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Environmental Impacts of Artificial Light at Night

Kevin J. Gaston[1] and Alejandro Sánchez de Miguel[2,3]

[1] Environment and Sustainability Institute, University of Exeter, Cornwall, United Kingdom; email: k.j.gaston@exeter.ac.uk

[2] Departamento de Física de la Tierra y Astrofísica, Instituto de Física de Partículas y del Cosmos (IPARCOS), Universidad Complutense de Madrid, Madrid, Spain; email: alejasan@ucm.es

[3] Instituto de Astrofísica de Andalucía, Glorieta de la Astronomía, Granada, Spain

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Abstract

The nighttime is undergoing unprecedented change across much of the world, with natural light cycles altered by the introduction of artificial light emissions. Here we review the extent and dynamics of artificial light at night (ALAN), the benefits that ALAN provides, the environmental costs ALAN creates, approaches to mitigating these negative effects, and how costs are likely to change in the future. We particularly highlight the consequences of the increasingly widespread use of light-emitting diode (LED) technology for new lighting installations and to retrofit pre-existing ones. Although this has been characterized as a technological lighting revolution, it also constitutes a revolution in the environmental costs and impacts of ALAN, particularly because the LEDs commonly used for outdoor lighting have significant emissions at the blue wavelengths to which many biological responses are particularly sensitive. It is clear that a very different approach to the use of artificial lighting is required.

Contents

1. INTRODUCTION

For everywhere on Earth that experiences substantial natural light cycles, somewhat less than a half of each year is nighttime (the difference being caused by light still reaching the ground when the sun is below the horizon—twilight). Excepting those times when nighttime is accompanied by low temperatures (e.g., at high elevations or latitudes), much biological activity, ecological function, and ecosystem process occurs during the night. Indeed, it is not unlikely that across the globe almost as many organisms are physically active at night as during the day, and some of the greatest global shifts of material are associated with day-night cycles [e.g., carbon in the oceans as a consequence of diel vertical movements of organisms (1)].

This said, the environment and ecology of the nighttime has attracted far less attention and study than has that of the daytime, arguably because humans belong to a species that is evolutionarily adapted to be diurnally active (1). Although some nocturnally active groups of organisms (e.g., moths, bats, primates) have been subject to much research, this has not typically been in the context of their contribution to the environment and the ecology of the nighttime. This same bias extends further to anthropogenic impacts on the natural environment. Vastly more attention has been paid to what happens during the daytime than during the nighttime, even for those pressures that are exerted during both (e.g., climate change). In this regard, a key consideration is outdoor artificial light at night (ALAN), from streetlights and multiple other sources (**Figure 1**). On purely theoretical grounds, one would predict that ALAN would have powerful environmental effects, for the simple reason that natural light cycles are key drivers of biological processes, and because ALAN disrupts those cycles.

In this article, we review the extent and dynamics of ALAN, the benefits that ALAN provides, the environmental costs and impacts ALAN creates, approaches to mitigating the negative effects, and how the costs are likely to change in the future. Understanding these issues is particularly

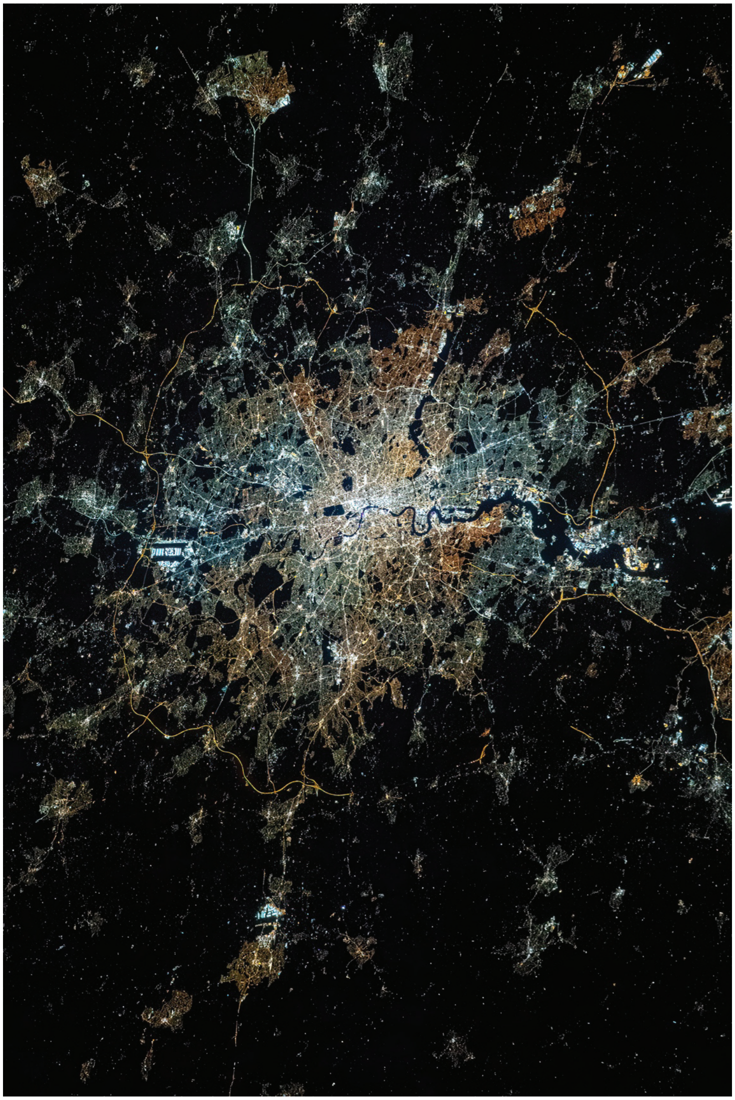

Figure 1

Greater London and its environs at night. View (25.03.2020 at 21:19:41 GMT) from the International Space Station (ESA/NASA), after image processing (image ISS062-E-112720). Variation in the colors of the light emissions reflect predominant lamp technologies. Image used with permission from the Earth Science and Remote Sensing Unit, NASA Johnson Space Center (**https://eol.jsc.nasa.gov**). Abbreviations: ESA, European Space Agency; GMT, Greenwich Mean Time; NASA, National Aeronautics and Space Administration.

important. First, the extent of ALAN is growing rapidly and it is an increasingly pervasive environmental pressure. Second, it is also changing in its form in significant ways, primarily as a consequence of widespread use of light-emitting diode (LED) technology—often referred to as constituting a lighting revolution—for new lighting installations and to retrofit pre-existing ones. Third, the need to respond to the environmental impacts of ALAN is increasingly being highlighted by national and international bodies, epitomized by the motion approved at the

Light-emitting diode (LED): a semiconductor (solid-state) light source that emits photons when an electric current is applied to the material

IUCN (International Union for Conservation of Nature) World Conservation Congress in 2021 on "Taking action to reduce light pollution" (2). Throughout, we focus particularly, although where important for context not exclusively, on more recent research developments and insights.

Light pollution: artificial nighttime lighting

Skyglow: the increased nighttime sky brightness that results predominantly from upwardly emitted artificial light being scattered in the atmosphere by water, dust, and gas molecules

2. EXTENT AND DYNAMICS OF ARTIFICIAL LIGHT

ALAN alters natural light cycles in terms of the intensity of light as well as its timing, dynamics, spectrum, and polarization (3, 4). These changes have arisen at scale largely with the use of electric-powered light sources and thus only in the past approximately 100 years (5); the presence of networks of outdoor lights may be perceived by people, particularly in regions where they are presently unaffordable, as an indicator of modernity.

Global estimates of the long-term growth in ALAN remain wanting, because of a lack of suitable data. However, new estimates suggest that the power of global satellite observable light emissions increased from 1992 to 2017 alone by at least 49% (6), a faster rate than that of growth in the global human population [37% (7)] and in some other major environmental pressures. However, the transition to solid-state LED technology (with incandescent, halogen, high-intensity discharge and fluorescent technologies increasingly being phased out by regulation and manufactured in much reduced quantities) has increased emissions at visible wavelengths (in the blue part of the spectrum) that are undetectable to existing satellite sensors. Estimation of this component suggests that the true overall increase in radiance in the visible spectrum may be as high as 270% globally and 400% in some regions [**Figure 2** (6)].

Even recent global increases in ALAN result from a combination of greater artificial lighting of areas that were already lit, and in some cases may have been so for long periods, and its expansion into areas that were previously unlit [including through creation of new developments and electrification and lighting of pre-existing ones (8)]. Estimates of the spatial extent of ALAN emissions are challenging because of their dependence on the lighting threshold at which such emissions are measured and included, the spatial resolution (grain) at which this is determined, the time of day [emissions typically peak in the evening and decline subsequently (**Figure 3**)], and how continuously lighting needs to be present for—e.g., number of days—to be counted. A recent analysis determined that globally (between 59°N and 55°S), at $1.6 \times 2.1\ \mathrm{km}^2$ resolution direct emissions were detected over 26.5% of the land surface from data obtained for repeatable light sources at 01:30 (9). Importantly, this emphasizes that the occurrence of ALAN is far from isolated to urban areas [which cover less than 1% of the global land surface (e.g., 10)], particularly given that this occurrence is likely much greater if one accounts for isolated artificial lights and those that are otherwise difficult to detect from publicly readily available satellite imagery. Of course, ALAN emissions show great variation at both this and finer spatial resolutions, often varying dramatically at scales of a meter or less.

Although it is convenient to consider the extent of ALAN in two-dimensional terms, it is a three-dimensional issue. This is because not only is artificial light emitted at multiple heights (from ground level to skyscrapers and communication towers, and airplanes) and at multiple angles above the horizontal, but it is also widely reflected. Skyglow is the increased nighttime sky brightness that results predominantly from upwardly emitted and reflected artificial light being scattered in the atmosphere by water, dust, and gas molecules. Particularly when amplified by clouds or snow, it can be sufficient to obscure lunar cycles (11) and render a moonless night as bright as one lit by a full moon (12, 13). Skyglow has been estimated to extend over 23% of terrestrial land area (14), although distance-decay functions for skyglow from urban sources suggest this may be an underestimate. The brightening of the night sky may be further exacerbated by the proliferation of low Earth orbit artificial satellites (particularly through ongoing deployment of megaconstellations) and space debris (15).

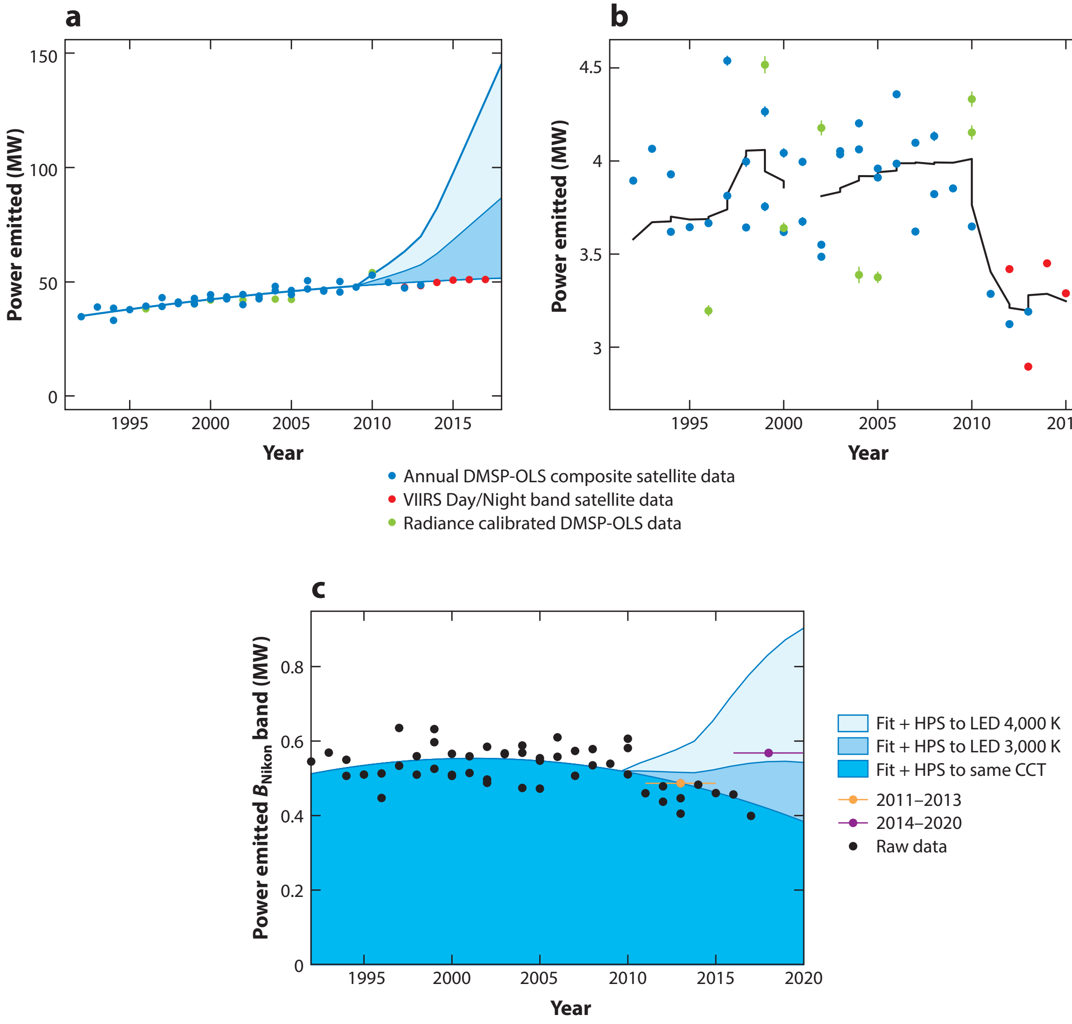

Figure 2

Emitted power (MW) globally (*a*) and for the United Kingdom (*b*,*c*) from artificial light sources from 1992 to 2017 detected by satellites. (*a*,*b*) Blue circles represent annual DMSP-OLS composite satellite data, green circles radiance calibrated DMSP-OLS data, and red circles VIIRS Day/Night band satellite data. Plotted data points assume constant spectral composition of light emissions. (*c*) The same data as in panel *b* are plotted as black circles but in terms of the blue light content of the emissions (based on 6, 145); the orange circle is determined from data obtained from the International Space Station for 2011 to 2013 and the purple circle for 2014 to 2020. (*a*,*c*) The shaded areas represent the possible range of undetected light assuming a recent phased transition from high-pressure sodium lighting to LEDs of color temperature 3,000 K (*intermediate blue*) or 4,000 K (*light blue*) and (for *c*) the fit to the data and then assuming HPS lighting of 2,000 K (*dark blue*). Panel *a* adapted from Sánchez de Miguel et al. (6) (CC BY 4.0). Abbreviations: CCT, correlated color temperature; DMSP, Defense Meteorological Satellite Program; HPS, high-pressure sodium; LED, light-emitting diode; OLS, Operational Linescan System; VIIRS, Visible Infrared Imaging Radiometer Suite; MW, Megawatts.

These direct emission and skyglow effects can also extend substantial distances out to sea, particularly because light paths are typically unhindered. Davies et al. (16) estimated from satellite-derived data that 22% of the world's coastlines (excluding Antarctica) alone were exposed to ALAN.

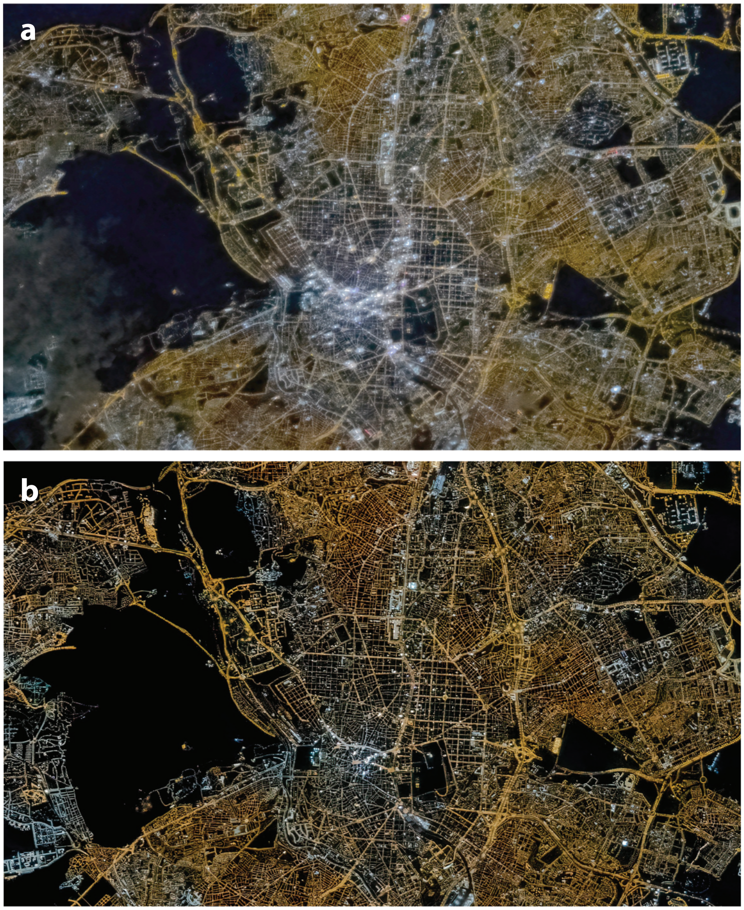

Figure 3

The city of Madrid earlier (*a*) and later (*b*) at night. Images from the International Space Station acquired on 13.05.2021 at 21:38:14 GMT (image ISS065-E-45335) and on 24.07.2021 at 23:35:05 GMT (ISS065-E-203751; ESA/NASA). It is clear how most light sources have been turned off in the later night image. Reprinted with permission from the Earth Science and Remote Sensing Unit, NASA Johnson Space Center (**https://eol.jsc.nasa.gov**). Abbreviations: ESA, European Space Agency; GMT, Greenwich Mean Time; NASA, National Aeronautics and Space Administration.

These statistics highlight the growing scarcity of areas (particularly large ones) that are experiencing pristine natural light cycles as well as the increasing need to protect areas that do so and to treat the natural nighttime as an important resource. The root causes of artificial nighttime lighting are well evidenced by the fact that satellite imagery of the earth at night has been employed to estimate variation in levels of human population density, urbanization and development, and economic activity (17–21). Indeed, for regions for which direct estimates are difficult or impossible to obtain these can be the best available.

3. BENEFITS

Key context for the environmental impacts of ALAN is the benefit that it is intended to provide. This takes five key broad forms, which we term as using the nighttime, safety and security, advertising and aesthetics, harvesting, and pest and predator control.

3.1. Using the Nighttime

Much outdoor lighting is intended to enable or facilitate people's use of the nighttime, including for working, socializing, and way-finding. This includes both static lighting (e.g., associated with housing, streetlighting, transport hubs, sports stadia, and other businesses) and mobile lighting (e.g., from vehicle headlights). It is commonly assumed that streetlighting is the primary source of outdoor ALAN emissions, and experiments to determine the environmental impacts of ALAN frequently use, or are designed to simulate, emissions from streetlights. Nonetheless, recent studies have shown that other sources are important (22, 23), and streetlights are seldom the brightest sources (which are often associated with sports stadia and transport and industrial facilities).

3.2. Safety and Security

A high proportion of outdoor lighting is installed on the grounds of improving human safety and security, with often a widespread sense that more lighting is better and that any criticism or risk of legal proceedings for the use of too much lighting is likely to be less than for too little lighting (24). Some of this is industrial lighting, where the safety concerns are principally operational. More commonly this is civic or domestic lighting where the safety concerns are more generic. Disentangling actual from perceived benefits (both of which are important) in these civic regards is challenging. However, it is clear that the actual benefits are often much less than those perceived, with evidence that impacts of civic lighting and changes thereof on road traffic accidents (at least away from critical junctions) and levels of crime may often be limited (25, 26); where reductions in crime do occur these may have more to do with lighting increasing civic pride and informal social control than increased surveillance of potential offenders (27). Indeed, there are circumstances under which the presence of artificial lighting can reduce human safety and the security of property, with, for example, streetlighting encouraging vehicles to be driven at greater speeds and with less attention and facilitating burglaries without the need for additional lighting.

3.3. Advertising and Aesthetics

Artificial lighting is used extensively outdoors for advertising hoardings or billboards; in 2020 there were an estimated 343,000 billboards in the United States alone (28). It is also used widely for aesthetic purposes, including the lighting up of built structures and ornamental lighting, both permanently and temporarily (e.g., seasonally or for particular events). Many historical buildings have increasingly been lit (e.g., 29), and some cities have gained almost iconic artificially lit nightscapes (e.g., Hong Kong, Shanghai).

3.4. Harvesting

Artificial lights are used widely to facilitate, legal and illegal, harvesting of animals. Terrestrially, this occurs foremost through the use of torches and spotlights to locate and illuminate quarry, with the growing availability of LED torches/flashlights having recently increased the frequency and efficiency of nocturnal hunting in the tropics (30).

Artificial lights are also used widely to attract quarry in both artisanal and commercial fisheries, and this may be one of the most effective fishing methods (31, 32). Large aggregations of vessels using surface lights are apparent in satellite imagery of the earth at night, to the point where the occurrence of lights may indicate the effectiveness or otherwise of fishery closures [intended to promote the sustainability of stocks (33)]. The use of underwater lights to attract fish is also widespread and likely to grow (32). Somewhat ironically, attaching lights to nets has also been found to be a way of reducing the bycatch of nontarget fish as well as turtles and cetaceans (32, 34).

3.5. Pest and Predator Control

Although such use is as yet limited, and other consequences do not seem to have been evaluated, ALAN has been promoted as a means of reducing the effects of pests on crops by suppressing certain behaviors [e.g., feeding (35, 36)] and by attracting their predators (37). It is widely used, often in the form of ultraviolet emissions, in greenhouses (which, given their use also of artificial light to promote plant growth, may in some regions be major contributors to outdoor ALAN emissions) and food stores to attract insects to electric killers (36). Artificial lights (often with low frequency flicker) are also used to deter large mammalian herbivores from raiding crops (38) and large mammalian predators from taking livestock (39).

Life-cycle assessment (LCA): method of evaluating the environmental impacts of a product through its life cycle, from extraction and processing of raw materials, through manufacturing, distribution and use, to recycling and disposal

4. COSTS

On the other side of the ledger, ALAN has a wide diversity of environmental costs or negative impacts, much more so than is often appreciated.

4.1. Resources

A full life-cycle assessment (LCA) of the environmental impacts of ALAN would include the impacts of the production of the lighting devices themselves and the associated infrastructure (light poles, fixtures, cabling, control systems, etc.), including raw material extraction and acquisition, manufacturing, packaging and distribution, installation, and maintenance. That these impacts are likely to be substantial is indicated by the sheer numbers of lights in operation. A few indicative figures are that there are globally an estimated 317 million streetlights (40), 41,000 airports or airfields (41), 947 million passenger cars and 335 million commercial vehicles in use (42), 3.7 million marine fishing vessels (43), and 98,000 vessels in the global merchant fleet (44).

The ongoing transformation of outdoor lighting to predominantly LED sources has been much championed as a means of dramatically reducing its environmental footprint. However, the resource impacts of lighting devices vary greatly, depending on the technology and the manufacturer, and can be calculated in very different terms (e.g., per device, unit of light emission, unit of power consumption, unit of lit road). Depending on the details, LED lamps may or may not have lower resource impacts than other technologies, but end of life impacts may often be greater (45–48). One particular concern is the high precious metal and rare earth element content of LED lamps (including gadolinium, gallium, germanium, indium, lanthanum, lutetium, yttrium), many of these being more generally in high demand. LED lamps may also be challenging to recycle. The maintenance requirements and lifespan of lamps can also be an issue, as LEDs may not perform as well as has been assumed in resource impact calculations [long-term reliability may be compromised by thermal overload, irreversible color shift, decrease of efficacy, and other material fatigue issues (49)].

4.2. Energy Use and Carbon Dioxide Emissions

Electric-powered light sources (indoor and outdoor) presently consume approximately 17–20% of global electricity production (50), with public (predominantly street) lighting consuming approximately 2.3% (51). Artificial lighting thus has significant potential for increasing or reducing energy use and carbon dioxide emissions, and thus influencing global climate change trajectories.

LEDs are often referred to as low carbon technology and can result in substantial increases in luminous efficacy [lm/W; the ratio of output, in lumens (lm), to power consumed, in Watts (W)] per lamp compared with many other modern sources (52); compared with high-pressure sodium lamps, which LEDs are often replacing, energy use benefits tend to be greater at lower luminance levels (53). However, although much attention focuses on luminous efficacy, determining the energy use consequences of using LEDs is complicated because this will depend on (*a*) precisely what technology is being replaced and with what (54); (*b*) how the numbers of lamps are changed; (*c*) the intensity of light emissions and how this is intentionally changed through the nighttime and seasonally; (*d*) how light emissions change over the operating life of lamps (they commonly depreciate relative to initial specifications, in part because of buildups of dust or dirt on housings); (*e*) the source of electricity (renewable or otherwise) and the daily timing of demand (which can influence both the likely source and unit cost); and (*f*) public acceptability of new lighting (costs can increase dramatically if contracts with suppliers have to be renegotiated or further retrofitting schemes conducted because of public discontent). Moreover, the increased use of LEDs for outdoor lighting appears to have been associated with a rebound effect or the Jevon's paradox in lighting, where increases in power efficiency, and the associated perceived decrease in economic cost, have driven increased demand for outdoor lighting, and hence any efficiency gains have been counteracted by increased consumption of light (8).

Combining resource usage and lifetime energy usage into full LCAs suggests that LED technologies perform more favorably, in large part because lifetime energy usage dominates the outcome (46, 54, 55). However, impacts on astronomical observations, human health and well-being, and other organisms (see below)—all of which attract significant public and media attention—are routinely excluded from such assessments (indeed, it is not unusual for energy use and environmental impacts of artificial lighting to be treated as largely synonymous, although environmental impacts of resource extraction and end of life disposal are often included in LCAs). In large part, this is because this is methodologically challenging, but these other considerations may overwhelm those that are more tractable and that have been included in analyses.

4.3. Astronomical Observations

The spread of ALAN, particularly skyglow, has progressively limited the opportunities for both amateur and professional astronomers to make observations and measurements of the night sky and component celestial bodies, despite this continuing to be a source of significant discoveries (56, 57). Indeed, the avoidance of ALAN is a critical consideration in the location of new optical astronomical observatories. Its growth and changes in form have seriously compromised the operation of others, and for most optical observatories changes in ALAN remain a potential threat to their activities.

This said, contrary to common perception, there is limited research on how ALAN affects professional astronomical observations (e.g., the consequences of shifting spectra of ALAN for astronomical measurements are not well understood), compared, for example, with how these are being affected by satellite constellations, which is a much more recent problem. This is arguably in large part because with regard to such observations it is principally necessary to protect the large optical observatories that meet a variety of key positional requirements, usually including being far from major sources of ALAN. Moreover, major fields of astronomy/astrophysics research are largely uninfluenced by ALAN, the exceptions including those observatories concerned with space debris, meteors, and asteroid detections.

Of course, the impacts of ALAN on astronomical observations remain for amateurs, who almost invariably use optical methods. However, given the other important environmental impacts of ALAN beyond the production and use of lighting sources (see below), the burden of championing mitigation should not rest disproportionately on this group, as it seems often to have done.

4.4. Human Health and Well-Being

Principally, although not exclusively, rooted in the resultant changes in circadian rhythms, nighttime exposure to artificial lighting has been argued, on both theoretical and empirical grounds, to have important impacts on multiple dimensions of human health. These include immune function, and risks of vector-borne diseases, cancer (particularly breast and prostate), obesity and mood disorders (58–63). ALAN could thus be contributing to some of the key health concerns of our times. Given the complexity of many people's patterns of light exposure (with effects potentially also accumulating over long periods of a person's "light history"), a challenge remains in differentiating the relative contributions of indoor and outdoor lighting to these impacts (including the influence of outdoor lighting on indoor light experiences) and particularly in determining the significance of the latter.

In addition to the more direct impacts of ALAN, it may also have consequences for people through the loss of views of the natural night sky that are associated particularly with skyglow. Eighty percent of the global human population lives under light-polluted skies, and more than a third in areas where, as a consequence, the Milky Way is hidden from sight (14). This may have consequences for cultural benefits, including the sense of place (both local and universal), to which natural night skies contribute. Evidence that levels of ALAN experienced by human populations, and thus presumably their impacts, vary with their racial/ethnic composition and socioeconomic status has raised concerns of environmental justice (64).

4.5. Other Organisms

Beyond humans, ALAN has been documented to have biological impacts that are arguably epitomized by their breadth of forms and their taxonomic, spatial, and temporal pervasiveness. This breadth seems at least as great, if not more so, than that of other anthropogenic environmental pressures. One might argue that evidence of this breadth has resulted from a failure to develop one or a few model systems on which much of the research community could have focused investigation of the impacts of ALAN, there instead being a plethora of different systems that have been the subject of one or perhaps a few studies. These impacts include on the physiology and behavior of individual organisms, the abundance and distribution of species, and the structure and function of communities and ecosystems (**Figure 4**).

Five kinds of responses seem particularly key. First, the nighttime production of the hormone melatonin is acutely sensitive to ALAN (65). In most studies, this production is suppressed at even the lowest levels of artificial light tested, with the level of suppression often exhibiting a positive dose-response relationship (65). In animals this molecule plays roles in the regulation of sleep, modulation of circadian rhythms, reduction of oxidative stress, enhancement of immunity, and suppression of carcinogenesis (66). Thus the effects of ALAN on the biology of individual animals ramify quickly.

Second, exposure to ALAN can alter the feeding, growth, reproduction, and survival of individual wild organisms (67–71), something that should come as no surprise given that artificial lighting is used to such ends in cultivation settings (e.g., 72, 73) and also has unintended impacts on crops (74). For example, in a field experiment wild juvenile orange-fin anemonefish (*Amphiprion chrysopterus*) exposed to underwater illuminance of 4.3 lux were found to have reduced growth and survival compared to individuals exposed to natural moonlight (75).

Third, ALAN interferes with the orientation and movement of organisms, by either confusing their orientation mechanisms or acting as a more direct attractor or repellent [epitomized by the long-established use of light traps in sampling insects and evidence that this also works well for marine biota (76)]. Such responses can result, for example, in profound reshaping of the large-scale

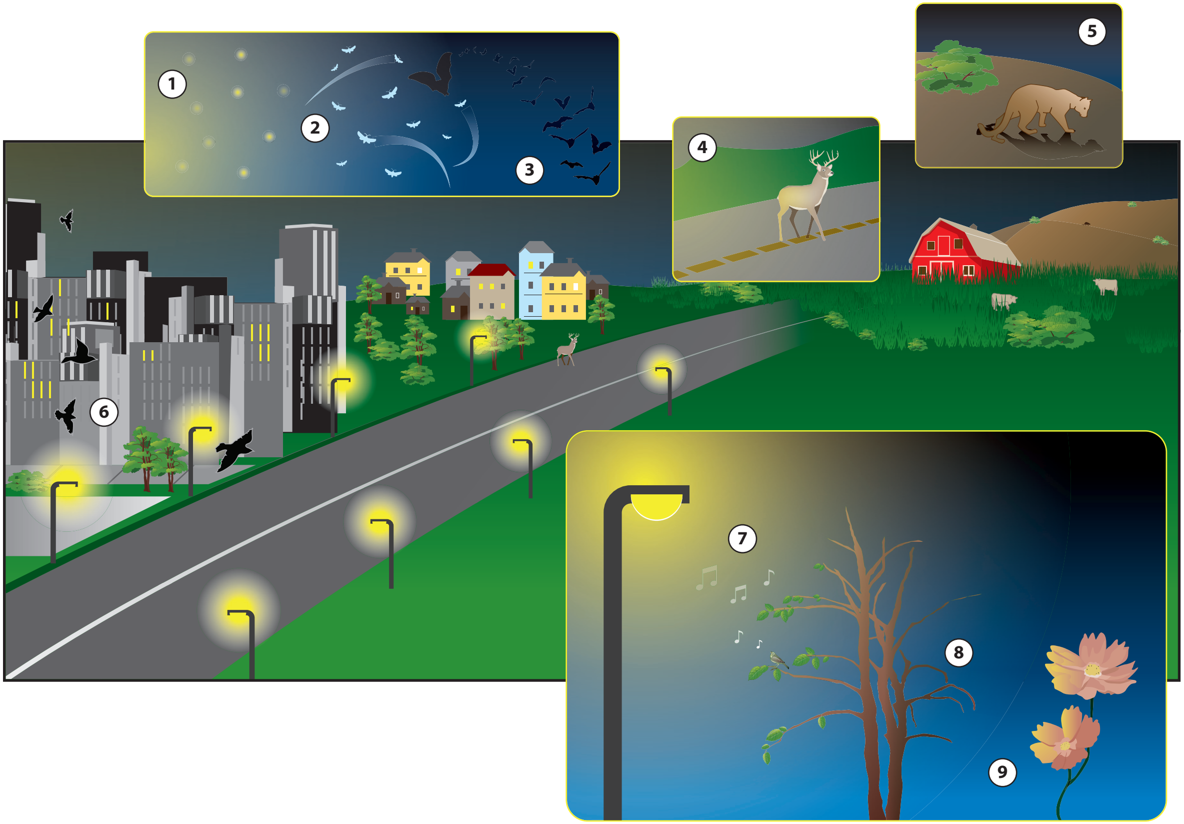

Figure 4

Examples of the biological impacts of ALAN on terrestrial organisms. ① Firefly light signal being obscured by competing lights; ② bats drawn to moths attracted to lights; ③ bats moving through dark corridors; ④ mammals (e.g., deer) crossing roads in darker gaps between lights; ⑤ mammals (e.g., cougar) moving away from lit areas; ⑥ migratory birds (e.g., thrushes) attracted to city by nighttime lighting; ⑦ birds singing at night near streetlight; ⑧ leaves retained on side of tree near to streetlight; ⑨ plants flowering earlier closer to streetlight.

migratory patterns of birds [most of which migrate at night (77, 78)], likely exacerbated by the greater distance at which sources of artificial light emissions are visible from altitude. Attraction to, or distraction by, artificial light sources can more generally result in organisms becoming exhausted, colliding (perhaps fatally) with obstacles, and being drawn into areas without adequate resources and with enhanced predation risk, and that may act as population sinks (79–82). These may be sufficient to create substantial population declines.

Fourth, ALAN obscures changes in natural daylength and hence cues for timings of seasonal (phenological) events, such as bud burst (83), reproduction (84–86), and migration (87). Perhaps most striking is evidence that ALAN can advance the plant growing season over huge areas (88). The magnitude of phenological change seems in some cases to be similar to those that have raised profound concern (including because of the creation of phenological mismatches between different groups of organisms) when driven by other anthropogenic environmental pressures, such as climate change. Disentangling these effects can be challenging, but they have the potential to be mutually reinforcing.

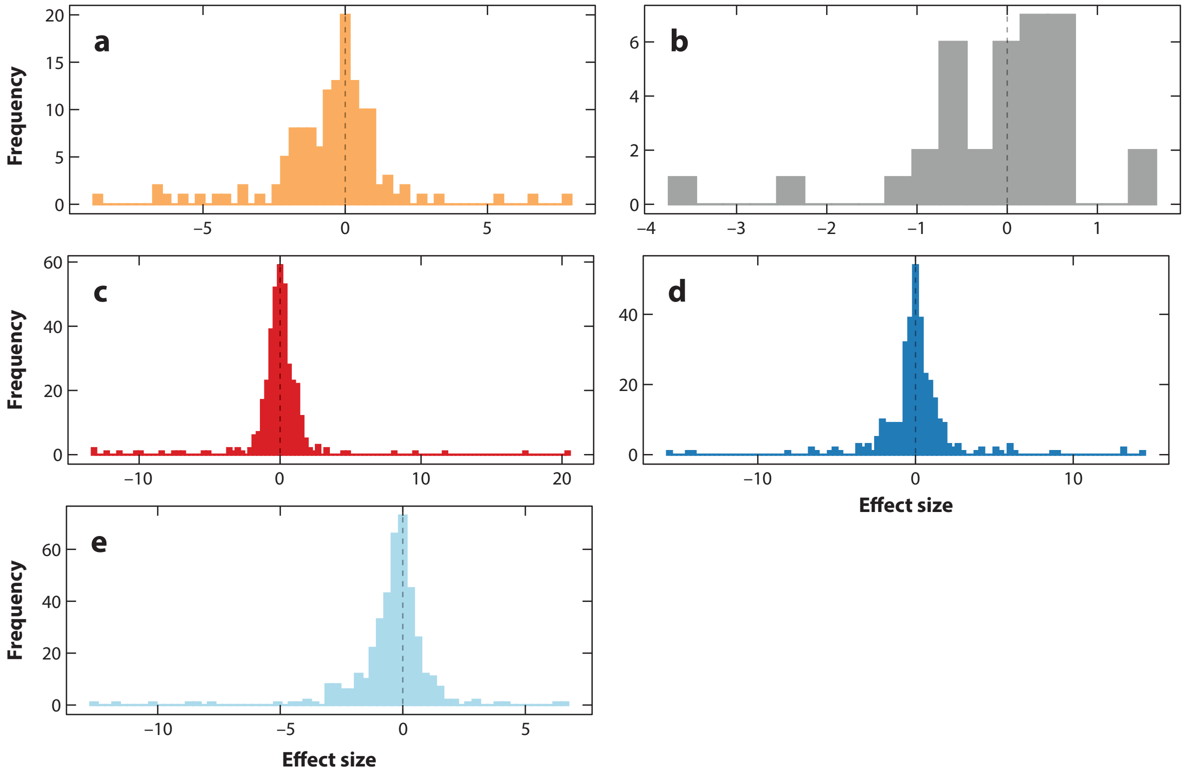

Figure 5

Frequency of effect sizes from observational and experimental studies of potential biological impacts of artificial light at night for (*a*) activity patterns, (*b*) phenology, (*c*) population/community structure, (*d*) organismal physiology, and (*e*) life history traits. See Reference 97 for methodological details, including how the directionality of effects (negative, positive) was scored, and data.

Fifth, ALAN interferes with interspecific relations [e.g., pollinator-plant, predator-prey, parasitoid-host (89–93)]. It does so by influencing not only the timings and spatial occurrence of the activity of species (94–96) but also their visual ecology, including the ability to find resources and to camouflage themselves from predators (93). One consequence of the influence of ALAN on interspecific relations is that the effects can ramify through interaction networks and may often thus impact species that may not themselves be experiencing, or are not directly responding to, ALAN itself.

A recent meta-analysis of the findings of 126 empirical studies found that the effect sizes of ALAN on particular biological traits are often quite variable [**Figure 5** (97)]. Many of the impacts of ALAN on organisms are clearly negative, some potentially positive for particular species, and some difficult to characterize (e.g., an increase in the time available for activity because of ALAN could have a variety of outcomes). What is perhaps more significant is that ALAN commonly causes profound disruption of natural situations. This is similar to what occurs with climate change. Thus, although there must be particular concern about those taxonomic groups for which ALAN is regarded as a contributor to major declines in abundances [e.g., fireflies, glowworms, moths, seabirds (79, 98–100)]—and the array of species for which such a contribution is suspected seems continuously to grow—there must also be concern over how more generally it restructures ecological systems.

Studies of the biological impacts of ALAN have increased dramatically in the past decade. Some key general findings include the following:

1. ALAN impacts a wide breadth of taxa, including bacteria, fungi, plants, and animals (97, 101, 102). It seems likely that representatives of all taxa that experience marked natural light cycles will be affected. Thus, effects of ALAN have been documented in benthic and pelagic [including Arctic (103, 104)], freshwater, and terrestrial systems (97).
2. As evidenced by data on the spatial occurrence of ALAN, across much of the world high proportions of species experience ALAN at some point in their life cycle, as do many hotspots of biodiversity, key biodiversity areas, and areas protected for biological conservation (105–107). The erosion of natural light cycles in many protected areas is particularly troubling and typically arises as a consequence of the incursion of ALAN from outside with variable contributions from sources within their bounds. The incursions from outside are exacerbated because of the small extent of many protected areas, and because areas immediately beyond their bounds may have accelerated human population growth (108).
3. Although there can be a temptation to think just in terms of the impacts of ALAN on nocturnal organisms, many diurnal species are also affected. This can happen directly through perceived changes in hours for activity and in daylength, and through the disruption of sleep (91, 109–111). It can also happen by the ramification of impacts through interspecific interactions.
4. Low intensities of ALAN can have important biological impacts (65, 91, 97, 112, 113); quite what is regarded as constituting dim light is variable, but what is important is that biological impacts are stimulated by artificial light levels that might be experienced well away from the immediate area lit by a typical outdoor lamp and thus over large extents. Indeed, although some impacts clearly exhibit positive response functions with increasing intensity of ALAN, across multiple impacts there is no simple relationship (97). The duration of exposure may have a role to play, particularly at low light intensities, and it would be valuable to explore how this and light intensity interact in their influence on different biological processes. The importance of low intensities of ALAN has highlighted a need for greater attention to the "normal" artificial nighttime lighting conditions under which laboratory organisms are commonly maintained, as these may stimulate physiological, behavioral, and other responses that are different from those that would occur under natural light regimes, and may prove misleading if used to infer the latter.
5. There is growing evidence, albeit limited, that skyglow has important biological impacts (114, 115). This has long been suspected, although concerns have principally focused on possible effects on diel vertical migration in aquatic systems. Given its spatial extent particularly beyond urban areas, biological impacts of skyglow could be extremely widespread. This may especially be the case if artificially lit horizons, which away from urban centers tend to have the greatest skyglow, influence orientation (through attraction or repulsion) and/or predator-prey relations (e.g., through silhouetting individuals against unnaturally bright backgrounds).
6. Almost all biological responses to ALAN are sensitive to the spectrum of the emissions. These include physiology and behavior, and phenomena that they influence such as abundance and community structure (100, 101, 116–119). Broad spectrum lighting is regarded as particularly problematic, because it can stimulate responses across a wide range of wavelengths; it is somewhat ironic that much of the energy efficiency of LED lamps arises from emissions in the blue part of the spectrum [hence lamps with higher correlated color temperature (CCT) are more efficient], which environmentally is often the most problematic.

Correlated color temperature (CCT): temperature of an ideal black-body radiator that radiates light of a color comparable to that of a light source; lower ("warmer") correlated color temperatures tend to be more yellowish, and higher ("cooler") ones tend to be bluer

Narrow spectrum lighting will often have less impact, with amber lighting having been heavily promoted for this reason, but it is increasingly clear that the variation in spectral sensitivities of different biological processes and organisms makes it difficult to identify the narrow spectra with least effect and that provide useful/acceptable lighting for people. It is also important to distinguish between spectral outputs and human perception of the color of lighting. Thus, the "amber" emissions of low-pressure sodium lighting, which has an extremely narrow spectrum (but is more useful for human vision than a red light), can have very different biological impacts from the emissions of phosphor-converted (PC) amber LED lighting, which has a broad spectrum (93).

7. Biological impacts of ALAN can extend far beyond the spatial occurrence of light emissions, because those emissions can attract or repel organisms over long distances and because they can disrupt spatial processes [e.g., dispersal (120)]. It seems likely that these effects are significantly underreported, because they may be exhibited at local sites where ALAN itself does not actually occur and may thus be attributed to other causes.
8. There is limited direct evidence for evolutionary responses to ALAN (but see 121, 122). This could be because ALAN is an evolutionarily rather novel pressure and that the use of lighting as a cue for biological processes is evolutionarily deep-rooted and not easily changed. It could also be because insufficient effort has as yet been put into testing for evolutionary responses to ALAN.

Some key gaps that persist in understanding the biological impacts of ALAN that have not been mentioned above include (*a*) biological impacts of ALAN in tropical regions where, because of limited variation in actual daylength, organisms may be particularly sensitive to small shifts in perceived daylength; (*b*) whether and, if so, how biological impacts change with the historical duration of ALAN in an area; (*c*) how biological impacts of isolated and aggregated lights differ and how skyglow changes effects of individual lights; (*d*) how different forms of ALAN (e.g., direct emissions, skyglow) combine in causing biological impacts; (*e*) the potential role in biological impacts of the high frequency flicker of many artificial light sources (123); and (*f*) the biological impacts of the lower frequency pulsed lighting caused by passing road vehicle headlights (124).

4.6. Covariation and Interaction with Other Pressures

The impacts of ALAN have almost exclusively been studied in isolation from other anthropogenic environmental pressures; the most compelling experimental studies of the impacts of ALAN are often regarded as those conducted in otherwise naturally dark rural landscapes. However, these will very often not occur in such isolation. Most obviously ALAN is commonly associated with urbanization and the other environmental changes that co-occur, including in land use, disturbance, and noise, atmospheric and water pollution. Moreover, there may be interactions between ALAN and other anthropogenic environmental pressures, potentially giving rise to additive or synergistic effects.

4.6.1. Habitat loss and fragmentation. The loss of habitat and its fragmentation are foremost characterized in terms of changes relevant to day-active organisms, particularly when it comes to identifying opportunities and challenges to the persistence and movement of organisms, such as habitat patch area, corridors, habitat "stepping-stones," and barriers. For night-active organisms, these effects may be altered by the occurrence of ALAN, which can create both changes in habitat conditions—and thus what constitutes suitable habitat and area thereof—and also other barriers to, and directors of, movements.

4.6.2. Overexploitation. The heavy use of artificial lighting in some forms of harvesting activities (see Section 3.4) doubtless has significant wider environmental impacts, including on many organisms that are not being directly targeted. This may particularly be so with fishing boats, because of their often night-long operations and their large numbers. Concerns that artificial lighting of research vessels creates a "halo" of environmental disturbance should presumably extend to other vessels (104).

4.6.3. Climate change. Light and temperature are both key determinants of the timing of biological activity, raising the potential for combined effects of ALAN and climate change. These effects may be further exacerbated for nocturnal species, because as a consequence of human activity nighttime (and therefore minimum) temperatures are increasing more rapidly across much of the land surface than are daytime temperatures (125). However, the two pressures may influence day-active organisms as well. Miller et al. (126) found nonadditive effects of temperature and ALAN, which together caused much greater suppression of aphid numbers by a visually hunting predatory ladybeetle species.

4.6.4. Pollution. ALAN frequently co-occurs with other forms of pollution (e.g., noise, chemical, particulate). Understanding the extent to which this exacerbates the challenges of each remains poor, but additive and synergistic outcomes seem likely to be widespread. For example, increases in atmospheric pollution result in increases in skyglow (127), ALAN exacerbates impacts of noise pollution on birds (128), and the effects of ALAN and noise pollution have been found to interact in a study of frog-biting midges (129). In laboratory experiments, exposure to ALAN has also been found to counter reductions in leaf litter decomposition rates in freshwater resulting from lead or silver nanoparticle contamination (130, 131).

4.6.5. Alien species. It seems likely that ALAN will change the presence of many alien species, their behavior, and thus their potential interspecific and ecosystem influences (132, 133). Whether there are many cases in which this exacerbates the substantial pressures that alien species can otherwise exert is unclear, but this is an issue that probably deserves some attention. This is especially so because many mammal species, for example, are known to change their diel activity in the presence of alien species (e.g., 134, 135).

5. MITIGATION

Given the widespread occurrence of ALAN (including within protected areas) and its diverse environmental impacts, its mitigation needs routinely to be addressed in both urban and rural contexts, and by governmental, business, and third sector bodies (including conservation organizations). The broad mechanisms for doing so are well-established and for the most part technically straightforward [**Figure 6** (136, 137)], with a focus particularly on limiting lighting to the forms, places, and times in which it is actually required by people. These might usefully be framed in terms of the mitigation hierarchy.

5.1. Mitigation Hierarchy

The conventional sequence of progressively reducing desirability of elements of the mitigation hierarchy is that of avoid, minimize, restore or rehabilitate, and offset. In the case of ALAN, this is probably instead that of avoid, restore or rehabilitate, minimize, and then offset.

5.1.1. Avoid. The retention of remaining dark areas is an increasingly important strategy as such spaces become more scarce, particularly in heavily urbanized regions such as Europe (138).

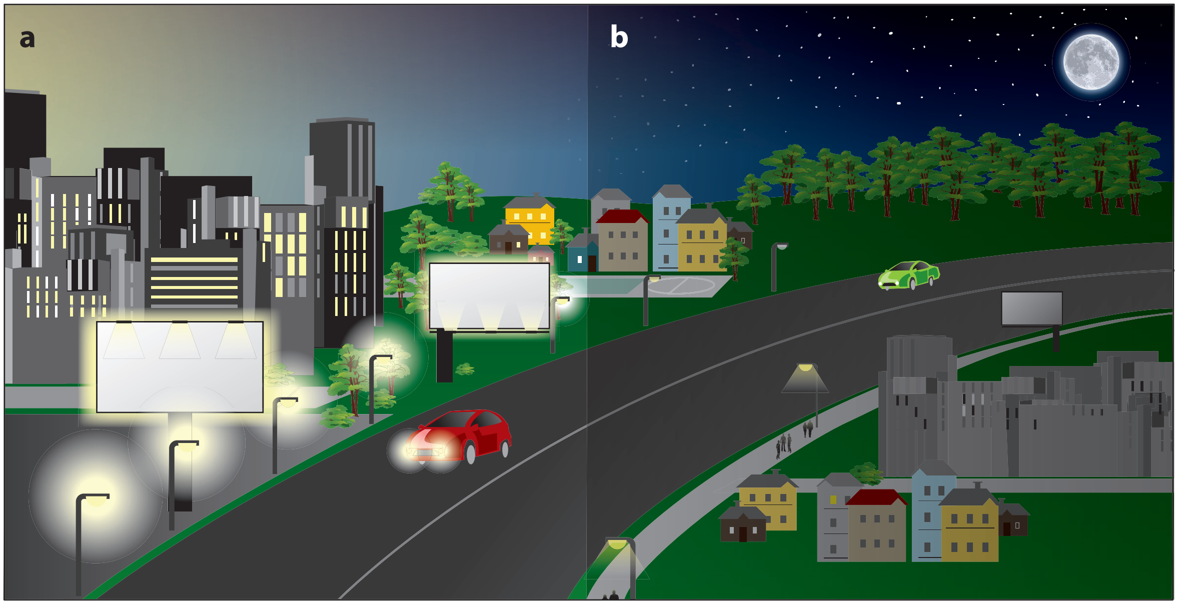

Figure 6

Good and bad lighting practices. (*a*) Bad lighting practices: numerous, bright streetlights emitting light above the horizontal, more white light, lights from home interiors showing, building lights always on, lit advertisement hoardings/billboards, brighter skyglow, cars with bright glaring headlights. (*b*) Good lighting practices: fewer, dimmer lights that do not emit light above the horizontal (i.e., are well shielded), lighting responsive to the presence of people, less white lights, curtains drawn, building lights off when not in use, unlit advertisement hoardings/billboards, less skyglow, dimmer and less glaring headlights.

Indeed, although this is not done, darkness needs to be included in spatial conservation planning so as to ensure that networks are retained to provide organisms with adequate naturally dark spaces and enable them to move between these in natural darkness.

5.1.2. Restore or rehabilitate. There is plenty of opportunity to remove sources of ALAN from areas and thereby recreate dark spaces, particularly associated with the ongoing urbanization of the human population and the associated depopulation of some rural areas. In this context it is important to remember that much lighting was introduced to use excess power production and/or when power was cheap, rather than because there was necessarily a strong need for the lighting itself. Evaluations need to be conducted of the desirability of retaining particular lighting schemes at all, rather than just the desirability of replacing existing ones with new or retrofit lighting schemes (recognizing that there can be regulatory and liability structures that mean that the removal of artificial lighting from an area is more difficult than is deciding not to install lighting in a previously unlit area).

5.1.3. Minimize. Most discussion of mitigation of ALAN focuses on minimization of its environmental impacts. This can variously be achieved by limiting numbers of lights, increasing lighting shielding/reducing lighting trespass (both at source and through employing barriers, artificial or preferably natural), dimming the intensity of light emissions, reducing the duration of lighting (through part-night lighting, seasonal lighting, adaptive/user responsive lighting), and/or using less damaging spectra. There is evidence that all of these are to some degree beneficial (136, 137, 139, 140), although determining the consequences of actual lighting changes can often be complicated because in practice multiple changes are often made simultaneously (e.g., changes in spectra of emissions by employing different lighting technology are often accompanied by changes in numbers of lamps, in the kinds of luminaires, in light intensity, and sometimes in timing of lighting). Most doubt is associated with the effectiveness of reducing the nighttime duration of lighting because, although this creates energy savings and general reduction in light pollution, there is often overlap between the times when such lighting is required by people and when other organisms are active, although part-night lighting can be helpful for those active later at night (141). There tends also to be confusion in much discourse about minimizing the environmental impacts of ALAN between the use of LED technology and the broad white spectra that it is commonly used to produce in public lighting schemes. LED technology can be used to produce a wide array of spectral outputs (often very precisely), and the frequently heightened negative biological impacts of broad white lighting is not per se a criticism of the use of LED technology, although it is often expressed as such. This flexibility of LED technology may prove valuable in enabling selective tuning of white light spectra to reduce emissions at wavelengths that trigger particularly problematic biological responses (142, 143); this approach has become easier to implement with the emergence of color-mixing white LEDs (40).

5.1.4. Offset. There has been little discussion of the use of offsetting approaches in the context of ALAN, although it is not hard to envisage that its introduction in some areas might usefully be offset by its removal elsewhere. In other environmental contexts, such as habitat destruction, offsetting schemes can be plagued by issues of equivalency (between what is lost and gained), time differentials (e.g., how quickly habitat can be lost compared with how long it takes to create equivalent or better new habitat), and gaming (e.g., removing valuable habitat early to establish a fresh baseline for subsequent offsetting). How similar such concerns are in the context of ALAN is unclear, although obviously one would not want to see ALAN being introduced into areas of high biodiversity value in exchange for its removal from areas of low such value.

5.2. Opportunity and Challenge

Unlike many other environmental pressures, these mitigation steps often potentially provide energy (and thus carbon dioxide emission), resource (including precious metal and rare earth element), and financial savings, alongside benefits for human health, astronomy, and biological conservation, and are for the most part technically straightforward to employ. Although the balance of perceived versus actual need for ALAN may be challenging to navigate, even quite substantial changes to ALAN (such as dimming and part-night switch offs) may also often pass relatively unnoticed by the users or residents of areas, especially if implemented incrementally (144); making unannounced changes does beg questions of democratic process.

Unlike the solutions to many other environmental pressures, those for ALAN can also have rapid benefits. It would be overly simplistic to envisage that removing artificial lighting will immediately remove all of the environmental impacts of ALAN, as there are doubtless significant lag effects in recovery (particularly where ALAN has impacts on population and community structures). But many responses are likely to be rapid, and where there are lags these are likely to be much shorter than those associated with the reduction of many other anthropogenic environmental pressures. To date, although many experiments have introduced ALAN into previously naturally dark areas to determine the biological impact, the converse experiments, removing ALAN from lit areas and tracking the biological consequences, have not been conducted. These would be valuable in understanding trajectories of recovery and whether there are any tipping points, where ALAN moves ecosystems into alternative stable states from which it is hard to return them.

In reducing the environmental impacts of ALAN, four particular challenges are noteworthy. First, there is a need to agree on standards for measuring artificial light in a way that can be used as readily obtained indicators for environmental impacts and how they are changing (for better or worse). This is difficult both because of the complexity of artificial light and its impacts and because of the different emphases of interested parties (impacts on night skies, on human health, on migratory birds, etc.). Measurement using the RGB (Red-Green-Blue) sensor systems of digital cameras has increasingly been championed, given how widely available these are (especially associated with mobile phones) and the critical importance of the spectral composition of ALAN to many of its environmental impacts (145).

Second, there is a need to agree on lighting standards—moving beyond just arguments that more environmentally friendly or less lighting is better—that can best guide the minimization of negative environmental impacts while delivering the human benefits that are required from outdoor lighting (e.g., CCT, intensity, timing). This is particularly significant, because in many contexts the forms, levels, and timing of lighting that can be used—particularly minimum acceptable requirements (rather than upper limits on emissions)—are practically (sometimes legally) constrained by regulation or linked to recognized formal sources of guidance. Again this has proven problematic, because (*a*) of the diversity of reasons for which artificial lighting is employed and the complexity of the "nightscapes" that it creates; (*b*) scientific understanding of the environmental impacts of ALAN is continuing to develop rapidly with, for example, the importance of effects at low light intensities (e.g., 91, 97) and broad spectra weighted toward longer wavelengths [e.g., PC amber LED (93)] only recently becoming widely recognized; and (*c*) this scientific understanding increasingly underlines that virtually all forms of ALAN have biological impacts, making it challenging just what intensities, timings, and spectra to recommend. Break points, at which negative impacts become markedly reduced, are not usually evident, suggesting that rules of thumb will need to be agreed upon that balance benefits and costs.

Third, although important to maintain and further develop, there is a need to complement a regulatory approach that focuses on individual lights and installations with one that sets areal limits on ALAN (146, 147). This latter approach is challenging but serves to limit the cumulative degradation of nighttime environments that may arise even if individual lights and installations meet regulatory requirements.

6. THE FUTURE

Forecasting how ALAN will change over the coming years and decades is challenging. However, several things seem likely. (*a*) The global numbers of outdoor lights will continue to grow, particularly with expansion of urban areas and growth in the economies of middle- and lower-income countries; urban land area is predicted to increase by 1.8 to 5.9 times its 2000 coverage by 2100 (148). The global numbers of streetlights are predicted to grow by 15% between 2021 and 2027 (40). (*b*) This growth will be facilitated by off-grid technology that enables artificial lighting to be introduced into areas in which previously this has been difficult. This has the potential to change dramatically the occurrence of ALAN, and is of major concern given that these areas are likely to have been disproportionately protected from multiple anthropogenic environmental impacts and thus be environmentally more pristine than much of the rest of the planet. (*c*) Most of the growth in artificial lighting will use LED technology; 89% of streetlights are predicted to use LEDs by 2027 (40). Given that the luminous efficacy of LED lamps is projected to continue to be increased with further technological developments, the potential for previously documented rebound effects (8) to continue is evident. (*d*) New artificial lighting technologies may start to spread markedly. OLED (organic light-emitting diode) lamps may become the next generation of lighting, having further advantages including in terms of their mechanical flexibility, color quality, luminous efficacy, controllability, and lifetime (40). (*e*) ALAN will continue to become "whiter," as the proportion of "broad white" lamps grows relative to narrow spectrum lamps (e.g., low-pressure sodium). It seems likely that use of lower CCT (and perhaps PC amber) LED lamps will also grow, and how much of the market these gain will be critical to the global environmental impact of ALAN. Finally, (*f*) "smart" lighting control systems, which enable centralized management of individual streetlights, will become more common, increasing the potential for both conducting experiments to understand ALAN and its impacts (e.g., 23) and introducing systematic changes to the levels, occurrence, and timing of ALAN.

SUMMARY POINTS

1. Artificial light at night (ALAN) is globally extensive and continues to expand rapidly.
2. The benefits of ALAN include facilitating human use of the nighttime and its use in safety and security, advertising and aesthetics, harvesting of natural resources, and pest and predator control.
3. The environmental impacts of ALAN include its use of resources in the production of lighting devices and associated infrastructure, its energy use and carbon dioxide emissions, and its effects on astronomical observations, human health and well-being, and on other organisms.
4. Given the breadth and severity of its environmental impacts, a fresh approach to the use of artificial lighting is needed. This particularly requires avoidance of its use where possible, restoring or rehabilitating areas that have previously been lit, minimizing use wherever possible (limiting numbers of lights, increasing lighting shielding/reducing lighting trespass, dimming the intensity of light emissions, reducing the duration of lighting, and/or using less damaging spectra), and potentially offsetting introduction of lighting into new areas with its removal from previously lit areas.
5. Mitigation is often technically straightforward. The bigger challenge is that of closing the gap between perceived and actual human need for ALAN.

FUTURE ISSUES

1. Improved multispectral detection and monitoring of artificial light at night (ALAN) is required at global extents and fine spatial and temporal resolutions.
2. Research is needed to understand better people's perceptions of the necessity for ALAN and how this influences its use.
3. Life-cycle assessments of artificial lighting are required that include impacts on astronomical observations, human health and well-being, and other organisms.
4. Research is needed into the biological impacts of ALAN in tropical regions, where organisms may be particularly sensitive to small shifts in perceived daylengths.
5. Agreement is required on standard metrics of ALAN, on its environmental impacts, and for minimizing these impacts.
6. It would be valuable routinely to determine the likely environmental impacts of new and emerging lighting technologies before these begin to be installed widely.

DISCLOSURE STATEMENT

The authors declare that they have no competing interests. In the interest of full disclosure, they note that they serve as uncompensated members of the board of directors of the International Dark-Sky Association. In addition, A. Sánchez de Miguel discloses that he does consulting work sporadically for Savestars Consulting S.L. and is a member of the board of Cel Fosc. The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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