing any effect of nighttime lighting alone problematic (Crabb and Crinson 2008). The type of road, pedestrian flow, absence or presence of junctions, and traffic speed, type, and density are all contributing factors to the occurrence of road traffic accidents at night. At night, average speeds tend to be higher as there is less traffic, and there may also be more road users influenced by alcohol, drugs, or fatigue (Corfitsen 1996). Nonetheless, this study did find that road lighting appears to have an effect on reducing accident severity and in particular on accidents involving pedestrian casualties rather than vehicle occupants.

Second, when part-night lighting and dimming are conducted this is often preceded by the implementation of mitigation strategies, such as the use of reflective signage and improvement of road markings (Buckinghamshire County Council 2012). These infrastructural changes obviously confound the interpretation of any changes in the incidence of vehicle accidents. Third, there is likely to be a strong interaction between the effect of street lighting on such accidents and the prevailing vehicle headlight technology. The brightness of headlights has increased by a factor of more than eight over the past 60 years, yet the illumination of roads by fixed lighting has also increased dramatically over this period (Illinois Coalition for Responsible Lighting 2011; www.illinoislighting.org/moonlight). However, this increase in brightness may also bring its own problems, particularly for older drivers, with evidence that it can increase glare from oncoming vehicles (Mainster and Timberlake 2003). Fourth, there is evidence that drivers change their behaviour in the presence of street lighting and engage in risk compensation such as driving faster or paying less attention (Assum et al. 1999).

More than 90% of the world's road fatalities occur in low- and middle-income countries, although these have only 48% of registered vehicles (World Health Organisation 2009). Moreover, deaths in these countries as a result of road traffic accidents are projected to rise from 1.3 million in 2004 to 2.4 million in 2030 (World Health Organisation 2008). The introduction or improvement of street lighting has been suggested as a relatively low cost intervention to avoid this scenario, based on the aforementioned assumption that this reduces nighttime accident rates by an average of 30% (CIE 2007). This could dramatically increase the extent of artificial nighttime lighting. Plainly, there is an urgent need for further well-designed studies (particularly exploiting the introduction of lighting as an experimental methodology) to determine the effectiveness of street lighting as a solution, particularly in these low- and middle-income countries (Beyer and Ker 2010). Here, and elsewhere, a key issue is clearly not simply the influence of street lighting on road accidents, but also the extent to which similar levels of investment could be more effective if made in other accident reduction measures.

4. Crime

Criminal behaviour has traditionally been heavily linked to the cover of darkness. Poor visibility increases a sense of threat for humans and unlit areas were historically to be avoided (Jakle 2001). The introduction of artificial nighttime lighting not only increased human economic activity from the latter part of the nineteenth century but it was also believed to make the nighttime urban environment safer for much of society; "gaslight is found to be the best nocturnal police" (Emerson 1860). This perceived link between street lighting and public safety persists to the present. It is suggested that improvements in street lighting, and potentially other sources, help to reduce crime either by increasing surveillance and thus providing deterrence or because they lead locally to increasing community pride and informal social control which in turn reduce crime (Welsh and Farrington 2008).

Evidence that there is a causal relationship between the introduction of nighttime lighting and a decrease in crime is, however, far from clear. Some studies conclude that recorded crime decreases where lighting is introduced or improved (Painter 1989; Painter and Farrington 1997; Pease 1999). Others conclude that there is no clear correlation and that it may be the public's fear of crime that diminishes with lighting rather than actual crime itself (Atkins et al. 1991); from a policy perspective the perception of safety may be as important as any practical effects. Indeed, in some instances it appears that introducing lighting to a previously unlit area initially increased the incidents of recorded crime (Ramsey 1991). It may also be possible that the introduction of street lighting to one area has the unintended consequence of increasing crime in other locations (termed displacement or leakage), merely moving criminal activity rather than reducing it (Schumacher and Leitner 1999).

A systematic review of 13 evaluations of improved lighting schemes in relation to crime reduction showed that these were more effective as crime prevention measures in the UK than in the USA. It also showed that, unexpectedly, nighttime crimes did not decrease more than those committed during the day, possibly due to a more general wariness amongst offenders caused by lighting installation itself (Welsh and Farrington 2008). Why differences between the 13 studies should be found is unclear but may reflect the different research methodologies used. Studies undertaken in this field are relatively few in number, have tended to focus on small-scale street lighting projects, and to be conducted over relatively short periods, making it difficult to provide statistically robust results (Marchant 2004, 2005). Moreover, as with road safety, a major challenge to determining the influence of artificial nighttime lighting on crime lies in the ethical and moral difficulties of conducting randomized trials. Much of the work conducted to date asserts that improving street lighting is an effective situational crime prevention measure (Painter and Farrington 1999: Farrington and Welsh 2002, 2007; Welsh and Farrington 2008), while recognizing that there is a need to develop more effective and consistent protocols for evaluating this.

Even locally, the relationship between nighttime lighting and crime is likely to be complex. Poorly designed and unshielded installations can create permanent areas of shadow that may be used to provide cover for criminal activity. Conversely, the light source can itself be used to assess potential targets and provide visibility for the criminal. The constant illumination provided by street lighting may draw less attention from potential witnesses than a moving light source such as a torch in a dark area. Increasing illumination far from improving security may in some circumstances make it easier for crimes to be committed and for the criminal to escape (Fleming and Burrows 1986; Sherman et al. 1997). Extreme contrast between areas of light and darkness promotes low peripheral visibility and night vision of potential witnesses is severely compromised by this type of lighting.

As authorities look to changing lighting schemes, and in particular reducing lighting levels, as a means of improving energy efficiency it may be possible to use this as an opportunity to undertake more systematic and robust evaluations of the role of street lighting in influencing crime. It will be particularly important to understand the consequences of technological developments. For example, white light sources with good colour rendering have been shown to improve facial recognition and contribute to the perception of safety for pedestrians by engendering confidence in determining potential threats from others (Raynham and Saksvikronning 2003; Raynham 2007). Likewise, experimental studies of dynamic street lighting have revealed that people prefer having light in their own immediate surroundings rather than on the road that lies ahead (Haans and de Kort 2012).

5. Energy consumption and carbon emissions

Artificial nighttime lighting consumes substantial quantities of energy, and likewise results in the emission of much carbon dioxide (and other greenhouse gases). Indeed, now somewhat dated figures estimated that worldwide, grid-based electric lighting accounted for 19% of electrical power production, the energy consumed to supply lighting generated 1900 Mt of CO_2 per year, and annual lighting cost $360 billion (including energy, equipment, and labour; International Energy Agency 2006). Particularly, since the global financial crisis, and severe pressures on public expenditure, local, regional, and national governmental bodies in many developed countries have sought to reduce the costs of public lighting (especially street lighting). The focus has principally been on finances, although the consequences for carbon accounting have often been highlighted.

Most readily, this takes the form of part-night lighting, in which costs and emissions are limited to parts of the night, and switched off typically during the hours immediately after midnight. It is also achieved through the dimming of lighting devices. However, this requires central management systems, which often necessitate retrofitting of more flexible lighting infrastructure, particularly based on LEDs. The move toward LEDs has been doubly attractive, in that as well as enabling greater control of nighttime lighting it has also enabled a move toward whiter lighting, with its improved colour rendering for human vision.

The desire for greater control over public lighting, and especially to be able to dim lighting at certain times, may under some circumstances increase the extent to which flicker becomes an environmental concern. Most importantly, flicker can be induced by the inclusion of phase-control dimming mechanisms.

In the context of low- and middle-income countries there are estimated to be in the region of 670 million kerosene lamps used for providing nighttime lighting, resulting in an estimated 74 Mt of annual carbon emissions (UNEP 2013). The use of such fuel-based lighting has considerable cost implications not only in terms of energy efficiency but also in terms of health, in relation to respiratory disease and the risk of burn injuries (Mills 2005). Increasingly, solar-powered LED technology is being considered in these contexts as an environmentally beneficial alternative. Although the main focus to date has been on the provision of nighttime lighting in domestic contexts there are also initiatives to provide solar-powered street lighting in conjunction with the lighting industry (Phillips 2012).

Many countries regard the provision of lighting at night and street lighting in particular as a key indicator of the relative socioeconomic development status of a country (Republic of Ghana Department of Energy 2011). The potential negative effects of introducing light into hitherto dark regions, and how these can best be minimized, remain largely unconsidered.

6. Aesthetics

A substantial proportion of artificial nighttime lighting has been introduced for reasons of aesthetics. It has long been used to illuminate both natural and human-made structures and areas, exemplified by the opening of the Brooklyn Bridge in 1883 and General Electric sponsorship of the lighting of Niagara Falls in 1908 (Jakle 2001). People can derive benefit from artificial nighttime lighting particularly in urban contexts, and lighting for aesthetic purposes can enhance their sense and enjoyment of a place (Dawson 2008). Aesthetic nighttime lighting highlights buildings or features, defines spaces, and can create a sense of character for a locale. Aesthetic lighting can also be seen as an art form in its own right and is increasingly being used to contribute to municipal celebration or to create a sense of spectacle (City of Melbourne Lighting Strategy 2002). Since the latter part of the twentieth century, nighttime illumination of historic or iconic buildings or specific areas of cultural significance has explicitly been used by many cities in attempts to increase economic development, in addition to the purely commercial use of illumination such as advertising hoardings and the lighting of retail frontages. Indeed, some cities, such as Shanghai, have achieved iconic status through intensive use of nighttime lighting to create a distinctive nighttime skyline. The Cities of Light Partnership (LUCI) actively promotes such lighting as a means of increasing tourism revenue in cities across Europe. However, although projected benefit is frequently claimed (Dawson 2008; Brätt et al. 2010), attributing economic regeneration purely to increasing aesthetic lighting is difficult (Mansfield and Raynham 2005). In other contexts more natural environments are promoted for tourism, with an increased advertisement of unpolluted night skies emphasised by initiatives such as the United Nations World Tourism Organisation's Starlight Tourism initiative (International Initiative in Defence of the Quality of the Night Sky as Mankind's Scientific, Cultural and Environmental Heritage 2012).

The broader environmental impacts of lighting schemes established for aesthetic purposes have only recently been explicitly addressed (Dawson 2008). Artificial aesthetic lighting has without doubt eroded the natural aesthetic of the night sky (The Royal Commission on Environmental Pollution 2009). Stars are no longer visible in many urban areas. "Shifting baseline syndrome" may lead to the perception that an illuminated night is natural and darkness is abnormal and threatening (Lyytimäki 2013), while conversely, pressure has grown to preserve access to dark skies as a recreational resource (IDSA 2013). Meanwhile, there are longstanding concerns about the effect of sky glow on scientific astronomy (Riegel 1973). Those cities that are noted for extensive use of nighttime lighting, for example Hong Kong, contribute particularly markedly to sky glow (Pun and So 2011). Older styles of floodlighting and poorly shielded luminaires that direct light above the horizontal contribute to glare and light trespass, although more recent architectural lighting strategies may be designed with an attempt to mitigate some of these issues. Considerable undesirable light as a result of indirect reflection from buildings or road surfaces will still occur, however, and the quantity of artificial decorative and commercial lighting employed in affluent countries mean that these mitigating measures can have only limited effect. This said, issues of energy efficiency and sustainability are increasingly being considered (City of Melbourne Lighting Strategy 2002).

7. Ecosystems

The environmental influences of artificial nighttime lighting extend far beyond those on people. A wide diversity of such impacts has been documented on individuals and populations of species from many taxonomic groups, and also communities (Longcore and Rich 2004; Rich and Longcore 2006*b*; Perkin et al. 2011; Gaston et al. 2012, 2013). Arguably, the principal effects, aside from those following from the associated carbon emissions, operate through the impacts on time partitioning by organisms (how they distribute activity through the day) and on their circadian rhythms and patterns of photoperiodism (Gaston et al. 2013). Artificial nighttime lighting has been documented to change both the timing and the period over which organisms can capture resources, typically increasing the opportunities for diurnal species and reducing those for nocturnal ones (e.g., Garber 1978; Wolff 1982; Martin 1990; Negro et al. 2000; Bird et al. 2004; Perry and Fisher 2006; Frank 2009; Santos et al. 2010; Rotics et al. 2011). This alters species interactions (e.g., competition, predator–prey), and may in turn reshape community structure, and presumably associated ecosystem functions and processes, although the latter has yet to be demonstrated (Moore et al. 2001, 2006; Longcore and Rich 2004; Davies et al. 2012).

Given that most organisms anticipate environmental changes using the daily cycle of day and night, lunar cycles, and (or) seasonal cycles in daylength, the disruption of these patterns by artificial nighttime lighting by altering natural ratios of apparent day and night, apparent patterns of nighttime illumination, and apparent seasonal variation in those ratios has profound implications (Gaston et al. 2013). Explicit study of these effects remains limited (e.g., Miller 2006; Kempenaers et al. 2010, Dominoni et al. 2013), but they seem likely to influence such processes as growth, reproduction, eclosion, diapause, moult, embryonic development, and migration. Key questions that remain to be answered centre on the interplay between biological mechanisms for daily and seasonal time keeping — which have themselves to be robust to effects of weather conditions, habitat structure, and behavioural variation (Beersma et al. 1999) — and the extent to which artificial nighttime lighting disrupts significant components of natural light cycles.

In addition to the above effects, the introduction of artificial nighttime lighting also changes the movement patterns of organisms. Much focus has been placed on those species that are actively attracted to lights (especially, insects, turtles, and seabirds; e.g., Witherington and Bjorndal 1991; Lorne and Salmon 2007; Warrant and Dacke 2010; Rodríguez et al. 2012). However, at least as important is likely to be the constraint on movements of light-repelled species caused particularly by the fragmentation of habitats by nighttime lighting, and the barriers posed by continuously lit linear features such as roads and footpaths (e.g., Beier 2006; Frank 2006; Nightingale et al. 2006; Rydell 2006; Kuijper et al. 2008; Stone et al. 2009, 2012; Polak et al. 2011; Riley et al. 2012, 2013).

Variation in the spectral composition of artificial nighttime lighting doubtless influences the nature and extent of the impacts on ecosystems. Much remains to be understood about these effects. However, broader spectrum lighting enables animals to detect objects that reflect light over more of the spectrum to which they are sensitive. Importantly, the move to broader spectrum lighting creates greater disparities in this ability between major taxonomic groups, potentially altering the balance of species interactions and changing community structure (Davies et al. 2013). The presence/absence of ultraviolet emissions may also be particularly significant, as these are known to be disproportionately attractive to moths (e.g., van Langevelde et al. 2011) and also detectable by some bat species (Müller et al. 2009; Zhao et al. 2009; Xuan et al. 2012), both groups for which the effects of artificial light at night has been considered a notable concern (many other groups also detect emissions in the ultraviolet; Davies et al. 2013).

The influences of the intensity and spectrum of artificial nighttime lighting on ecosystems are unlikely to be independent. One of the attractions of broader spectrum lighting is that the improved colour rendering that results enables the intensity of the lighting employed to be reduced whilst still creating net benefits for human vision. Experiments will need to be conducted to map out the net effects on ecosystems of different combinations of light intensity and spectra.

The impacts of the flickering of artificial nighttime light on ecosystems are not understood. However, it is clear that this flickering is perceptible by a wide diversity of species (Woo et al. 2009;

Inger et al. 2014). There is also scattered evidence for a range of physiological and behavioral effects on both invertebrates and vertebrates (Inger et al. 2014). We suspect that the effects may in some instances be quite profound.

8. In conclusion

The artificial lighting of the nighttime environment has brought many benefits to humankind. It has also given rise to substantial costs. The key, and pressing, issue now is how best to maximize the former whilst limiting the latter. To do so, three main things are required. First, some key research questions need to be answered and key knowledge gaps need to be filled. Of these, we would highlight the following as being particularly significant:

(*i*) Under what lighting conditions do different impacts of artificial nighttime lighting on human health and wellbeing occur? It is difficult to extrapolate from much of the work that has been done, particularly in laboratory settings, to effects that are experienced under the, often complex, patterns of lighting experienced by people under normal circumstances, and to disentangle the relative impacts of artificial lighting that is experienced outdoors and within buildings.

(*ii*) What are the minimum required levels of, and what is the optimal trade-off between, street and vehicle lighting to limit the incidence of accidents involving either vehicle occupants or pedestrians? These two kinds of lighting have very different environmental impacts, and their respective roles need to be much better understood, particularly in the context of rapid growth in vehicle numbers in low- and middle-income countries.

(*iii*) What is the relative importance, under different lighting conditions, of the actual and the perceived risk of crime? Much lighting policy seems to be driven more by fear of crime than its real likelihood, raising the possibility of mitigation in alternative ways than the introduction of further artificial nighttime lighting.

(*iv*) How are public cognitive and emotional perceptions of artificial lights formed and how do resultant public attitudes facilitate or impede seemingly rational choices for nighttime lighting?

(*v*) Which are the "low-hanging fruit" in installing and using lighting systems that best align reductions in energy consumption and carbon emissions with reductions in other environmental impacts? Focus to date has been placed almost exclusively on limiting energy costs, but wider opportunities clearly exist.

(*vi*) How can artificial lighting be used to best effect for aesthetic purposes whilst minimizing the contribution to light trespass and sky glow? Significant advances are occurring in lighting design for such purposes, but standardized ways of evaluating their environmental pros and cons remain wanting.

(*vii*) In which kinds of ecosystems are the impacts of nighttime lighting on other species of most significance? Although impacts have been documented on a diversity of species it is unclear which ecosystems are most threatened by these.

Second, there is an urgent need to connect the work being done in different disciplines, which to date has been very disjointed. Research into the impacts of artificial nighttime lighting is carried out in a wide variety of fields, including astronomy, criminal justice, ecology, energy, engineering, evolution, and medicine. A mechanism for the much better coordination of insights gained from such a range of disciplines needs to be developed in order to better understand the complexities and challenges that the implications of lighting the nighttime environment create (e.g., shared forums, journals, meetings).

Third, it is also imperative that much firmer and well-developed links are made between research, policy, and practice. An opportunity for this may currently be provided by the increasing global understanding of the need to reduce energy consumption and the demand to reduce expenditure on artificial nighttime lighting, and on street lighting in particular (Gaston 2013). As civic authorities seek to change their lighting regimes to create both energy and cost savings, opportunities exist to develop better research methodologies for evaluating the impact of artificial nighttime lighting on, for example, crime and road safety and also for ecologists as well as astronomers to be involved in the development of urban lighting schemes (City of Melbourne Lighting Strategy 2002). As low- and middle-income countries seek the economic, social, and potential safety benefits that may be obtained from artificial light at night there will also be a need to consider the growth in understanding of the associated costs.

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References

Alliance for Solid-State Illumination Systems and Technologies (ASSIST). 2012. ASSIST recommends. Flicker parameters for reducing stroboscopic effects from solid-state lighting systems. Lighting Research Center, Troy, New York. http://www.lrc.rpi.edu/programs/solidstate/assist/recommends/flicker.asp [accessed May 2014].

Assum, T., Bjornskau, T.Ø., Fosser, S., and Sagberg, F. 1999. Risk compensation — the case for road lighting. Accident Analysis Prev. **31**: 545–553. doi:10.1016/S0001-4575(99)00011-1.

Atkins, S, Hussain, S., and Storey, A. 1991. The influence of street lighting on crime and fear of crime. Crime Prevention Unit Paper 28 Home Office, Crown Publications, London.

Aubé, M., Roby, J., and Kocifaj, M. 2013. Evaluating potential spectral impacts of various artificial lights on melatonin suppression, photosynthesis, and star visibility. PLoS One, **8**: e67798. doi:10.1371/journal.pone.0067798. PMID: 23861808.

Bauer, S.E., Wagner, S.E., Burch, J., Bayakly, R., and Vena, J.E. 2013. A case-referent study: light at night and breast cancer risk in Georgia. Int. J. Health Geog. **12**: 23. doi:10.1186/1476-072X-12-23.

Bedrosian, T.A, Fonken, L.K., Walton, J.C., Haim, A., and Nelson, R.J. 2011*a*. Dim light at night provokes depression-like behaviors and reduces CA1 dendritic spine density in female hamsters. Psychoneuroendocrinology, **36**: 1062–1069. doi:10.1016/j.psyneuen.2011.01.004. PMID:21292405.

Bedrosian, T.A., Fonken, L.K., Walton, J.C., and Nelson, R.J. 2011*b*. Chronic exposure to dim light at night suppresses immune responses in Siberian hamsters. Biol. Lett. **7**: 468–471. doi:10.1098/rsbl.2010.1108. PMID:21270021.

Beersma, D.G.M., Daan, S., and Hut, R.A. 1999. Accuracy of circadian entrainment under fluctuating light conditions: contributions of phase and period responses. J. Biol. Rhythms, **14**: 320–329. PMID:10447313.

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

Berman, S.M., Greenhouse, D.S., Bailey, I.L., Clear, R., and Raasch, T.W. 1991. Human electroretinogram responses to video displays, fluorescent lighting and other high frequency sources. Optometry Vision Sci. **68**: 645–662. doi:10.1097/00006324-199108000-00012.

Beyer, F.R., and Ker, K. 2010. Street lighting for preventing road traffic injuries. Cochrane Database Syst. Rev. **2009**: 1.

Bird, B.L., Branch, L.C., and Miller, D.L. 2004. Effects of coastal lighting on foraging behaviour of beach mice. Conserv. Biol. **18**: 1435–1439. doi:10.1111/j.1523-1739.2004.00349.x.

Boyce, P.R. 2010. The impact of light in buildings on human health. Indoor Built Environ. **19**: 8–20. doi:10.1177/1420326X09358028.

Brätt, J., James, G., Price, R., and Sewell, J. 2010. Best Practices in Place Making Through Illumination. Virginia Tech Urban Affairs and Planning Program Report.

Buckinghamshire County Council Report. 2012. www.transportfor bucks.net/roadworks-centre/streetlighting works/streetlighting energy saving trial.asp [accessed December 2012].

Bullough, J.D., Donnell, E.T., and Rea, M.S. 2013. To illuminate or not to illuminate: roadway lighting as it affects traffic safety at intersections. Accident Analysis Prevent. **53**: 65–77. doi:10.1016/j.aap.2012.12.029.

Burns, S.A., Elsner, A.E., and Kreitz, M.R. 1992. Analysis of nonlinearities in the flickerERG.OptometryVisionSci.**69**:95–105.doi:10.1097/00006324-199202000-00002.

Cajochen, C., Frey, S., Anders, D., Spätl, J., Bues, M., Pross, A., Mager, R., Wirz-Justice, A., and Stephani, O. 2011. Evening exposure to a light-emitting diodes (LED)-backlit computer screen affects circadian physiology and cognitive performance. J. Appl. Physiol. **110**: 1432–1438. doi:10.1152/japplphysiol.00165.2011. PMID:21415172.

Chang, A-M., Santhi, N., St Hilaire, M., Gronfier, C., Bradstreet, D.S., Duffy, J.F., Lockley, S.W., Kronauer, R.E., and Czeisler, C.A. 2012. Human responses to bright light of different durations. J. Physiol. **590**: 3103–3112. doi:10.1113/jphysiol.2011.226555. PMID:22526883.

Chellappa, S.L., Steiner, R., Blattner, P., Oelhafen, P., Götz, T., and Cajochen, C. 2011. Nonvisual effects of light on melatonin, alertness and cognitive performance: can blue-enriched light keep us alert? PLoS One, **6**: e16429. doi:10.1371/journal.pone.0016429. PMID:21298068.

CIE. 2007. Road transport lighting for developing countries. CIE, Vienna.

Cinzano, P., Falchi, F., and Elvidge, C.D. 2001. The first world atlas of the artificial night sky brightness. Mon. Not. R. Astron. Soc. **328**: 689–707. 10.1046/j.1365-8711.2001.04882.x.

City of Melbourne Lighting Strategy. 2002. www.melbourne.vic.gov.au [accessed January 2013].

Cohen, M., Lippman, M., and Chabner, B. 1978. Role of pineal gland in aetiology and treatment of breast cancer. The Lancet, **312**: 814–816. doi:10.1016/S0140-6736(78)92591-6.

Corfitsen, M.T. 1996. Enhanced tiredness among young impaired male nighttime drivers. Accident Analysis Prevent. **28**: 155–162. doi:10.1016/0001-4575(95)00042-9.

Cos, S., Mediavilla, D., Martínez-Campa, C., González, A., Alonso-González, C., and Sánchez-Barceló, E.J. 2006. Exposure to light-at-night increases the growth of DMBA-induced mammary adenocarcinomas in rats. Cancer Lett. **235**: 266–271. doi:10.1016/j.canlet.2005.04.025. PMID:15950374.

Crabb, G.I., and Crinson, L. 2008. The impact of street lighting on nighttime road casualties. Transport Research Laboratory, Wokingham, Berkshire.

Davies, T.W., Bennie, J., and Gaston, K.J. 2012. Street lighting changes the composition of invertebrate communities. Biol. Lett. **8**: 764–767. doi:10.1098/rsbl.2012.0216. PMID:22628095.

Davies, T.W., Bennie, J., Inger, R., Hempel de Ibarra, N., and Gaston, K.J. 2013. Artificial light pollution: are shifting spectral signatures changing the balance of species interactions? Global Change Biol. **19**: 1417–1423. doi:10.1111/gcb.12166.

Dawson, J. 2008. Feature lighting in Liverpool City centre: an impact assessment of the city's lighting programme. North West Regional Development Agency, Liverpool City Council, and Liverpool Vision, Liverpool.

Dominoni, D., Quetting, M., and Partecke, J. 2013. Artificial light at night advances avian reproductive physiology. Proc. R. Soc. B, **280**: 20123017. doi:10.1098/rspb.2012.3017.

Duffy, J.F. and Wright, K.P., Jr. 2005. Entrainment of the human circadian system by light. J. Biol. Rhythms, **20**: 326–338. PMID:16077152.

Elvidge, C.D., Keith, D.M., Tuttle, B.T., and Baugh, K.E. 2010. Spectral identification of lighting type and character. Sensors, **10**: 3961–3988. doi:10.3390/s100403961. PMID:22319336.

Emerson, R.W. 1860. XVII. Worship. *In* Emerson, R.W. Essays and English traits. The Harvard Classics.

Erren, T.C., and Reiter, R.J. 2009. Light hygiene: time to make preventive use of insights — old and new — into the nexus of the drug light, melatonin, clocks, chronodisruption and public health. Medical Hyp. **73**: 537–541. doi:10.1016/j.mehy.2009.06.003.

Evans, J.A., Elliott, J.A., and Gorman, M.R. 2007. Circadian effects of light no brighter than moonlight. J. Biol. Rhythms, **22**: 356–367. PMID:17660452.

Falchi, F., Cinzano, P., Elvidge, C.D., Keith, D.M., and Haim, A. 2011. Limiting the impact of light pollution on human health, environment and stellar visibility. J. Environ. Manage. **92**: 2714–2722. doi:10.1016/j.jenvman.2011.06.029. PMID:21745709.

Farrington, D.P., and Welsh, B.C. 2002. Effects of street lighting on crime: a systematic review. HMSO, London.

Farrington, D.P., and Welsh, B.C. 2007. Improved street lighting: a systematic review. The Swedish National Council for Crime Prevention, Stockholm.

Fleming, R., and Burrows, J. 1986. The case for lighting as a means of preventing crime. Home Office Res. Bull. **22**: 14–17.

Fonken, L.F., and Nelson, R.J. 2011. Illuminating the deleterious effects of light at night. F1000 Medicine Rep. **3**: 18.

Frank, K.D. 2006. Effect of artificial night lighting on moths. *In* Ecological consequences of artificial night lighting. *Edited by* C. Rich and T. Longcore. Island Press, Washington, D.C. pp. 305–344.

Frank, K.D. 2009. Exploitation of artificial light at night by a jumping spider. Peckhamia, **78**: 1–3.

Garber, S.D. 1978. Opportunistic feeding behaviour of *Anolis cristatellus* (Iguanidae: Reptilia) in Puerto Rico. Transactions of the Kansas Academy of Science, **81**: 19–80.

Gaston, K.J. 2013. A green light for efficiency. Nature, **497**: 560–561. doi:10.1038/497560a. PMID:23719447.

Gaston, K.J. (*Editor*) 2010. Urban ecology. Cambridge University Press, Cambridge.

Gaston, K.J., Davies, T.W., Bennie, J., and Hopkins, J. 2012. Reducing the ecological consequences of night-time light pollution: options and developments. J. Appl. Ecol. **49**: 1256–1266. doi:10.1111/j.1365-2664.2012.02212.x. PMID:23335816.

Gaston, K.J., Bennie, J., Davies, T.W., and Hopkins, J. 2013. The ecological impacts of nighttime light pollution: a mechanistic appraisal. Biol. Rev. **88**: 912–927. PMID:23565807.

Gooley, J., Chamberlain, K., Smith, K.A., Khasala, S.B.S., Czeisler, C.A., and Lockley, S.W. 2011. Exposure to room light before bedtime suppresses melatonin onset and shortens melatonin duration in humans. J. Clin. Endocrinol. Metab. **96**: E463–E472. doi:10.1210/jc.2010-2098. PMID:21193540.

Haans, A., and de Kort, Y.A.W. 2012. Light distribution in dynamic street lighting: two experimental studies on its effects on perceived safety, prospect, concealment, and escape. J. Environ. Psychol. **32**: 342–352. doi:10.1016/j.jenvp.2012.05.006.

Hale, J.D., Davies, G., Fairbrass, A.J., Matthews, T.J., Rogers, C.D.F., and Sadler, J.P. 2013. Mapping lightscapes: spatial patterning of artificial lighting in an urban landscape. PLoS One, **8**: e61460. doi:10.1371/journal.pone.0061460.

Hansard, 2013. Available from www.publications.parliament.uk/pa/cm201213/cmhansard/ [accessed April 2013].

Hazell, J., and Wilkins, A. 1990. A contribution of fluorescent lighting to agoraphobia. Psychol. Medicine, **20**: 591–596.

Hébert, M., Martin, S.K., Lee, C., and Eastman, C.I. 2002. The effects of prior light history on the suppression of melatonin by light in humans. J. Pineal Res. **33**: 198–203. doi:10.1034/j.1600-079X.2002.01885.x. PMID:12390501.

Holman, D.C. 2010. What's in a colour? The unique human health effects of blue light. Environ. Health Perspectives, **118**: A22–27. doi:10.1289/ehp.118-a22.

IARC. 2010. International Agency for Research on Cancer. IARC Monographs 98, Lyon.

IDSA. 2013. International Dark-Sky Association Dark Sky Park Program Criteria [online]. IDSA, Tucson. Available from http://www.darksky.org/idsp/Guidelines/IDSP%20Guildelines%20Final-May13-BP.pdf [accessed November 2013].

IEE. 2010. Standard P1789. Available from http:/grouper.ieee.org/groups/1789 [accessed March 2013].

Illinois Coalition for Responsible Lighting. 2011. Available from http://www.illinoislighting.org/moonlight.html [accessed December 2012].

Inger, R., Bennie, J., Davies, T., and Gaston, K.J. 2014. Potential biological and ecological effects of flickering artificial light. PLoS One, **9**: e98631. doi:10.1371/journal.pone.0098631. PMID:24874801.

International Energy Agency. 2006. Light's labour's lost: policies for energy-efficient lighting. International Energy Agency, Paris.

International Initiative in Defence of the Quality of the Night Sky as Mankind's Scientific, Cultural and Environmental Heritage. 2012. Available from http://www.starlight2007.net/index.php?option=com_content&view=article&id=169&Itemid=158&lang=en [accessed June 2014].

Jakle, J.A. 2001. City lights: illuminating the American night. Johns Hopkins University Press, Baltimore.

Kempenaers, B., Borgström, P., Loës, P., Schlicht, E., and Valcu, M. 2010. Artificial night lighting affects dawn song, extra-pair siring success, and lay date in songbirds. Current Biol. **20**: 1735–1739. doi:10.1016/j.cub.2010.08.028.

Kloog, I., Stevens, R.G., Haim, A., and Portnov, B.A. 2010. Nighttime light levels co-distribute with breast cancer incidence worldwide. Cancer Causes Control, **21**: 2059–2068. doi:10.1007/s10552-010-9624-4. PMID:20680434.

Koslofsky, C. 2011. Evening's empire: a history of the night in early modern Europe. Cambridge University Press, Cambridge.

Kubo, T., Ozasa, K., Mikami, K., Wakai, K., Fujino, Y., Watanabe, Y., Miki, T., Nakao, M., Hayashi, K., Suzuki, K., Mori, M., Washio, M., Sakauchi, F., Ito, Y., Yoshimura, T., and Tamakoshi, A. 2006. Prospective cohort study of the risk of prostate cancer among rotating-shift workers: findings from the Japan collaborative cohort study. Am. J. Epidemiol. **164**: 549–555. doi:10.1093/aje/kwj232. PMID:16829554.

Kuijper, D.P.J., Schut, J., van Dullemen, D., Toorman, H., Goossens, N., Ouwehand, J., and Limpens, H.J.G.A. 2008. Experimental evidence of light disturbance along the commuting routes of pond bats (*Myotis dasycneme*). Lutra, **51**: 37–49.

Kyba, C.C.M., Ruhtz, T., Fischer, J., and Hölker, F. 2011. Cloud coverage acts as an amplifier for ecological light pollution in urban ecosystems. PLoS One, **6**: e17307. doi:10.1371/journal.pone.0017307. PMID:21399694.

Kyba, C.C.M., Ruhtz, T., Fischer, J., and Hölker, F. 2012. Red is the new black: how the colour of urban skyglow varies with cloud cover. Mon. Not. R. Astron. Soc. **425**: 701–708. doi:10.1111/j.1365-2966.2012.21559.x.

Lewy, A.J. 1983. Effects of light on human melatonin production and the human circadian system. Prog. Neuropsychopharmacol. Biol. Psych. **7**: 551–556. doi:10.1016/0278-5846(83)90024-6.

Lin, M.C., Kripke, D.F., Parry, B.L., and Berga, S.L. 1990. Night light alters menstrual cycles. Psychiatry Research, **33**: 135–138. doi:10.1016/0165-1781(90)90067-F. PMID:2243890.

Longcore, T., and Rich, C. 2004. Ecological light pollution. Frontiers Ecol. Environ. **2**: 191–198. doi:10.1890/1540-9295(2004)002[0191:ELP]2.0.CO;2.

Lorne, J.K., and Salmon, M. 2007. Effects of exposure to artificial lighting on orientation of hatchling sea turtles on the beach and in the ocean. Endangered Species Res. **3**: 23–30. doi:10.3354/esr003023.

Luginbuhl, C.B., Boley, P.A., and Davis, D.R. 2014. The impact of light source spectral power distribution on sky glow. J. Quant. Spectrosc. Radiat. Transfer, **139**: 21–26. doi:10.1016/j.jqsrt.2013.12.004.

Lyytimäki, J. 2013. Nature's nocturnal services: light pollution as a non-recognised challenge for ecosystem services research and management. Ecosyst. Serv. **3**: e44–e48. doi:10.1016/j.ecoser.2012.12.001.

Mainster, M.A., and Timberlake, G.T. 2003. Why HID headlights bother older drivers. Brit. J. Opthalmol. **87**: 113–117. doi:10.1136/bjo.87.1.113.

Mansfield, K., and Raynham, P. 2005. Sustainable urban lighting for town centre regeneration. Lux Europa, Berlin.

Marchant, P. 2004. A demonstration that the claim that brighter lighting reduces crime is unfounded. Brit. J. Criminol. **44**: 441–447. doi:10.1093/bjc/azh009.

Marchant, P. 2005. What works? A critical note on the evaluation of crime reduction initiatives. Crime Prev. Comm. Safety, **7**: 7–13.

Marchant, P. 2010. What is the contribution of street lighting to keeping us safe? An investigation into a policy. Radical Stat. **102**: 32–42.

Martin, G. 1990. Birds by night. T. and A.D. Poyser, London.

Miller, M.W. 2006. Apparent effects of light pollution on singing behavior of American robins. Condor, **108**: 130–139. doi:10.1650/0010-5422(2006)108[0130:AEOLPO]2.0.CO;2.

Mills, E. 2005. The specter of fuel-based lighting. Science, **308**: 1263–1264. doi:10.1126/science.1113090. PMID:15919979.

Moore, M.V., Pierce, S.M., Walsh, H.M., Kvalvik, S.K., and Lim, J.D. 2001. Urban light pollution alters the diel vertical migration of *Daphnia*. Verh. Int. Ver. Theor. Angew. Limnol. **27**: 779–782.

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

Müller, B., Glösmann, M., Peichl, L., Knop, G.C., Hagemann, C., and Ammermüller, J. 2009. Bat eyes have ultraviolet-sensitive cone photoreceptors. PLoS One, **4**: e6390. doi:10.1371/journal.pone.0006390. PMID:19636375.

Navara, K.J., and Nelson, R.J. 2007. The dark side of light at night: physiological, epidemiological, and ecological consequences. J. Pineal Res. **43**: 215–224. doi:10.1111/j.1600-079X.2007.00473.x. PMID:17803517.

Negro, J.J., Bustamante, J., Melguizo, C., Ruiz, J.L., and Grande, J.M. 2000. Nocturnal activity of lesser kestrels under artificial lighting conditions in Seville, Spain. J. Raptor Res. **34**: 327–329.

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

O'Leary, E.S., Schoenfeld, E.R., Stevens, R.G., Kabat, G.C., Henderson, K., Grimson, R., Gammon, M.D., and Leske, M.C. 2006. Electromagnetic fields and breast cancer a Long Island study group: shift work, light at night and breast cancer on Long Island, New York. Am. J. Epidemiol. **164**: 358–366. doi:10.1093/aje/kwj211. PMID:16777931.

Packer, C., Swanson, A., Ikanda, D., and Kushnir, H. 2011. Fear of darkness, the full moon and the nocturnal ecology of African lions. PLoS One, **6**: e22285. doi:10.1371/journal.pone.0022285. PMID:21799812.

Painter, K. 1989. Lighting and crime prevention for community safety: the Tower Hamlets study, First Report. Centre for Criminology, Middlesex Polytechnic, London.

Painter, K., and Farrington, D.P. 1997. The crime reducing effect of improved street lighting: the Dudley project. *In* Situational crime prevention: successful case studies. *Edited by* R.V. Clarke, Harrow and Heston, Guilderland, New York pp. 209–226.

Painter, K., and Farrington, D.P. 1999. Street lighting and crime: the diffusion of benefits in the Stoke–on-Trent project. *In* Surveillance of public space: CCTV, street lighting and crime prevention. *Edited by* K. Painter and N. Tilley. Crime Prev. Stud. **10**: 77–122.

Parry, B.L., and Newton, R.P. 2001. Chronobiological basis of female-specific mood disorders. Neuropsychopharmacology, **25**: S102–108. doi:10.1016/S0893-133X(01)00340-2. PMID:11682284.

Pease, K. 1999. A review of street lighting evaluations: crime reduction effects. Crime Prev. Stud. **10**: 47–76.

Perkin, E.K., Hölker, F., Richardson, J.S., Sadler, J.P., Wolter, C., and Tockner, K. 2011. The influence of artificial light on stream and riparian ecosystems: questions, challenges, and perspectives. Ecosphere, **2**: 122. doi:10.1890/ES11-00241.1.

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

Phillips. 2012. www.gov.today.co.uk [accessed June 2014].

Plainis, S., Murray, I.J., and Pallikaris, I.G. 2006. Road traffic casualties: understanding the night-time death toll. Injury Prevention, **12**: 125–138. doi:10.1136/ip.2005.011056. PMID:16595429.

Polak, T., Korine, C., Yair, S., and Holderied, M.W. 2011. Differential effects of artificial lighting on flight and foraging behaviour of two sympatric bat species in a desert. J. Zool. **285**: 21–27. doi:10.1111/j.1469-7998.2011.00808.x.

Pun, C.S.J., and So, C.W. 2011. Night-sky brightness monitoring in Hong Kong. A city-wide assessment. Environ. Monitor. Assess. **184**: 2537–2557.

Ramsey, M. 1991. The effect of better street lighting: a review. Crime Prevention Unit Paper 29, Crown Publications, London.

Raynham, P. 2007. Public lighting in cities. *In*: Proceedings of the International Conference Iluminat 2007. Cluj-Napoca, Romania.

Raynham, P., and Saksvikronning, T. 2003. White light and facial recognition. The Lighting Journal, **68**: 29–33.

Republic of Ghana Department of Energy. 2011. Available from http://www.energymin.gov.gh/wp-content/upLoads/Draft-Street-Lighting-Policy-August-14-2011.pdf [accessed May 2013].

Rich, C., and Longcore, T. 2006*a*. Introduction. *In* Ecological consequences of artificial night lighting. *Edited by* C. Rich and T. Longcore. Island Press, Washington, D.C. pp. 1–13.

Rich, C., and Longcore, T. (eds) 2006*b*. Ecological consequences of artificial night lighting. Island Press, Washington, D.C.

Riegel, K.W. 1973. Light pollution. Science, **179**: 1285–1291. doi:10.1126/science.179.4080.1285. PMID:17835929.

Riley, W.D., Bendall, B., Ives, M.J., Edmonds, N.J., and Maxwell, D.L. 2012. Street lighting disrupts the diel migratory pattern of wild Atlantic salmon, *Salmo salar* L., smolts leaving their natal stream. Aquaculture, **330–333**: 74–81. doi:10.1016/j.aquaculture.2011.12.009.

Riley, W.D., Davison, P.I., Maxwell, D.L., and Bendall, B. 2013. Street lighting delays and disrupts the dispersal of Atlantic salmon (*Salmo salar*) fry. Biol. Conserv. **158**: 140–146. doi:10.1016/j.biocon.2012.09.022.

Rodríguez, A., Rodríguez, B., and Lucas, M.P. 2012. Trends in numbers of petrels attracted to artificial lights suggest population declines in Tenerife, Canary Islands. Ibis, **154**: 167–172. doi:10.1111/j.1474-919X.2011.01175.x.

Rotics, S., Dayan, T., and Kronfeld-Schor, N. 2011. Effect of artificial night lighting on temporally partitioned spiny mice. J. Mammal. **92**: 159–168. doi:10.1644/10-MAMM-A-112.1.

Rydell, J. 2006. Bats and their insect prey at streetlights. *In* Ecological consequences of artificial night lighting. *Edited by* C. Rich and T. Longcore. Island Press, Washington, D.C. pp. 43–60.

Saha, S., and Sassone-Corsi, P. 2007. Circadian clock and breast cancer: a molecular link. Cell Cycle, **6**: 1329–1331. doi:10.4161/cc.6.11.4295. PMID:17534151.

Santos, C.D., Miranda, A.C., Granadeiro, J.P., Lourenço, P.M., Saraiva, S., and Palmeirim, J.M. 2010. Effects of artificial illumination on the nocturnal foraging of waders. Acta Oecologica, **36**: 166–172. doi:10.1016/j.actao.2009.11.008.

Schumacher, B.J., and Leitner, M. 1999. Spatial crime displacement resulting from large-scale urban renewal programs in the city of Baltimore. IV. International Conference of Geographical Computation, GeoComputation 99, www.geovista.psu.edu.geocomp [accessed January 2013].

Scientific Committee on Emerging and Newly Identified Health Risks. 2012. Health Effects of Artificial Light. European Commission, Brussels.

Sherman, L., Gottfredson, D., Mackenzie, D., Eck, J., Reuter, P., and Bushway, S. 1997. Preventing crime: what works, what doesn't, what's promising. US Department of Justice, Washington, D.C.

Small, C., and Elvidge, C.D. 2013. Night on earth: mapping decadal changes of anthropogenic night light in Asia. Int. J. Appl. Earth Obs. Geoinfor. **22**(S1): 40–52. doi:10.1016/j.jag.2012.02.009.

Stevens, R.G. 2009. Light at night, circadian disruption and breast cancer: assessment of existing evidence. Int. J. Epidemiol. **38**: 963–970. doi:10.1093/ije/dyp178. PMID:19380369.

Stone, E.L., Jones, G., and Harris, S. 2009. Street lighting disturbs commuting bats. Current Biol. **19**: 1123–1127. doi:10.1016/j.cub.2009.05.058.

Stone, E.L., Jones, G., and Harris, S. 2012. Conserving energy at a cost to biodiversity? Impacts of LED lighting on bats. Global Change Biol. **18**: 2458–2465. doi:10.1111/j.1365-2486.2012.02705.x.

Straif, K., Baan, R., Grosse, Y., Secretan, B., Ghissassi, F., Bouvard, V., Altieri, A., Benbrahimtallaa, L., and Cogliano, V. 2007. Carcinogenicity of shift-work, painting, and fire-fighting. Lancet Oncol. **8**: 1065–1066. doi:10.1016/S1470-2045(07)70373-X. PMID:19271347.

The Royal Commission on Environmental Pollution. 2009. Artificial light in the environment. TSO, London.

UK Highways Agency. 2007. Advice Note TA49/07. Design manual for roads and bridges 8. HMSO, London.

UNEP. 2013. Available from http://www.unep.org/Documents.Multilingual/Default.asp?DocumentID=2704&ArticleID=9407&l=en [accessed June 2014].

van Langevelde, F., Ettema, J.A., Donners, M., WallisDeVries, M.F., and Groenendijk, D. 2011. Effect of spectral composition of artificial light on the attraction of moths. Biol. Conserv. **144**: 2274–2281. doi:10.1016/j.biocon.2011.06.004.

Vanderwalle, G., Schwartz, S., Grandjean, D., Wuillaume, C., Balteau, E., Degueldre, C., Schabus, M., Phillips, C., Luxen, A., Dijk, D.J., and Maquet, P. 2010. Spectral quality of light modulates emotional brain responses in humans. Proc. Nat. Acad. Sci., U.S.A. **107**: 19549–19554. doi:10.1073/pnas.1010180107. PMID:20974959.

Wahnschaffe, A., Haedel, S., Rodenbeck, A., Stoll, C., Rudolph, H., Kozakov, R., Schoepp, H., and Kunz, D. 2013. Out of the lab and into the bathroom: evening short-term exposure to conventional light suppresses melatonin and increases alertness perception. Int. J. Molecular Sci. **14**: 2573–2589. doi:10.3390/ijms14022573.

Warrant, E., and Dacke, M. 2010. Visual orientation and navigation in nocturnal arthropods. Brain Behav. Evol. **75**: 156–173. doi:10.1159/000314277. PMID:20733292.

Warwickshire County Council Final Report. 2012. Available from http://www.warwickshire.gov.uk/Web/corporate/wccweb.nsf/Links/1E327B0D7FF4BDB4802579FF002F2B3F/$file/Item+5+-+Street+Lighting+Task+and+Finish+Group+Report.pdf [accessed April 2013].

Welsh, B.C., and Farrington, D.P. 2008. Effects of improved street lighting on crime. Campbell Syst. Rev. **2008**: 13.

Winterbottom, M., and Wilkins, A. 2009. Lighting and discomfort in the classroom. J. Environ. Psychol. **29**: 63–75. doi:10.1016/j.jenvp.2008.11.007.

Witherington, B.E., and Bjorndal, K.A. 1991. Influences of artificial lighting on the seaward orientation of hatchling loggerhead turtles *Caretta caretta*. Biol. Conserv. **55**: 139–149. doi:10.1016/0006-3207(91)90053-C.

Wolff, R.J. 1982. Nocturnal activity under artificial lights by the jumping spider *Sitticus fasciger*. Peckhamia, **2**: 32.

Woo, K.L., Hunt, M., Harper, D., Nelson, N.J., Daugherty, C.H., and Bell, B.D. 2009. Discrimination of flicker frequency rates in the reptile tuatara (*Sphenodon*). Naturwissenschaften, **96**: 415–419. doi:10.1007/s00114-008-0491-8. PMID:19089401.

World Health Organisation. 2008. Global burden of disease (2004 update). WHO, Switzerland.

World Health Organisation. 2009. Global status report on road safety. WHO Department of Violence and Injury Prevention and Disability, Switzerland.

Wyse, C.A., Selman, C., Page, M.M., Coogan, A.N., and Hazlerigg, D.G. 2011. Circadian desynchrony and metabolic dysfunction; did light pollution make us fat? Medical Hyp. **77**: 1139–1144. doi:10.1016/j.mehy.2011.09.023.

Xuan, F., Hu, K., Zhu, T., Racey, P., Wang, X., and Sun, Y. 2012. Behavioral evidence for cone-based ultraviolet vision in divergent bat species and implications for its evolution. Zoologia, **29**: 109–114. doi:10.1590/S1984-46702012000200002.

Zeitzer, J.M., Dijk, D.J., Kronauer, R., Brown, E., and Czeisler, C. 2000. Sensitivity of the human circadian pacemaker to nocturnal light: melatonin phase resetting and suppression. J. Physiol. **526**: 695–702. PMID:10922269.

Zhao, H., Rossiter, S.J., Teeling, E.C., Li, C., Cotton, J.A., and Zhang, S. 2009. The evolution of color vision in nocturnal mammals. Proc. Natl. Acad. Sci. U.S.A. **106**: 8980–8985. doi:10.1073/pnas.0813201106. PMID:19470491.