Why artificial light at night should be a focus for global change research in the 21st century

Davies, Thomas W.; Smyth, Tim

Global Change Biology

DOI:
10.1111/gcb.13927

Published: 01/03/2018

Why artificial light at night should be a focus for global change research in the 21st century

Running head: Artificial light is a global change issue

Thomas W. Davies[1,2] and Tim Smyth[3]

[1]School of Ocean Sciences, Bangor University, Menai Bridge, UK

[2]Centre for Geography, Environment and Society, University of Exeter, Penryn, UK

[3]Plymouth Marine Laboratory, Prospect Place, Plymouth, Devon, UK

Corresponding author: Thomas Davies; School of Ocean Sciences, Bangor University, Menai Bridge, UK; Thomas.Davies@exeter.ac.uk

Key Words: Artificial light at night, Global change, Ecology, Human health, Human-environment interrelationships.

Opinion

Abstract

The environmental impacts of artificial light at night have been a rapidly growing field of global change science in recent years. Yet light pollution has not achieved parity with other global change phenomena in the level of concern and interest it receives from the scientific community, government and non-governmental organisations. This is despite the globally widespread, expanding and changing nature of night-time lighting; and the immediacy, severity and phylogenetic breath of its impacts. In this opinion piece, we evidence ten reasons why artificial light at night should be a focus for global change research in the 21st century. Our reasons extend beyond those concerned principally with the environment, to also include impacts on human health, culture and biodiversity conservation more generally. We conclude that the growing use of night-time lighting will continue to raise numerous ecological, human health and cultural issues, but that opportunities exist to mitigate its impacts by combining novel technologies with sound scientific evidence. The potential gains from appropriate management extend far beyond those for the environment, indeed it may play a key role in transitioning towards a more sustainable society.

Introduction

While artificial light at night (ALAN) has been a long established man-made disturbance (Longcore and Rich, 2004), the number of studies documenting its ecological and human health impacts has grown dramatically in the last decade (Figure 1). Collectively, this body of research now highlights the pervasiveness of ALAN's impacts across a broad array of biomes, ecosystems, species and behaviours. The measured biological responses occur at intensities and spectra of artificial light that are currently encountered in the environment, and the global distribution of night-time lighting means that it is likely already having widespread impacts in marine, freshwater and terrestrial habitats around the world.

While ALAN research has gained notable momentum in recent years it is yet to achieve notoriety among environmental scientists as a driver of global change. Here, we argue that ALAN should be a focus for global change research in the 21st century. Our argument is broken down into ten points that highlight the global extent of ALAN; the geographic scale of its influence; the potential to reverse its environmental impacts; the rise of new human-environment conflicts with emerging lighting technologies; its evolutionary novelty; the diverse array of species now known to be affected; the extreme sensitivity of organisms to light; impacts on human health; cultural impacts on human-environment interrelationships; and the feasibility of solutions. While we do not assert that ALAN is any more important than other global change phenomena, we draw comparisons where they help highlight the need for greater parity of concern.

Globally widespread

As with greenhouse gas emissions, ALAN is a globally widespread environmental pollutant. It is estimated that 23% of the land surface between 75°N and 60°S (Falchi *et al.*, 2016), is exposed to artificial skyglow (artificial light that is scattered in the atmosphere and reflected back to the ground). This is comparable to the area of global ice-free land converted to either pasture or cropland, estimated to be 35% in the year 2000 (Klein Goldewijk *et al.*, 2011). The degree of exposure increased in all global terrestrial ecosystems between 2008 and 2012, with those important for biodiversity conservation often most affected (Bennie *et al.*, 2015b). Exposure to ALAN is not limited to terrestrial environments, with current best estimates indicating that 22% of the worlds' coastal regions (Davies *et al.*, 2014) are experiencing some degree of artificial illumination and 20% of marine protected areas are exposed across their entire range (Davies *et al.*, 2016). The amount of artificial light is also increasing in 13,061 terrestrial protected areas across Europe, Asia and South and Central America (Gaston *et al.*, 2015a), and 1,687 (14.7%) of the worlds marine protected areas (Davies *et al.*, 2016). Given that more than 95% of global population increases are projected to occur in the cities of economically developing countries over the next 50 years (Grimm *et al*., 2008), and levels of light pollution are closely associated with population density and economic activity (Gallaway *et al*., 2010), ALAN will continue to expand both in spatial extent and intensity throughout the 21st century without intervention.

Sphere of influence

Artificial light arises from point sources (municipal, industrial, commercial and residential), giving the impression that its impacts on the environment are highly localised. Indeed the majority of studies into the ecological impacts of ALAN quantify responses to direct lighting (Gaston *et al.*, 2015b). Artificial sky-glow increases the sphere of ALAN's potential influence far beyond a patch of habitat in the vicinity of a street light (Kyba & Hölker, 2013, Falchi *et al.*, 2016). Numerous taxa are adapted to make use of spatial and temporal patterns of natural sky brightness at intensities equivalent to or less than those created by artificial sky-glow (Naylor, 1999, Moore *et al.*, 2000, Dacke *et al.*, 2013, Last *et al.*, 2016, Warrant & Dacke, 2016), suggesting that lights in urban centres will have impacts in environments tens to hundreds of kilometres away. A dung beetle navigating its landscape using the Milky Way could, for example, become disorientated by artificial skyglow from a city tens or perhaps even hundreds of kilometres away (Kyba *et al*., 2013), an effect comparable to a moth becoming disorientated by a street light hundreds of metres away (van Grunsven *et al*., 2014).

While ALAN can be misconstrued as being a highly localised anthropogenic stressor, climate warming is likewise misrepresented as globally widespread in its occurrence. Like ALAN, ecologically relevant warming occurs at more localised spatial scales (Hannah *et al.*, 2014) (Figure 2), and is influenced by variable topographical features such as slope and aspect that create refuges where rates of warming are reduced (Bennie *et al.*, 2008, Maclean *et al.*, 2016). The ecological impacts of climate change - like light pollution – are therefore likely to be spatially heterogeneous for organisms with low mobility, but more widespread for taxa that depend on large scale movements for their survival and reproduction. In the case of both stressors, population impacts on the former species are manifest foremost through the loss and fragmentation of suitable habitat (Hannah *et al.*, 2014), while impacts on the latter species are manifest via direct effects on population demography (Gaston & Bennie, 2014).

Lag effects

Abating future rises in global temperatures constitutes one of the most significant challenges facing humanity in the 21st century. Yet even if all fossil fuel combustion ceased with immediate effect, the recovery of atmospheric CO_2 concentrations, global temperatures, ocean pH and oxygen concentrations to pre-industrial levels would take hundreds to thousands of years (Frolicher *et al.*, 2014, Frölicher & Paynter, 2015, Mathesius *et al.*, 2015), and there is the very real possibility that temperatures would continue to rise in the medium term (Frolicher *et al.*, 2014). By contrast, globally widespread artificial light can be ‘switched off’ instantaneously. There would be no lag effect on the physical environment following such an event, allowing the biological environment to immediately begin the recovery process. While such a scenario would likely prove controversial, recent technological advances present tangible ways of mitigating the ecological impacts of artificial light at night (see reason ten). Failure to abate the environmental consequences of a man-made disturbance using available viable solutions, would not inspire confidence in our ability to solve the apparently insurmountable challenges posed by global climate change phenomena.

The rise of LEDs

Light-Emitting Diodes (LEDs) have grown from a 9% share of the lighting market in 2011 to 45% in 2014, and are forecast to reach 69% by 2020 (Zissis & Bertoldi, 2014). Their rising popularity stems from the variety of colours that LEDs can be tailored to produce, their improved energy efficiency over alternative electric light sources, and ability to produce 'white' light that is aesthetically pleasing and provides enhanced visual performance (Schubert & Kim, 2005, Pimputkar *et al.*, 2009,). Whilst LEDs are often advocated for their potential to reduce global CO_2 emissions, and the ability to tailor their spectra to avoid unwanted environmental impacts (see 'Feasibility of solutions'), environmental scientists and human health experts have raised concerns about the broad-spectrum light (Davies *et al.*, 2013, Macgregor *et al.*, 2014), and prominent short wavelength peak (Haim & Portnov, 2013, Haim & Zubidat, 2015) that the commonly used white models emit (Figure 3).

Firstly, the broad range of wavelengths emitted by white LEDs likely enables organisms to perform colour guided behaviours at night that were previously only possible during the day (Davies *et al.*, 2013). A range of intra and interspecific interactions could be affected including foraging (for example seeking nectar rich flowers), predation (ability to locate and successfully capture prey), sexual communication (ability to locate, identify and assess the fitness of conspecifics through visual displays) and camouflage (ability to avoid detection by predators). Nocturnal species may find themselves competing for resources with diurnal species where such interactions had previously not existed (Macgregor *et al.*, 2014), and differences in the sensitivity of animal visual systems to white LED light spectra could change the balance of species interactions (Davies *et al.*, 2013). Some alternative lighting technologies also emit light across a broad range of wavelengths (for example Metal Halide and Mercury Vapour lighting, Figure 3), however the energy efficiency of LEDs makes them the lighting of choice in the 21st century, and as such research should focus on how any unforeseen deleterious impacts can best be mitigated.

Secondly the short wavelength peak emitted by white LEDs coincides with the wavelengths to which many biological responses are known to be sensitive. Many invertebrate behaviours (Cohen & Forward, 2009, Gorbunov & Falkowski, 2002, Haddock *et al.*, 2010, van Langevelde *et al.*, 2011) and the melatonin response (West *et al.*, 2011) are sensitive to short wavelengths of light (between 350 and 500nm), and some studies have demonstrated that white LED lighting has a greater impact on short wavelength sensitive responses compared to alternative lighting technologies (Pawson & Bader, 2014).

Thirdly, because LEDs illuminate a broad range of wavelengths, they have the potential to affect a greater variety of biological responses that are sensitive to specific wavelengths of light. To give one example, while many invertebrate behaviours and the melatonin response are most sensitive to short wavelength light, the phytochrome system in plants – which is associated with the timing of flowering- is sensitive to red/far red light (660 and 720nm) (Bennie *et al.*, 2016). Using broad wavelength light sources such as white LEDs therefore risks affecting more biological responses across a greater variety of taxa than using narrow wavelength light sources such as low pressure sodium lighting (Gaston *et al.*, 2012).

Fourthly, the improved energy efficiency offered by LEDs may encourage growth in the amount of artificial light produced around the world. This 'rebound effect' can be observed in historical lighting trends (see Kyba *et al*. 2014), and partly explains why aesthetic and decorative lighting installations are now increasingly seen in municipal centres, on monuments, bridges and waterfront developments.

Finally, improvements in the energy efficiency of LED lighting coupled with the production efficiency of solar cells is resulting in a rapid growth in off grid lighting installations, typically in remote regions containing previously artificial light naive ecosystems (Mills & Jacobson 2007, Adkins *et al*., 2010, Dalberg Global Development Advisors 2013). The greatest ecological impacts of ALAN over the next 50 years will likely occur in these previously artificial light naive regions, with an ecology not previously shaped by night-time lighting.

Evolutionary novelty

Organisms have evolved with large scale fluctuations in atmospheric CO_2, climate temperatures and ocean pH throughout history, while sudden changes to natural light regimes are unprecedented over evolutionary time-scales. The harmonic movements of the earth, moon and sun provide reliable cues to which many biological events are now highly attuned (Kronfeld-Schor *et al.*, 2013).
The ability of organisms to rapidly adapt to the introduction of ALAN through behavioural, genetic or epigenetic changes is likely to be far more limited than for climate warming due to the unprecedented nature of this change (Swaddle *et al.*, 2015). Further, the scattered growth of artificial lighting around the world is a significant barrier to predicting where organisms will be able to seek out suitably dark habitats in the future, and identifying where to allocate dark corridors that enable such migrations to happen. While challenging, identifying where species need to go to survive climate warming, and how they get there, is made simpler by the predictability of regional climatic shifts (for example poleward migrations by land and sea, and upward migrations in high altitude regions) (Hannah *et al.*, 2007).

Diversity of biological responses

ALAN is now known to cause a plethora of environmental impacts from altering organism physiology to changing the structure of ecological communities. The diversity of taxa affected continues to grow and now includes birds (Kempenaers *et al.*, 2010, Dominoni, 2015), bats (Rydell, 1992, Stone *et al.*, 2009), sea turtles (Witherington, 1992, Kamrowski *et al.*, 2012), marsupials (Robert *et al.*, 2015), rodents (Bird *et al.*, 2004), anurans (Hall, 2016); freshwater and marine fish (Becker *et al.*, 2012, Riley *et al.*, 2013, Brüning *et al.*, 2015); moths (Frank, 1988, Wakefield *et al.*, 2015); beetles, spiders, harvestmen, woodlice and ants (Davies *et al.*, 2012, Davies *et al.*, 2017); branchiopod (Moore *et al.*, 2000), amphipod (Davies *et al.*, 2012, Davies *et al.*, 2015, Navarro-Barranco & Hughes, 2015) and copepod (Davies *et al.*, 2015) crustaceans; polychaete worms, colonial ascidians, and hydrozoans (Davies *et al.*, 2015); corals (Kaniewska *et al.*, 2015), and terrestrial plants (Bennie *et al.*, 2015a, Bennie *et al.*, 2016, ffrench-Constant *et al.*, 2016). The documented impacts include those on animal communication (Kempenaers *et al.*, 2010, van Geffen *et al.*, 2015), reproductive development (Dominoni *et al.*, 2013, Hansen *et al.*, 1992), the timing of reproduction (Kaniewska *et al.*, 2015, Robert *et al.*, 2015), orientation (Frank, 1988, Witherington, 1992), habitat selection (Davies *et al.*, 2012, Davies *et al.*, 2015), predator avoidance (Wakefield *et al.*, 2015), predation pressure (Rydell, 1992, Becker *et al.*, 2012, Bolton *et al.*, 2017), circadian disruption (Brüning *et al.*, 2015, Raap *et al.*, 2015, Raap *et al.*, 2016), plant phenology (Bennie *et al.*, 2015a, Bennie *et al.*, 2016, ffrench-Constant *et al.*, 2016), and ecosystem services (Lewanzik & Voigt, 2014, Knop *et al*. 2017).

While those impacts on survival and reproductive success highlight that ALAN is likely causing widespread population losses for a variety of taxa, no population-level effects have so far been reliably demonstrated. This is in part because satellite images of night-time lights are not available in sufficiently high spatial resolution for inferences to be drawn regarding impacts on species populations that can be variable on the scale of tens to hundreds of metres (Elvidge *et al*. 2007). Disentangling the effects of street and residential lighting from those of urbanisation and land use change is challenging, since all of these explanatory variables likely contributes to population declines but all co-vary. Analyses using higher resolution images from the international space station (capable of identifying individual roads), may yield further insights, but tend to be focused on cities, preventing comparisons from being drawn across sufficiently large spatial scales. Recent developments in hemispherical photography allow 'biologically relevant' artificial skyglow to be mapped from ground level across thousands of square kilometres (Luginbuhl *et al*., 2009, Zoltan, 2010), better enabling ecologists to quantify its impacts on populations of organisms that utilize celestial patterns of sky brightness, but perhaps not the population effects of direct lighting. Techniques to model the distribution of artificial light across towns and cities have also been developed (Bennie *et al*. 2014), however such models can be computationally expensive and have not yet been applied to the question of whether direct lighting has an impact on organism populations. Before After Control Impact (BACI) experiments have the potential to provide insights into the long-term responses of sessile species populations and those mobile taxa with <1km home ranges, however the finances and time required to implement them at appropriate spatial and temporal scales make this approach less feasible in a limited funding environment. For now, quantifying the population level impacts of ALAN remains one of the most important and challenging problems facing ecologists working in this area.

Sensitivity of biological responses

Many organisms are extremely sensitive to natural light, utilizing light cues as dim as the Moon and the Milky Way to orientate themselves, navigate landscapes and identify conspecifics and resources at night (Ugolini *et al.*, 2005, Dacke *et al.*, 2013, Last *et al.*, 2016, Warrant & Dacke, 2016). Perhaps most striking is the growing number of documented responses to white LEDs in marine systems (Gorbunov & Falkowski, 2002, Davies *et al.*, 2015, Navarro-Barranco & Hughes, 2015, Bolton *et al.*, 2017), where species are both adapted to utilize short wavelengths that penetrate deeper in seawater, and are incredibly sensitive to natural light. Examples of this extreme sensitivity include copepods (*Calanus* sp.) that undergo diel vertical migration to depths of 50m guided only by variations in moonlight intensity during the arctic winter (Båtnes *et al.*, 2013, Last *et al.*, 2016); sessile invertebrate larvae that move and identify suitable settlement locations guided by light levels equivalent to moonless overcast nights (Thorson, 1964, Crisp & Ritz, 1973); and polychaete worms, corals and echinoderms that synchronise broadcast spawning events using monthly and annual variations in lunar light intensity (Naylor, 1999). Many of these responses are clearly sensitive enough to be affected both by direct lighting and artificial skyglow (Figure 4), and indeed such impacts have been demonstrated for zooplankton diel vertical migration in freshwater ecosystems (Moore *et al.*,2000). Given the spatial extent of artificial skyglow in coastal regions (Davies *et al*., 2014, Falchi *et al*., 2016), the disproportionate importance of these regions for global biogeochemical cycles [coastal zones account for 30% of global ocean primary production but only 10% of global ocean surface area (Wollast, 1998)], and the role of diel vertical migration in maintaining these cycles (Hays, 2003), it is not unreasonable to surmise that ALAN could have detectable effects on ocean carbon and nutrient budgets in the near future.

Impacts on human health

In 2007, The World Health Organisation classified shift work that disrupted human circadian rhythms as a probable human carcinogen (International Agency for Research on Cancer, 2007). While this classification is primarily associated with shift work, exposure to ALAN has been linked to a variety of health disorders in people through the same circadian disruption mechanism. These include sleep disorders, depression, obesity, and the progression of some cancers (Cajochen *et al.*, 2011, Haim & Portnov, 2013, Chang *et al.*, 2014, Keshet-Sitton *et al.*, 2015). The prominent peak of blue wavelength light emitted by LEDs is of increasing concern, since it occurs at the most effective frequency for suppressing the production of melatonin (West *et al.*, 2011, Haim & Zubidat, 2015), a hormone released by the pineal gland that regulates sleep wake cycles and acts as an antioxidant. Over the last decade, LEDs have become a ubiquitous feature of human life, and can be found in street, residential, commercial and aesthetic lighting installations, laptops, televisions, e-readers, smart phones and tablets. Late evening exposure to LED light from handheld devices has been linked to circadian disruption of sleep wake cycles, and alertness and cognitive performance during the day (Cajochen *et al.*, 2011, Chang *et al.*, 2014).

The extent to which outdoor lighting impacts human health is yet to be reliably determined. While epidemiological studies have found correlations between the amount of outdoor lighting and some health effects (Kloog *et al.*, 2008, Koo *et al.*, 2016), as with ecological patterns they are limited by the inferences that can be drawn from satellite images (Defence Meteorological Satellite Programme Operational Line Scan) with insufficient spatial resolution (5km) to differentiate exposure to ALAN from other factors that co-vary across city districts at fine spatial scales (Elvidge *et al*. 2007, Kyba, 2016). The need for higher resolution images or novel approaches that can disentangle the effects on both ecology and human health of multiple urban pollutants that co-vary is clear, although individual level sensors can also reveal important impacts of daily light exposure on circadian disruption and stress (Figueiro *et al*. 2017). A more recent analysis using higher resolution (0.75km) images from the Visible Infrared Imaging Radiometer Suite (VIIRS) on board the Suomi National Polar-orbiting

Partnership satellite has revealed a significant association between ALAN and breast cancer incidence in the Greater Haifa Metropolitan Area in Israel (Rybnikova & Portnov, 2016). This analysis accounted for several potential co-varying explanatory factors, but not noise pollution, and atmospheric pollution explicitly.

Human-environment interrelationships

In a recent analysis that combined high resolution night-time satellite images with atmospheric dispersion models of artificial sky-glow, Falchi *et al*. (2016) estimated that more than 80% of the worlds' population currently live under light polluted skies, such that the Milky Way is hidden from one third of people alive today. This extraordinary change in our night-time environment escalated in the developed world during the mid to late 20th century, and is now rapidly transforming the cultures of billions in the developing world. The trend is concurrent with urbanisation [66% of the worlds' population will reside in urban areas by 2050 (United Nations, 2014)], and it contributes to the growing disconnect between people and nature that has become known as 'the extinction of experience' (Miller, 2005). This growing disconnect undermines public support for conservation issues by preventing individuals from connecting with, understanding, and forming attachments to the natural world (Miller, 2005).

The extinction of experience is another of the great challenges facing humanity in the 21st century. Miller (2005) argues it can be addressed by designing urban landscapes to facilitate 'meaningful interactions with the natural world'. There is perhaps no more profound way in which people can reconnect with nature, than giving them access to the Milky Way, and allowing them to experience the natural rhythms of moonlight and sunlight that they are evolutionarily pre-adapted to synchronise their physiology and behaviour with (Cajochen *et al.*, 2013, Wright Jr *et al.*, 2013). Like biodiversity conservation however, pristine skies have become tourist attractions restricted to regions awarded special status for their value to dark sky conservation (Collison & Poe, 2013, Rodrigues *et al.*, 2014, Pritchard, 2017) where many in the developed world can no longer afford to reside or visit. Pritchard

(2017) argues that dark sky protection programmes also risk supressing the economic and cultural development of poorer nations in a way analogous to biodiversity conservation in the 20th century. In her appraisal of NASA's '*City Lights*' composite satellite image of the worlds lights at night (http://earthobservatory. nasa.gov/Features/IntotheBlack/) Pritchard (2017) warns against 'neo-colonial approaches to the conservation of natural night-sky brightness'. While it is clear the continued growth in artificial lighting risks perpetuating the disconnect between people and the environment - and this will inevitably contribute to the concomitant shifting baseline in conservation objectives (Pauly, 1995, Papworth *et al.*, 2009) – any intervention should seek to support the modernisation of societies while retaining their connections with the natural world. Pritchard (2017) describes achieving this balance as a 'new frontier in 21st century conservation'.

Feasibility of solutions

While the recent growth in LED lighting has raised concerns among environmental scientists and human health experts, this technology offers lighting managers greater flexibility when it comes to tailoring the timing, intensity and spectral power distribution of municipal lighting systems (Gaston, 2013, Davies *et al.*, 2017). Of the local authorities in England, 23% are engaged in permanent part-night lighting schemes where street lights are turned off between midnight and 04:00 to 05:00 AM, while 39% are engaged in permanent dimming schemes where lights are dimmed for at least some period of the night (Campaign to Protect Rural England, 2014). Increasing constraints on local authority budgets have incentivized the adoption of these lighting strategies in the wake of the 2008 global financial crash, however more often the reasons given for their implementation are improved energy savings and reduced CO_2 emissions. Both dimming and part-night lighting are better enabled by switching to LED, and introducing central management systems that use wireless communication technology to programme individual street lights remotely.

The ecological benefits of dimming and part-night lighting are not yet well explored (although see Azam *et al.*, 2015, Day *et al.*, 2015, Davies *et al.*, 2017). A recent emphasis in the ecological literature has instead been on tailoring spectral power distributions to reduce known ecological impacts (Pawson & Bader, 2014, Longcore *et al.*, 2015, Brüning *et al.*, 2016, Rivas *et al.*, 2015, Spoelstra *et al.*, 2015, van Geffen *et al.*, 2015, Davies *et al.*, 2017), despite this approach being less popular among lighting managers and engineers who often focus on the improved visual performance offered by broad spectrum lighting as a key selling point. These studies collectively present an inconsistent picture of whether spectral manipulation can be used to effectively mitigate the ecological impacts of ALAN. This is partly because some studies compare narrow spectrum (for example red, green and blue) light with broad spectrum light sources, while others either decrease the amount of light occurring at wavelengths known to manifest certain ecological responses (usually shorter wavelengths in the visible spectrum), or increase the amount of light occurring at wavelengths that do not give rise to these responses (longer wavelengths in the visible spectrum). Even if a unified approach were adopted in spectral manipulation experiments, it seems unlikely that a publically acceptable light spectra that does not give rise to any ecological impacts can be developed, because different species responses are evolutionarily adapted to utilize different wavelengths of light.

Examples of this are abundant in the emerging literature on the ecological impacts of artificial light. The number of beetle taxa aggregating under white LED lighting can be reduced by switching to amber, but this has no discernible effect on the number of spider taxa that aggregate (Davies *et al.*, 2017). Many animal responses are sensitive to short wavelength light (van Langevelde *et al*., 2011, Rivas *et al*., 2015, Spoelstra *et al*., 2017), while phenological responses in plants are most sensitive to the longer wavelengths recommended to avoid such effects (Bennie *et al*., 2015a, Bennie *et al*., 2016). Male caterpillars of the moth *Mamestra brassicae* reared under green artificial light reached a lower maximum mass, pupated earlier and obtained a lower pupal mass than those reared under red light (van Geffen *et al*. 2014), while red light inhibited the attractiveness of a female pheromone lure to more adult males of the winter moth *Operophtera brumata* than did green light (van Geffen *et al*. 2015).

Studies investigating the ecological benefits of part-night lighting have also highlighted that different taxa respond in different ways (Azam *et al.*, 2015, Day *et al.*, 2015, Davies *et al.*, 2017), and the adoption of part-night lighting schemes is often inhibited by a perception among political actors that they lack popular support. There are both perceived and realised benefits of artificial light for society, including in the areas of road safety, crime, and the economy (Gaston *et al*., 2015c). The night time economy in the UK, for example, was worth £67bn in 2016 (MAKE Associates, 2017), and accounted for up to 27% of town and city centre turnover and 10% of most locations overall employment figure in 2009 (VisitEngland, 2012).

While modern lighting technologies offer the potential to reduce the ecological impacts of ALAN, identifying how this is best achieved is clearly complex. Studies are needed across a wide variety of taxonomic groups and lighting approaches, to develop options that are both socially and ecologically acceptable.

Conclusion

Research into the ecological, human health and societal consequences of ALAN is now growing rapidly. Here, we have highlighted ten reasons why ALAN should, and likely will be a focus for global change research in the 21st century. Most important to consider, is the notion that while ALAN is having widespread and profound impacts on people and the environment, strategies for abating them are already being explored. Solving the challenges posed by ALAN would not only improve environmental and human health outcomes, but also enhance the human experience of nature and change perceptions of the natural world in a way that facilitates the necessary transition towards a more environmentally orientated and hence sustainable society. It would also inspire greater confidence in our ability to tackle the problems posed by other global change phenomena. The challenge now is identifying how best to address to the complex array of ecological, human health and cultural problems presented by society's propensity for illuminating the night.

Acknowledgements

The authors would like to thank Dr Ilya Mclean (University of Exeter) for granting permissions to use images in Figure 2. The work leading to this publication was supported by a Welsh Government and European Regional Development Fund funded Sêr Cymru II Fellowship awarded to TWD.

References

Adkins E, Eapen S, Kaluwile F, Nair G, Modi V (2010) Off-grid energy services for the poor: introducing LED lighting in the Millennium Villages Project in Malawi. Energy Policy, **38**, 1087-1097.

Azam C, Kerbiriou C, Vernet A, Julien J-F, Bas Y, Plichard L,…Le Viol I (2015) Is part□night lighting an effective measure to limit the impacts of artificial lighting on bats? Global Change Biology, **21**, 4333-4341.

Båtnes AS, Miljeteig C, Berge J, Greenacre M, Johnsen G (2013) Quantifying the light sensitivity of Calanus spp. during the polar night: potential for orchestrated migrations conducted by ambient light from the sun, moon, or aurora borealis? Polar Biology, **38**, 51-65.

Becker A, Whitfield AK, Cowley PD, Järnegren J, Næsje TF (2012) Potential effects of artificial light associated with anthropogenic infrastructure on the abundance and foraging behaviour of estuary-associated fishes. Journal of Applied Ecology, **50**, 43-50.

Bennie J, Davies TW, Cruse D, Gaston KJ (2016) Ecological effects of artificial light at night on wild plants. Journal of Ecology, **104**, 611-620.

Bennie J, Davies TW, Inger R, Gaston KJ (2014) Mapping artificial lightscapes for ecological studies. Methods in Ecology and Evolution, **5**, 534-540.

Bennie J, Davies TW, Cruse D, Inger R, Gaston KJ (2015a) Cascading effects of artificial light at night: resource-mediated control of herbivores in a grassland ecosystem. Philosophical Transactions of the Royal Society B: Biological Sciences, **370**, 20140131.

Bennie J, Duffy J, Davies T, Correa-Cano M, Gaston K (2015b) Global trends in exposure to light pollution in natural terrestrial ecosystems. Remote Sensing, **7**, 2715-2730.

Bennie J, Huntley B, Wiltshire A, Hill MO, Baxter R (2008) Slope, aspect and climate: spatially explicit and implicit models of topographic microclimate in chalk grassland. Ecological Modelling, **216**, 47-59.

Bird BL, Branch LC, Miller DL (2004) Effects of coastal lighting on foraging behavior of beach mice. Conservation Biology, **18**, 1435-1439.

Bolton D, Mayer-Pinto M, Clark GF, Dafforn KA, Brassil WA, Becker A, Johnston EL (2017) Coastal urban lighting has ecological consequences for multiple trophic levels under the sea. Science of the Total Environment, **576**, 1-9.

Brüning A, Hölker F, Franke S, Kleiner W, Kloas W (2016) Impact of different colours of artificial light at night on melatonin rhythm and gene expression of gonadotropins in European perch. Science of The Total Environment, **543**, 214-222.

Brüning A, Hölker F, Franke S, Preuer T, Kloas W (2015) Spotlight on fish: light pollution affects circadian rhythms of European perch but does not cause stress. Science of the Total Environment, **511**, 516-522.

Cajochen C, Altanay-Ekici S, Münch M, Frey S, Knoblauch V, Wirz-Justice A (2013) Evidence that the lunar cycle influences human sleep. Current Biology, **23**, 1485-1488.

Cajochen C, Frey S, Anders D, Späti J, Bues M, Pross A,…Stefani O (2011) Evening exposure to a light-emitting diodes (LED)-backlit computer screen affects circadian physiology and cognitive performance. Journal of Applied Physiology, **110**, 1432-1438.

Chang A-M, Aeschbach D, Duffy JF, Czeisler CA (2014) Evening use of light-emitting eReaders negatively affects sleep, circadian timing, and next-morning alertness. Proceedings of the National Academy of Sciences of the United States of America. **112**, 1232-1237.

Cohen JH, Forward RB (2009) Zooplankton diel vertical migration - a review of proximate control. Oceanography and Marine Biology: An Annual Review, **47**, 77-110.

Collison FM, Poe K (2013) "Astronomical Tourism": The Astronomy and Dark Sky Program at Bryce Canyon National Park. Tourism Management Perspectives, **7**, 1-15.

Campaign to Protect Rural England (2014) Shedding Light: A survey of local authority approaches to lighting in England, London.

Crisp DJ, Ritz DA (1973) Responses of cirripede larvae to light. I. Experiments with white light. Marine Biology, **23**, 327-335.

Dacke M, Baird E, Byrne M, Scholtz CH, Warrant EJ (2013) Dung beetles use the Milky Way for orientation. Current Biology, **23**, 298-300.

Dalberg Global Development Advisors (2013) Lighting Africa Market Trends Report 2012. In: *Lighting Africa.*

Davies TW, Bennie J, Cruse D, Blumgart D, Inger R, Gaston KJ (2017) Multiple night-time light-emitting diode lighting strategies impact grassland invertebrate assemblages. Global Change Biology, **23**, 2641-2648.

Davies TW, Bennie J, Gaston KJ (2012) Street lighting changes the composition of invertebrate communities. Biology Letters, **8**, 764-767.

Davies TW, Bennie J, Inger R, De Ibarra NH, Gaston KJ (2013) Artificial light pollution: are shifting spectral signatures changing the balance of species interactions? Global Change Biology, **19**, 1417-1423.

Davies TW, Coleman M, Griffith KM, Jenkins SR (2015) Night-time lighting alters the composition of marine epifaunal communities. Biology Letters, **11**, 20150080.

Davies TW, Duffy JP, Bennie J, Gaston KJ (2014) The nature, extent, and ecological implications of marine light pollution. Frontiers in Ecology and the Environment, **12**, 347-355.

Davies TW, Duffy JP, Bennie J, Gaston KJ (2016) Stemming the tide of light pollution encroaching into marine protected areas. Conservation Letters, **9**, 164-171.

Day J, Baker J, Schofield H, Mathews F, Gaston KJ (2015) Part-night lighting: implications for bat conservation. Animal Conservation, **18**, 512-516.

Dominoni D (2015) The effects of light pollution on biological rhythms of birds: an integrated, mechanistic perspective. Journal of Ornithology, **156**, 409-418.

Dominoni D, Quetting M, Partecke J (2013) Artificial light at night advances avian reproductive physiology. Proceedings of the Royal Society B: Biological Sciences, **280**, 20123017.

Elvidge CD, Cinzano P, Pettit D, Arvesen J, Sutton P, Small C,…Weeks J (2007) The Nightsat mission concept. International Journal of Remote Sensing, **28**, 2645-2670.

Falchi F, Cinzano P, Duriscoe D, Kyba CC, Elvidge CD, Baugh K,…Furgoni R (2016) The new world atlas of artificial night sky brightness. Science Advances, **2**, e1600377.

Ffrench-Constant RH, Somers-Yeates R, Bennie J, Economou T, Hodgson D, Spalding A, Mcgregor PK (2016) Light pollution is associated with earlier tree budburst across the United Kingdom. Proceedings of the Royal Society B: Biological Sciences, **283**, No 1833.

Figueiro MG, Steverson B, Heerwagen J, Kampschroer K, Hunter CM, Gonzales K,…Rea MS (2017) The impact of daytime light exposures on sleep and mood in office workers. Sleep Health, **3**, 204-215.

Forward RB, Cronin TW, Stearns DE (1984) Control of diel vertical migration: Photoresponses of a larval crustacean1. Limnology and Oceanography, **29**, 146-154.

Frank KD (1988) Impact of outdoor lighting on moths an assessment. Journal of the Lepidopterists' Society, **42**, 63-93.

Frölicher TL, Paynter DJ (2015) Extending the relationship between global warming and cumulative carbon emissions to multi-millennial timescales. Environmental Research Letters, **10**, 075002.

Frolicher TL, Winton M, Sarmiento JL (2014) Continued global warming after CO_2 emissions stoppage. Nature Climate Change, **4**, 40-44.

Gallaway T, Olsen RN, Mitchell DM (2010) The economics of global light pollution. Ecological Economics, **69**, 658-665.

Gaston KJ (2013) Sustainability: A green light for efficiency. Nature, **497**, 560-561.

Gaston KJ, Bennie J (2014) Demographic effects of artificial nighttime lighting on animal populations. Environmental Reviews, **22**, 323-330.

Gaston KJ, Davies TW, Bennie J, Hopkins J (2012) Reducing the ecological consequences of night-time light pollution: options and developments. Journal of Applied Ecology, **49**, 1256-1266.

Gaston KJ, Duffy JP, Bennie J (2015a) Quantifying the erosion of natural darkness in the global protected area system. Conservation Biology, **29**, 1132-1141.

Gaston KJ, Gaston S, Bennie J, Hopkins J (2015c) Benefits and costs of artificial nighttime lighting of the environment. Environmental Reviews, **23**, 14-23.

Gaston KJ, Visser ME, Hölker F (2015b) The biological impacts of artificial light at night: the research challenge. Philosophical Transactions of the Royal Society B: Biological Sciences, **370**, 20140133.

Gorbunov MY, Falkowski PG (2002) Photoreceptors in the cnidarian hosts allow symbiotic corals to sense blue moonlight. Limnology and Oceanography, **47**, 309-315.

Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bai X, Briggs JM (2008) Global change and the ecology of cities. Science, **319**, 756-760.

Haddock SHD, Moline MA, Case JF (2010) Bioluminescence in the sea. Annual Review of Marine Science, **2**, 443-493.

Haim A, Portnov BA (2013) Light pollution as a new risk factor for human breast and prostate cancers, New York, Springer.

Haim A, Zubidat AE (2015) LED light between Nobel Prize and cancer risk factor. Chronobiology International, **32**, 725-727.

Hall AS (2016) Acute artificial light diminishes central Texas anuran calling behavior. The American Midland Naturalist, **175**, 183-193.

Hannah L, Flint L, Syphard AD, Moritz MA, Buckley LB, Mccullough IM (2014) Fine-grain modeling of species' response to climate change: holdouts, stepping-stones, and microrefugia. Trends in Ecology & Evolution, **29**, 390-397.

Hannah L, Midgley G, Andelman S, Araújo M, Hughes G, Martinez-Meyer E,…Williams P (2007) Protected area needs in a changing climate. Frontiers in Ecology and the Environment, **5**, 131-138.

Hansen T, Stefansson S, Taranger GL (1992) Growth and sexual maturation in Atlantic salmon, *Salmo salar* L., reared in sea cages at two different light regimes. Aquaculture Research, **23**, 275-280.

Hays GC (2003) A review of the adaptive significance and ecosystem consequences of zooplankton diel vertical migrations. Hydrobiologia, **503**, 163-170.

International Agency for Research on Cancer (2007) IARC Monagraphs on the evaluation of carcinogenic risks to humans Volume 98: Painting, firefighting, and shiftwork. In: *World Heath Organisation International Agency for Research on Cancer*, Lyon 2010.

Kamrowski RL, Limpus C, Moloney J, Hamann M (2012) Coastal light pollution and marine turtles: assessing the magnitude of the problem. Endangered Species Research, **19**, 85-98.

Kaniewska P, Alon S, Karako-Lampert S, Hoegh-Guldberg O, Levy O (2015) Signaling cascades and the importance of moonlight in coral broadcast mass spawning. eLife, **4**, e09991.

Kempenaers B, Borgström P, Loës P, Schlicht E, Valcu M (2010) Artificial night lighting affects dawn song, extra-pair siring success, and lay date in songbirds. Current Biology, **20**, 1735-1739.

Keshet-Sitton A, Or-Chen K, Yitzhak S, Tzabary I, Haim A (2015) Can avoiding light at night reduce the risk of breast cancer? Integrative Cancer Therapies, **1534735415618787**.

Klein Goldewijk K, Beusen A, van Drecht G, De Vos M (2011) The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. Global Ecology and Biogeography, **20**, 73-86.

Kloog I, Haim A, Stevens RG, Barchana M, Portnov BA (2008) Light at night co□distributes with incident breast but not lung cancer in the female population of Israel. Chronobiology International, **25**, 65-81.

Knop E, Zoller L, Ryser R, Gerpe C, Hörler M, Fontaine C (2017) Artificial light at night as a new threat to pollination. Nature, **548**, 206-209.

Koo YS, Song J-Y, Joo E-Y, Lee H-J, Lee E, Lee S-K, Jung K-Y (2016) Outdoor artificial light at night, obesity, and sleep health: Cross-sectional analysis in the KoGES study. Chronobiology International, **33**, 301-314.

Kronfeld-Schor N, Dominoni D, De La Iglesia H, Levy O, Herzog ED, Dayan T, Helfrich-Forster C (2013) Chronobiology by moonlight. Proceedings of the Royal Society B: Biological Sciences, **280**, 20123088.

Kyba CM, Hölker F (2013) Do artificially illuminated skies affect biodiversity in nocturnal landscapes? Landscape Ecology, **28**, 1637–1640.

Kyba C, Hänel A, Hölker F (2014) Redefining efficiency for outdoor lighting. Energy & Environmental Science, **7**, 1806-1809.

Kyba CCM (2016) Defense Meteorological Satellite Program data should no longer be used for epidemiological studies. Chronobiology International, **33**, 943-945.

Last KS, Hobbs L, Berge J, Brierley AS, Cottier F (2016) Moonlight drives ocean-scale mass vertical migration of zooplankton during the Arctic winter. Current Biology, **26**, 244-251

Lewanzik D, Voigt CC (2014) Artificial light puts ecosystem services of frugivorous bats at risk. Journal of Applied Ecology, **51**, 388-394.

Longcore T, Aldern HL, Eggers JF, Flores S, Franco L, Hirshfield-Yamanishi E,…Barroso AM (2015) Tuning the white light spectrum of light emitting diode lamps to reduce attraction of nocturnal arthropods. Philosophical Transactions of the Royal Society B, **370**, 20140125.

Longcore T, Rich C (2004) Ecological light pollution. Frontiers in Ecology and the Environment, **2**, 191-198.

Luginbuhl CB, Duriscoe DM, Moore CW, Richman A, Lockwood GW, Davis DR (2009) From the ground up II: sky glow and near-ground artificial light propagation in Flagstaff, Arizona. Publications of the Astronomical Society of the Pacific, **121**, 204-212.

Macgregor CJ, Pocock MJO, Fox R, Evans DM (2014) Pollination by nocturnal Lepidoptera, and the effects of light pollution: a review. Ecological Entomology, **40**, 187-198.

Maclean IMD, Suggitt AJ, Wilson RJ, Duffy JP, Bennie JJ (2016) Fine-scale climate change: modelling spatial variation in biologically meaningful rates of warming. Global Change Biology, **23**, 253-268.

MAKE Associates Ltd. (2017) The NightMix index.

Mathesius S, Hofmann M, Caldeira K, Schellnhuber HJ (2015) Long-term response of oceans to CO_2 removal from the atmosphere. Nature Climate Change, **5**, 1107-1113.

Miller JR (2005) Biodiversity conservation and the extinction of experience. Trends in ecology & evolution, **20**, 430-434.

Mills E, Jacobson A (2007) The off-grid lighting market in western Kenya: LED alternatives and consumer preferences in a Millennium Development village. Lumina Project Technical Report.

Moore MV, Pierce SM, Walsh HM, Kvalvik SK, Lim JD (2000) Urban light pollution alters the diel vertical migration of *Daphnia*. Verhandlungen des Internationalen Verein Limnologie, **27**, 779-782.

Navarro-Barranco C, Hughes LE (2015) Effects of light pollution on the emergent fauna of shallow marine ecosystems: Amphipods as a case study. Marine Pollution Bulletin, **94**, 235-240.

Naylor E (1999) Marine animal behaviour in relation to lunar phase. Earth, Moon, and Planets, **85**, 291-302.

Papworth SK, Rist J, Coad L, Milner-Gulland EJ (2009) Evidence for shifting baseline syndrome in conservation. Conservation Letters, **2**, 93-100.

Pauly D (1995) Anecdotes and the shifting baseline syndrome of fisheries. Trends in Ecology and Evolution, **10**, 430.

Pawson SM, Bader MKF (2014) LED lighting increases the ecological impact of light pollution irrespective of color temperature. Ecological Applications, **24**, 1561-1568.

Pimputkar S, Speck JS, Denbaars SP, Nakamura S (2009) Prospects for LED lighting. Nature Photonics, **3**, 180-182.

Pritchard SB (2017) The trouble with darkness: NASA's Suomi satellite images of Earth at night. Environmental History, **22**, 312-330.

Raap T, Pinxten R, Eens M (2015) Light pollution disrupts sleep in free-living animals. Scientific Reports, **5**, 13557.

Raap T, Pinxten R, Eens M (2016) Artificial light at night disrupts sleep in female great tits (Parus major) during the nestling period, and is followed by a sleep rebound. Environmental Pollution, **215**, 125-134.

Riley WD, Davison PI, Maxwell DL, Bendall B (2013) Street lighting delays and disrupts the dispersal of Atlantic salmon (Salmo salar) fry. Biological Conservation, **158**, 140-146.

Rivas ML, Tomillo PS, Uribeondo JD, Marco A (2015) Leatherback hatchling sea-finding in response to artificial lighting: Interaction between wavelength and moonlight. Journal of Experimental Marine Biology and Ecology, **463**, 143-149.

Robert KA, Lesku JA, Partecke J, Chambers B (2015) Artificial light at night desynchronizes strictly seasonal reproduction in a wild mammal. Proceedings of the Royal Society B: Biological Sciences, **282**, 20151745.

Rodrigues ALO, Rodrigues A, Peroff DM (2014) The sky and sustainable tourism development: a case study of a dark sky reserve implementation in Alqueva. International Journal of Tourism Research, **17**, 292-302.

Rybnikova NA, Portnov BA (2016) Outdoor light and breast cancer incidence: a comparative analysis of DMSP and VIIRS-DNB satellite data. International Journal of Remote Sensing, 1-10.

Rydell J (1992) Exploitation of insects around streetlamps by bats in Sweden. Functional Ecology, **6**, 744-750.

Schubert EF, Kim JK (2005) Solid-state light sources getting smart. Science, **308**, 1274-1278.

Spoelstra K, van Grunsven RHA, Donners M, Gienapp P, Huigens ME, Slaterus R,…Veenendaal E (2015) Experimental illumination of natural habitat: an experimental set-up to assess the direct and indirect ecological consequences of artificial light of different spectral composition. Philosophical Transactions of the Royal Society B, **370**, 20140129.

Spoelstra K, van Grunsven RHA, Ramakers JJC, Ferguson KB, Raap T, Donners M,…Visser ME (2017) Response of bats to light with different spectra: light-shy and agile bat presence is affected by white and green, but not red light. Proceedings of the Royal Society B: Biological Sciences, **284**, 20170075.

Stone EL, Jones G, Harris S (2009) Street lighting disturbs commuting bats. Current Biology, **19**, 1123-1127.

Svane I, Dolmer P (1995) Perception of light at settlement: a comparative study of two invertebrate larvae, a scyphozoan planula and a simple ascidian tadpole. Journal of Experimental Marine Biology and Ecology, **187**, 51-61.

Swaddle JP, Francis CD, Barber JR, Cooper CB, Kyba CC, Dominoni DM,…Luther D (2015) A framework to assess evolutionary responses to anthropogenic light and sound. Trends in Ecology & Evolution, **30**, 550-560.

Tankersley RA, Mckelvey LM, Forward RB (1995) Responses of estuarine crab megalopae to pressure, salinity and light: Implications for flood-tide transport. Marine Biology, **122**, 391-400.

Thorson G (1964) Light as an ecological factor in the dispersal and settlement of larvae of marine bottom invertebrates. Ophelia, **1**, 167-208.

Ugolini A, Boddi V, Mercatelli L, Castellini C (2005) Moon orientation in adult and young sandhoppers under artificial light. Proceedings of the Royal Society B: Biological Sciences, **272**, 2189-2194.

United Nations Population Division (2014) World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352).

van Geffen KG, van Grunsven RHA, van Ruijven J, Berendse F, Veenendaal EM (2014) Artificial light at night causes diapause inhibition and sex-specific life history changes in a moth. Ecology and Evolution, **4**, 2802-2809.

van Geffen KG, van Eck E, De Boer RA, van Grunsven RHA, Salis L, Berendse F, Veenendaal EM (2015) Artificial light at night inhibits mating in a Geometrid moth. Insect Conservation and Diversity, **8**, 282-287.

van Grunsven RHA, Lham D, van Geffen KG, Veenendaal EM (2014) Range of attraction of a 6-W moth light trap. Entomologia Experimentalis et Applicata, **152**, 87-90.

van Langevelde F, Ettema JA, Donners M, Wallisdevries MF, Groenendijk D (2011) Effect of spectral composition of artificial light on the attraction of moths. Biological Conservation, **144**, 2274-2281.

VisitEngland (2012) The evening and night-time economy: realising the potential for destination organisations. VisitEngland & the Association of Town Centre Management.

Wakefield A, Stone EL, Jones G, Harris S (2015) Light-emitting diode street lights reduce last-ditch evasive manoeuvres by moths to bat echolocation calls. Royal Society Open Science, **2**, 150291.

Warrant E, Dacke M (2016) Visual navigation in nocturnal insects. Physiology, **31**, 182-192.

West KE, Jablonski MR, Warfield B, Cecil KS, James M, Ayers MA,…Hanifin JP (2011) Blue light from light-emitting diodes elicits a dose-dependent suppression of melatonin in humans. Journal of Applied Physiology, **110**, 619-626.

Witherington BE (1992) Behavioral responses of nesting sea turtles to artificial lighting. Herpetologica, **48**, 31-39.

Wollast R (1998) Evaluation and comparison of the global carbon cycle in the coastal zone and in the open ocean, in The Sea, vol. 10, The Global Coastal Ocean: Processes and Methods (Ideas and Observations on the Progress of the Studies of the Seas), edited by K. H. Brink, and A. R. Robinson, John Wiley, New York, pp. 213–252.

Wright KP, Mchill AW, Birks BR, Griffin BR, Rusterholz T, Chinoy ED (2013) Entrainment of the human circadian clock to the natural light-dark cycle. Current Biology, **23**, 1554-1558.

Young CM, Chia F-S (1982) Ontogeny of phototaxis during larval development of the sedentary polychaete, *Serpula vermicularis* (L.). The Biological Bulletin, **162**, 457-468.

Zissis G, Bertoldi P (2014) 2014 Update on the status of the LED market. European Commission Report EU 27000 E

Zoltan K (2010) Measuring and modelling light pollution at the Zselic Starry Sky Park. Journal of Physics: Conference Series, **218**, 012001.

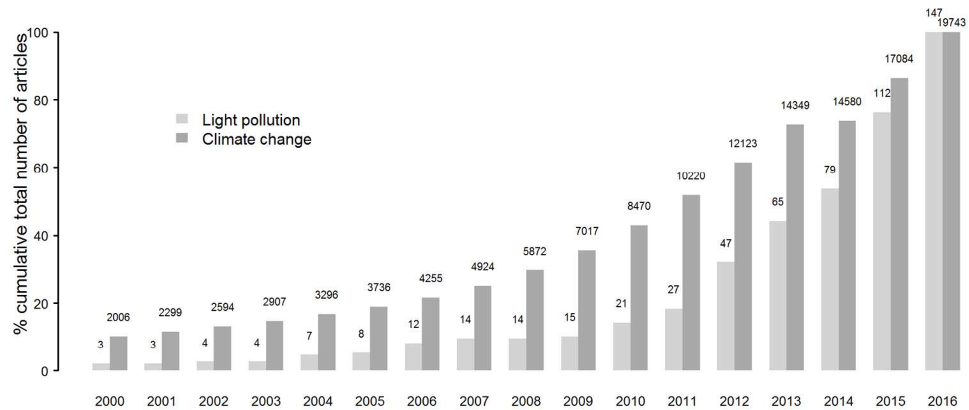
Figure 1. The trend in research outputs associated with light pollution and climate change since the year 2000. Bar heights represent the cumulative number of articles expressed as a percentage of the total number of articles published by the end of 2016; numbers are the cumulative number of articles published by the end of each year. Note that the total number of articles does not reflect the total number published in the research area, only the number returned from the search. The data were collected from a Web of Science search for phrases in article titles. The search phrases used for light pollution research outputs were "Light pollution" OR "Artificial Light at Night" OR " Nighttime lighting" OR "Night-time lighting" OR "Night time lighting" OR "Street Lighting" OR "LED lighting" OR "Light-emitting diode lighting". The search phrase for climate change was ‘Climate change’ and results were not refined by research area. The search for articles on light pollution was refined by research areas: (PLANT SCIENCES OR ORNITHOLOGY OR PSYCHOLOGY MULTIDISCIPLINARY OR ENVIRONMENTAL SCIENCES OR EVOLUTIONARY BIOLOGY OR PHYSICS APPLIED OR ENTOMOLOGY OR ENGINEERING ENVIRONMENTAL OR ECOLOGY OR URBAN STUDIES OR FISHERIES OR BIODIVERSITY CONSERVATION OR BIOLOGY OR PHYSICS MULTIDISCIPLINARY OR ZOOLOGY OR OCEANOGRAPHY OR GEOGRAPHY PHYSICAL OR GEOGRAPHY OR REMOTE SENSING OR PHYSIOLOGY OR MARINE FRESHWATER BIOLOGY OR PUBLIC ENVIRONMENTAL OCCUPATIONAL HEALTH).

Figure 2. A comparison of fine scale spatial variability in environmental warming and artificial light at night on the Lizard peninsula, Cornwall, UK. A) The increase in the number of growing degree-days (a measure of a measure of change in growing season length expressed in °C Days) between 1977 and 2014 (100m resolution). Adapted with permission from Maclean *et al*. (2016). B) The distribution of artificial light across the same area (750m resolution) recorded from the VIIRS sensor on board the Suomi NPP satellite.

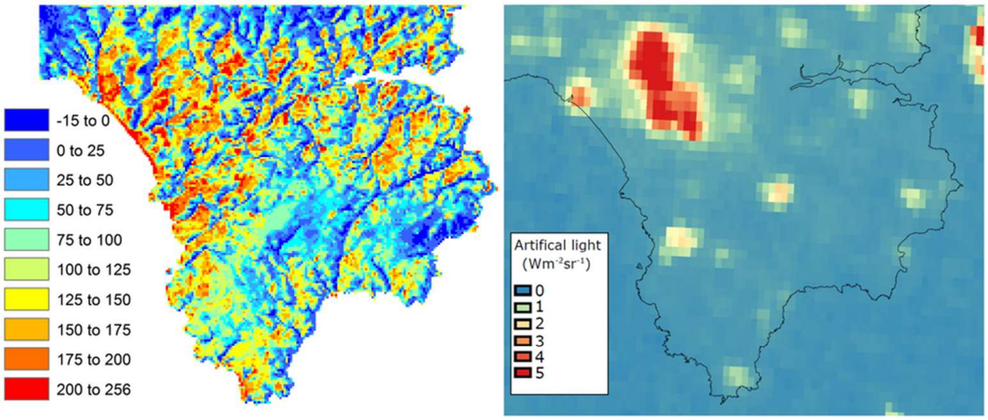
Figure 3. The potential ecological impacts of white Light Emitting Diode lighting compared to other light sources. Spectral power distributions are given for white Light Emitting Diode (LED),

Low Pressure Sodium (LPS), High Pressure Sodium (HPS) and Metal Halide (MH) lights recorded using a MAYA 200 pro spectrometer from street lighting in Cornwall. The amount of light at each wavelength is standardised to relative intensity (radiant energy divided by the maximum radiant energy recorded at any wavelength for each light source) so that the relative distribution of radiant energy across the light spectrum can be compared for each light source. Grey arrows represent the wavelength range over which different types of biological response are expected/recorded. Dashed lines represent the range of wavelengths over which Mammal, Bird, Reptile, Insect, and Arachnid visual systems can detect light [adapted from Davies *et al*. (2013)].

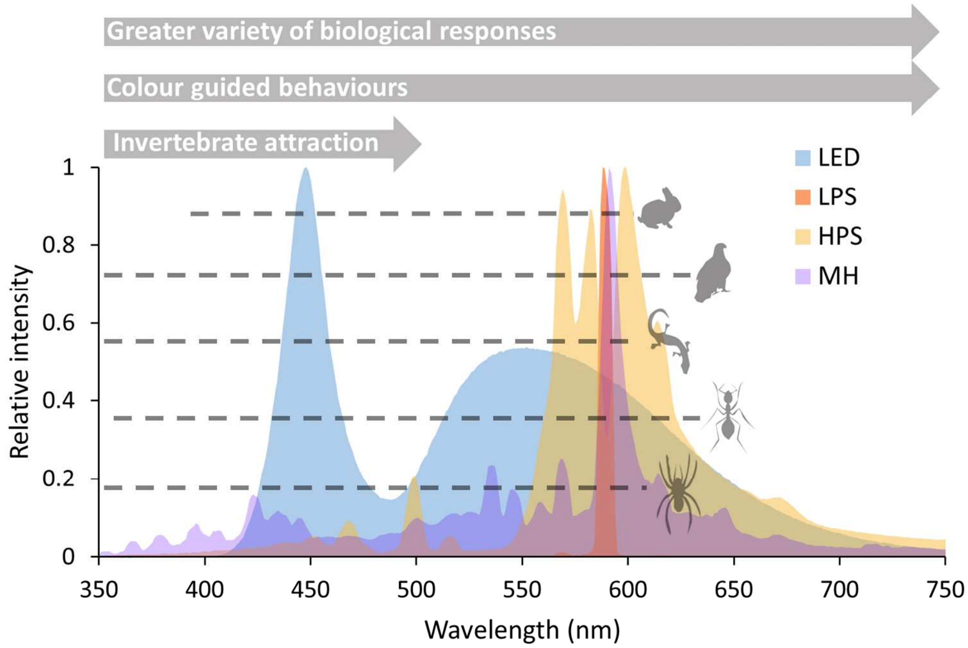
Figure 4. The sensitivity of marine invertebrates to direct artificial light and artificial sky glow. Solid lines represent the attenuation of scalar irradiance (between 400 and 700nm) with depth estimated using radiative transfer models under winter (**a & c**; Chlorophyll = 0.3mg m^3 uniform profile, wind = 5m s^{-1}) and spring (**b & d**; Chlorophyll = 5mg m^3 uniform profile, wind = 5m s^{-1}) water column properties. Models of scalar irradiance with depth are derived from spectral power distribution recorded from the spring high tide mark under a white LED street light on the Barbican in Plymouth (**a & b**), and artificial skyglow from predominantly white Metal Halide spectra recorded above Falmouth Harbour (**c & d**). Grey dashed lines indicate the maximum depth at which sufficient artificial light is available to perform species behaviours. SSS= Settlement Site Selection; PR=Polyp Retraction; LP=Larval Phototaxis; DVM=Diel Vertical Migration. Sensitivities to white light were calculated from experimentally derived values in existing literature (Crisp & Ritz, 1973, Young & Chia, 1982, Forward *et al.*, 1984, Svane & Dolmer, 1995, Tankersley *et al.*, 1995, Båtnes *et al.*, 2013, Gorbunov & Falkowski, 2002).



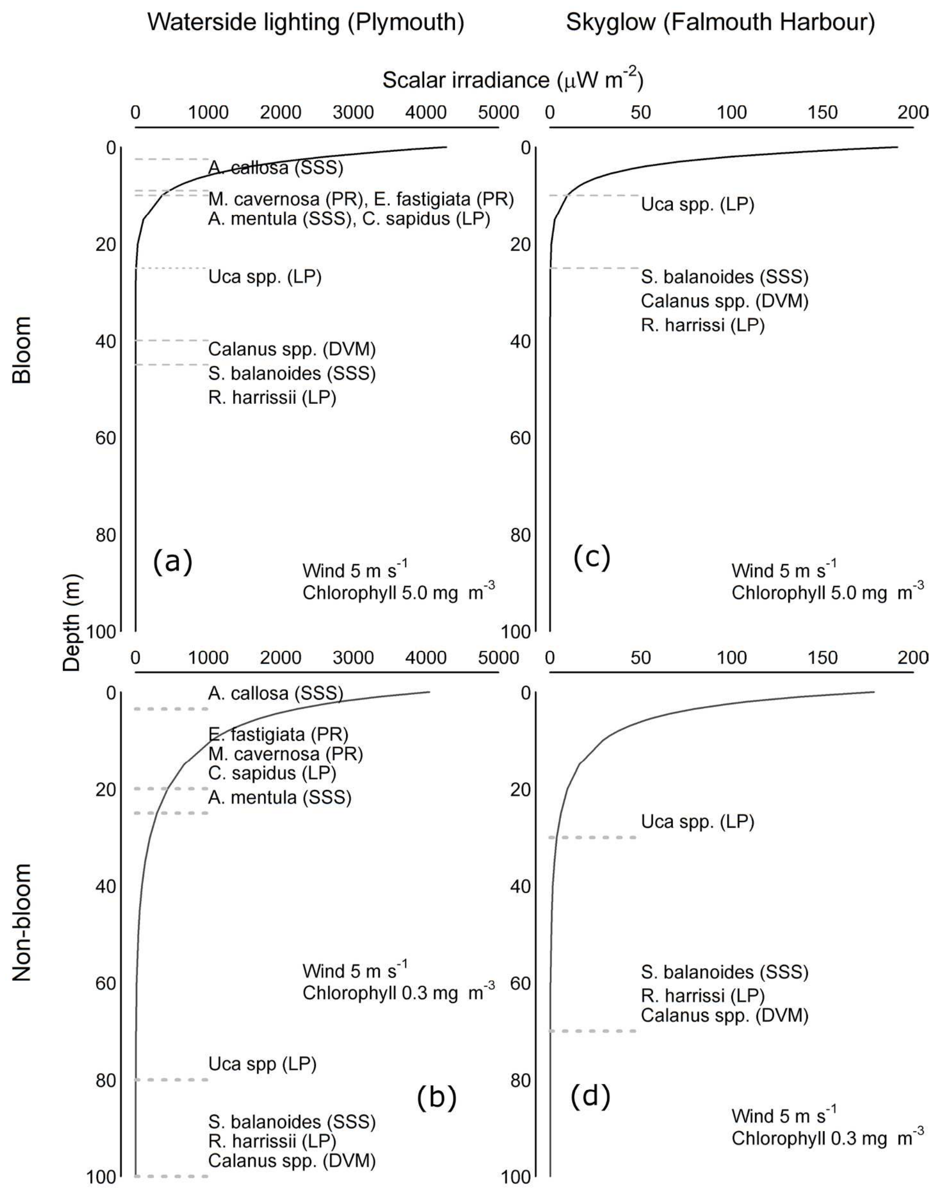
159x69mm (300 x 300 DPI)



80x37mm (300 x 300 DPI)



150x99mm (300 x 300 DPI)



179x231mm (300 x 300 DPI)