HHS Public Access
Author manuscript
J Exp Zool A Ecol Integr Physiol. Author manuscript; available in PMC 2019 October 01.

Published in final edited form as:
J Exp Zool A Ecol Integr Physiol. 2018 October ; 329(8-9): 387–393. doi:10.1002/jez.2241.

Artificial light at night as an environmental pollutant: An integrative approach across taxa, biological functions, and scientific disciplines

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Keywords

artificial light at night (ALAN); circadian rhythms; light pollution; sky glow; urbanization

1 | INTRODUCTION

With each day, the world is becoming number of people move into urban areas, and consequently these increase in area to consume rural and natural land (Seto, Guneralp, & Hutyra, 2012). Among the numerous changes that accompany urban sprawl, artificial light at night (ALAN) is one of the most immediate and evident (Falchi et al., 2016; Longcore & Rich, 2004). From a variety of anthropogenic sources, artificial light is introduced at times (the night) and in places where it does not naturally occur (Falchi et al., 2016). The characteristics of the introduced light sources are also very different from natural light. Artificial light is often of an intensity higher than naturally occurring light at night, for instance, because of moon or starlight (Gaston, Bennie, Davies, & Hopkins, 2013). Furthermore, the spectral properties of artificial light are often enriched of a specific wavelength, in particular, the blue portion of the spectrum (Gaston et al., 2013; Navara & Nelson, 2007). ALAN is increasing at a steady pace globally (6% per annum) (Falchi et al., 2016) but with tremendous spatial variation (from negative trends to positive changes of up to 20% per annum; Bennie, Davies, Duffy, Inger, & Gaston, 2014; Bennie, Duffy, Davies, Correa-Cano, & Gaston, 2015). Although the proportion of the Earth's surface covered by urban land is below 5% (Seto et al., 2012), between 10% and 20% of the global land experiences some degree of ALAN (Kyba et al., 2015). This is mainly due to the sky glow effect (Kyba et al., 2015) but further because artificial light is also used outside of urban areas, for instance on roads connecting different cities or in remote industrial installations (Falchi et al., 2016).

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A key question for biologists is whether the alteration of natural lightscapes by ALAN has any consequence for the organisms that inhabit light polluted areas, including humans (Dominoni, Borniger, & Nelson, 2016; Gaston et al., 2013; Navara & Nelson, 2007). Species have evolved over millions of years in habitats where daily, lunar, and seasonal cycles are dominant sources of environmental variation are driven by changes in light regimes (Foster & Kreitzmann, 2004; Helm et al., 2013). Organisms have thus developed specific molecular, physiological, and behavioral adaptations to such rhythms of life (Foster & Kreitzmann, 2004; Helm et al., 2013). How are these organismal adaptations coping with a light polluted world? How do responses at the individual level scale up to influence, populations, communities, and ultimately ecosystems? Importantly, can we identify lighting practices that minimize the environmental impacts of ALAN? In recent years the scientific interest in such questions, and more generally in the biological impacts of ALAN, has bloomed. This has led to an explosion of research papers that have investigated a plethora of effects of ALAN on individual organisms, species, and communities. This special issue was conceived to illustrate the breadth of research questions that the study of light pollution has focused on in recent years. Moreover, we aimed at highlighting recent developments and challenges in this field. We focus on three of these. First, the need to investigate the ecological effects of ALAN in a diverse array of species representing the extraordinary diversity of life, from microbes to plants and from invertebrates to all vertebrate classes. Second, the need for studies at different levels of biological organization, from molecules to physiology, behavior, populations, and communities. Third, the need to establish intensity and spectral-dependent effects of ALAN, with the ultimate goal to produce relatively simple guidelines that would inform policy-makers and produce tangible impacts on the way that lighting systems are designed, produced, and ultimately installed. We believe that to meet these challenges an integrative and multidisciplinary approach is needed.

2 | THE EFFECTS OF ALAN ON DIFFERENT SPECIES

The papers included in this special issue represent outstanding taxonomic breadth. From insects to mammals, several animal classes, both invertebrate and vertebrate, are represented. McLay, Nagarajan-Radha, Green, and Jones (2018) investigated effects of ALAN on reproduction and physiology in *Drosophila.* Insects were also the focus of Donners et al. (2018), who modeled the attraction of several insect orders to light sources of different colors, allowing the application of light sources that reduce insect attraction. Within the invertebrate group, van Grunsven, Jähnichen, Grubisic, and Hölker (2018) shift to Molluscs (Figure 1), and in particular to slugs, and show how this group actually benefits from nocturnal illumination, likely via reduced predation risk and increased foraging success (van Grunsven, Jähnichen, Grubisic, & Hölker, 2018). In vertebrates, the greatest majority of studies that looked at the impact of light pollution on wildlife concerning birds and mammals. This is also reflected in our special issue. In birds, Great Tits *(Parus major)* have been and continue to be a model organism. Three of our papers studied this species. de Jong et al. (2018) examined if and how the rate of extra-pair paternity was affected by lights of different colors. Dominoni et al. (2018) assessed dose-dependent responses of the reproductive system. Raap, Pinxten, and Eens (2018) asked whether roosting in cavities may limit the effects of light pollution on sleep. Other passerine bird species included in this issue are the Indian Weaver Bird *(Ploceus philippinus)* and the Zebra finch (*Taeniopygia guttata*). Through captive experiments, Kumar, Malik, Bhardwaj, and Rani (2018) demonstrated that light at night can alter day length perception in Weaver birds, whereas Alaasam et al. (2018) revealed that cool light temperatures disrupt sleep and increase corticosterone levels in zebra finches. Last but not the least among birds, Little Penguins *(Eudyptula minor)* were studied by Rodríguez, Holmberg, Dann, and Chiaradia, (2018; Figure 2), which showed increased use of light areas during colony attendance, probably because light enhances vision at night and thereby reduces energy expenditure and predation risk. Two different mammal species are also covered by our special issue. Spoelstra, Ramakers, van Dis, and Visser (2018) reveal that the choice of Daubenton's bats to commute through tunnels was unaffected by whether such tunnels were illuminated or not. Dimovski and Robert report spectral-dependent suppression of melatonin levels, as well as changes in oxidative status, in Tammar wallabies (*Macropus eugenii*).

Although such an impressive lineup of studies illustrates the taxonomic and geographic breadth of the current research on the ecological effects of light pollution, some groups remain understudied. For instance, we still have limited understanding of the effects of ALAN on plant species, as highlighted in a recent review (Bennie, Davies, Cruse, & Gaston, 2016). Being primary producers as well as photosynthetic organisms, plants play a key role in the trophic chain and are highly sensitive to changes in light regimes, calling for more research in this field. Similarly, studies on phytoplankton are also limited but extremely needed to better understand the impact of light pollution on aquatic ecosystems (Grubisic, 2018; Grubisic et al., 2017). Some vertebrate groups such as fish, amphibians, and reptiles are also underrepresented in the literature, at least when compared with the amount of information already available on birds and mammals responses to ALAN (Brüning, Hölker, Franke, Kleiner, & Kloas, 2016; Perkin et al., 2011; Perry, Buchanan, & Fisher, 2008). We also want to stress that besides generalizing across taxa, more studies are also needed within the same taxonomic group but focusing on different species. Indeed, species that are closely related might very well different in their sensitivity to light, as studies in moths and birds have suggested (Kempenaers, Borgström, Loës, Schlicht, & Valcu, 2010; van Langevelde et al., 2018).

3 | THE EFFECTS OF ALAN AT DIFFERENT LEVELS OF BIOLOGICAL ORGANIZATION

A major aim of our special issue was to reveal the multitude of molecular, physiological, and behavioral mechanisms that light pollution can affect. At the molecular and physiological level, these and previous papers have shown that ALAN can alter patterns of gene expression (Bedrosian, Galan, Vaughn, Weil, & Nelson, 2013; Dominoni et al., 2018; Fonken & Nelson, 2014; Shuboni & Yan, 2010), hormone secretion (Alaasam et al., 2018; de Jong et al., 2016; Dominoni, Goymann, Helm, & Partecke, 2013; Ouyang, Davies, & Dominoni, 2018), body temperature (Kumar et al., 2018), energy expenditure (Welbers et al., 2017), immune function (Bedrosian, Fonken, Walton, & Nelson, 2011; Cissé, Russart, & Nelson, 2017; Fonken, Lieberman, Weil, & Nelson, 2013), and oxidative stress (McLay et al., 2018; Navara & Nelson, 2007). Given, such extensive changes in the underlying physiology, it comes with no surprise that an impressive array of behavioral effects of ALAN have been shown. Russart & Nelson (2018) in our special issue review the behavioral effects of ALAN. Some of these refer to changes in mating (Baker & Richardson, 2006; Botha, Jones, & Hopkins, 2017; Hau et al., 2017; McLay et al., 2018; van Geffen et al., 2015), singing (Da Silva & Kempenaers, 2017; Kempenaers et al., 2010), sleep (Sun, Raap, Pinxten, & Eens, 2017), mood and anxiety-related behaviors (LeGates et al., 2013), habitat selection (Yuen & Bonebrake, 2017), predation (Yuen & Bonebrake, 2017), migratory (Doren et al., 2017), and commuting movements (Spoelstra et al., 2017). Moreover, the special issue also includes a timely perspective from ulsebrook, Jones, Mulder, and Lesku (2018) on the impacts of ALAN on sleep. Although evidence is accumulating for light pollution to alter sleep behavior, and nocturnal rest, the physiological basis for such changes is unknown. Advances in biologging of sleep (Lesku et al., 2012) offer exciting perspectives, especially if integrated with on-board recording of activity and light exposure (Dominoni, Åkesson, Klaassen, Spoelstra, & Bulla, 2017).

As knowledge of the individual responses to ALAN at different levels of biological organization is accumulating, so is the evidence for impacts at higher levels, such as population dynamics, community composition, and ecosystem function. Sanders and Gaston (2018) open our special issue with a review of the effects of light pollution on ecological communities. One of the evident impacts of ALAN is the disruption of biological timing, which can differ in the extent and nature between different species. This may lead to an alteration of interspecific interactions (Davies, Bennie, Inger, de Ibarra, & Gaston, 2013; McMahon, Rohr, & Bernal, 2017), population dynamics (Sanders et al., 2015), and ultimately community composition (Bennie, Davies, Cruse, Inger, & Gaston, 2015; Davies, Coleman, Griffith, & Jenkins, 2015; Knop et al., 2017; Sanders & Gaston, 2018; Sanders, Kehoe, Cruse, van Veen, & Gaston, 2018). Such cascading effects may be more common than previously thought, and may also underline trends in species abundance. For instance, light pollution has recently been suggested as an important threat to pollination (Knop et al., 2017), and one of the causes of the rapid, dramatic decline in insect biomass observed in recent decades (van Langevelde et al., 2018). However, how responses at the individual level drive changes in population dynamics and communities is still a knowledge gap and constitute an important research challenge for this field. Indeed, although trends in species abundance and ecosystem services may be the main functional output that conservation biologists and policy-makers focus on, we argue that without a knowledge of the mechanisms generating such trends it will be impossible to design evidence-based conservation plans.

4 | APPLYING FUNDAMENTAL KNOWLEDGE TO POLICY-MAKING AND CONSERVATION

Artificial light at night is the perfect example of a type of environmental pollution for which concrete management plans can be designed to reduce or completely eliminate its impact on species and ecosystems. The literature on this particular topic is growing, and new evidence is constantly adding (Gaston, Davies, Bennie, & Hopkins, 2012; Longcore et al., 2018). The first obvious mitigation measure should be eliminating any illumination when this is not strictly needed. When not possible, light emissions from streetlamps should be shielded so that light is only directed to the ground and not to the sky. Moreover, light has clear dose-dependent effects on many behavioral and physiological responses (see for instance Dominoni et al. (2018) in the special issue as well as Brüning, Hölker, Franke, Preuer, and Kloas (2015) and de Jong et al. (2016)). Thus, artificial light should be tuned to the intensity necessary to render an area visible to the human eye, while any excess lighting should be avoided.

A more complicated issue is that of the spectral composition of light. It is becoming increasingly evident that the color of the emitted light is important to determine whether or not, and the degree to which, a species is affected by ALAN. Thus far, mounting evidence seems to suggest that short wavelengths in the visible spectrum can cause the strongest effects. For instance, suppression of nocturnal melatonin by ALAN has been found to be highest under the blue light across taxa, from insects to fish, birds and mammals, including humans (Brüning et al., 2016; Ouyang et al., 2017; van Langevelde, Ettema, Donners, Wall-isDeVries, & Groenendijk, 2011; Ziv, Tovin, Strasser, & Gothilf, 2007). Other traits show similar strong responses to nocturnal blue light (Bayarri, Madrid, & Sanchez-Vazquez, 2002; De Jong, Caro, Gienapp, Spoelstra, & Visser, 2018; Longcore et al., 2015). Three articles in our special issue confirmed this evidence for insect phototaxis (Donners et al., 2018), corticosterone levels in birds (Alaasam et al., 2018) and oxidative status in wallabies (Dimovski & Robert, 2018). Thus, it seems that white light, which contains a high proportion of blue wavelengths and is one of the most common light sources used for nocturnal illumination, should be avoided. This is particularly relevant because of the ongoing switch to LED lighting. Such a switch, motivated by mostly economic reasons, has led to the widespread replacement of incandescent and low-pressure sodium vapor lamps (rich in long wavelengths but less efficient) with cool white LEDs. Such conversion has been suggested to be associated with recent increases in the radiance and spatial extent of light pollution, especially in developed countries (Kyba et al., 2017). However, more research on this topic is needed, because certain species and/or specific biological functions might be more sensitive to wavelengths other than blue light. For instance, magnetoreception in birds is mostly sensitive to red light (Wiltschko, Munro, Ford, & Wiltschko, 1993), and indeed red light has been associated with disruption of navigation in seabirds (Poot et al., 2008). Thus, caution needs to be taken when choosing a particular color for a new light installation.

5 | CONCLUSION

The papers of this special issue demonstrate that an integrative approach across taxa, biological functions, and scientific disciplines is needed to fully appreciate the effects of light pollution on individual, species, and ecological communities. Moreover, such an integrative approach will help us to develop a common, mechanistic framework to improve the design of future studies and identify knowledge gaps. This will allow comparing the results of different studies and also promote collaboration between researchers studying different species or coming from different scientific backgrounds, as the study of light pollution brings together chronobiologists, ecologists, conservationists, physicists, engineers, businesses, and policy-makers. Our ultimate goal should be to reconcile the need for artificial light in our society with the need to preserve our health as well as the health of the ecosystems we live in. We thus believe that this special issue comes at a very appropriate time.

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FIGURE 1.
Large -scale, long-term field experiments aimed at investigating the effects of realistic scenarios of light pollution on ecosystems have been established in the last decade. The picture shows one of these setups at the Leibniz Institute of Freshwater Ecology and Inland Fisheries, in Berlin, Germany. From van Grunsven et al., this issue (Image courtesy of Maja Grubisic) [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 2.

The impact of artificial light at night on the behavior and physiology of individual species is increasingly studied via field experiments. the picture illustrates one of these experiments, which was aimed at testing the effect of different light spectra on the colony attendance of little penguins (*Eudyptula minor*). From Rodriguez et al, this issue (Image courtesy of Beneharo Rodríguez) [Color figure can be viewed at wileyonlinelibrary.com]