Dark and Quiet Skies for Science and Society

Report for review

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Light pollution impact on the bio-environment

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Salvador Bara[1], Costis Bouroussis[2], Anika Jägerbrand[3], Andreas Jechow[4], Travis Longcore[5], James Lowenthal[6], Mario Motta[7], Pedro Sanhueza[8], Luc Schlangen[9], and Sibylle Schroer[4]

[1] Universidade de Santiago de Compostela, Spain
[2] National Technical University of Athens (NTUA), Greece and CIE
[3] Halmstad University, Sweden
[4] Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Germany
[5] University of California Los Angeles/The Urban Wildlands Group, USA
[6] Smith College, USA
[7] North Shore Medical Center/Tufts Medical School, USA
[8] Oficina de Protección de la Calidad del Cielo, Chile
[9] Eindhoven University of Technology, The Netherlands

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N.1 Introduction

For thousands of millennia, nearly all life on Earth has experienced regular daily and nightly rhythms of light and darkness imposed by the rotation of the Earth, and has evolved to depend on those cycles. The DNA in human cells includes multiple "clocks" that operate on roughly 24-hour (circadian) timescales and ultimately regulate many of our most important functions, including hormone secretion, sleep, digestion, and metabolism. While the daily behavior and function of humans was once thought to have evolved beyond sensitivity to light and to be mostly socially regulated, it is now widely recognized that in fact we are physiologically profoundly sensitive to even very low levels of light at night.

Many species of fauna and flora show strong sensitivity to daily light-dark cycles as well and many other impacts of artificial light at night are reported on wildlife and plants. The majority of all animals, a vast majority of invertebrates including crucial pollinators and more than three-quarters of mammal species are nocturnal (Hölker et al. 2010). About 40% of bird species migrate, and an estimated 80% of them do so at night. It has been shown that animals are capable of using the dim lights of the Milky Way and the stars to navigate (Foster et al. 2018).

Thus, the vast majority of life on Earth needs darkness at night to thrive. But humans and wildlife are now increasingly exposed to ever-brighter artificial light at night (ALAN), with a recent dramatic increase driven largely by the advent of new technologies, primarily inexpensive, durable, and energy efficient solid state lighting in the form of light-emitting diodes (LED). The emission of ALAN as detected by satellite imagery is growing exponentially by 2% per year, which is twice the rate of population growth (Kyba et al. 2017) and a skyglow model based on such data estimates that more than a third of the world's population -- and nearly 80% of North Americans -- can't see the Milky Way (Falchi et al. 2016).

A significant and growing body of scientific research shows that ALAN causes significant negative effects on the health of humans and flora and fauna. The impacts of ALAN are diverse and appear at many different scales. They include, for flora and fauna, changes in habitat use, migration, reproduction, predator-prey relationships, ecosystem functions and services, and fatalities at significant enough levels to pose extinction threats to some species. On humans, the impacts of ALAN include disruption of melatonin production and circadian rhythms and extend to elevated risks of hormonal cancers and other serious diseases.

In this chapter, we summarize the current state of understanding of the impacts of artificial light at night on humans and flora and fauna, and we put forward recommendations for how to mitigate these impacts.

N.2. Effects of Artificial Light at Night on Human Health

N.2.1. Introduction

With the introduction of efficient and bright LED lighting, there are strong economic arguments for a major overhaul in the street lighting of the roadways worldwide where most outdoor lighting is for streets and parking areas (IES RP-8, LED Facts). The energy efficacy of this type of lighting, with significant savings in energy use and operating costs makes the push for LED conversion compelling for purely economic reasons. Furthermore, maintenance costs are reduced due to longer LED lamp life. These are all compelling reasons to proceed with the conversion from current street high-pressure sodium (HPS) to LED lighting.

Not all LED light is optimal, however, including when used for exterior applications such as street and parking lot lighting. For example, glare from improperly designed fixtures may create serious road hazards by temporarily blinding road users (Yandan et al 2014, Gibbons and Edwards 2007). In some designs of white LED lighting the emission spectrum is relatively rich in short wavelength, blue light, and numerous studies have raised significant concerns about the negative human and environmental effects of those blue emissions. Excessive blue light at night can contribute to disability glare, as blue light scatters more in the human eye than longer wavelengths. There are studies showing possible retinal damage from exposure to blue spectrum wavelengths (Shang 2014, Lougheed 2014, EYE 2016).

Light is the most powerful stimulus for regulating human circadian rhythms and is the major environmental time cue for synchronizing the circadian clock (Wright 2013, Cajochen 2011). In addition to resetting the daily circadian rhythm, light also stimulates additional neuroendocrine and neurobehavioral responses, including suppression of melatonin release from the pineal gland, activating the limbic system improving alertness and performance (Evans 2013). Melatonin is now one of the most studied biomarkers of the human physiological response to light, and this substance is produced only at night, regardless of whether an organism is day-active (diurnal) or night active (nocturnal). The biochemical and genetic mechanism of action of circadian rhythm physiology was determined by the 2017 recipients of the Nobel prize in medicine, Jeffrey C. Hall, Michael Rosbash and Michael W. Young (Nobel Prize Medicine website).

Light exposure at night results in the immediate suppression of melatonin production. Under natural conditions, organisms would never be exposed to light during the night in substantial amounts and would not experience melatonin suppression. Light at night, however, efficiently suppresses melatonin at intensities commonly experienced both in outdoor and indoor typical lighting at night (AMA annual, 2012).

N.2.2. Glare

An Internationally accepted definition of glare is in the CIE S 017/E:2011 'International Lighting Vocabulary (ILV) ': "condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme contrasts. The disabling effect of the veiling luminance may have serious implications for nighttime driving visibility"

As LED lighting is often more directional than other forms of lighting, it can lead to stronger glare than conventional lighting if insufficient attention is paid to controlling the lighting's spatial and color properties; conversely, proper engineering of fixtures can greatly minimize glare. Some individuals are debilitated by the visual glare from LEDs that are not properly directed and diffused (Ticleanu and Littlefair 2015). LED's are very intense point sources unless shielded or diffused properly that lead to vision discomfort when viewed by the human eye, especially by older drivers. This effect is magnified by higher-color-temperature LED's, i.e. blue-rich white LED lighting, because blue light scatters more in the human eye, leading to increased disability glare (Sweater-Hickcox 2013). In many localities where 4000K and higher lighting have been installed, there have been community complaints of glare and a "prison atmosphere" by the high intensity blue-rich lighting. Many localities in the USA have replaced high CCT lighting with 3000K or lower CCT because of such public opposition (e.g. Seattle WA; Davis, CA; Queens NY; Scigliano 2013, CBS-13-TV 2014; Chaban 2015). In contrast, lighting with CCT 3000K and lower, while still very "white" compared with legacy HPS, is much better received by citizens in general in side-by-side comparisons with higher-CCT lighting.

There is significant discomfort from glare from unshielded LED lighting. A French government report in 2013 stated that due to the point source nature of LED lighting, their luminance level is inherently higher than 10,000 cd/m2, causing visual discomfort whenever the lighting unit is within the field of vision. As the emission surfaces of LEDs are highly concentrated nearly point sources, the luminance of each individual source can be 1000 times higher than the discomfort level (Anses 2014). Discomfort and disability glare can decrease safety and are considered a road hazard in cases where they compromise visual performance and acuity (Lighting Res. Tech 2012, Vos 2003). Currently lighting installations are tested by measuring illuminance on the ground, in units of lux (or, in the US, foot-candles). This is useful for determining efficiency and evenness of lighting installations; however, this method does not take into account the human biological response to the lighting installation. It is well known that unshielded light sources cause pupillary constriction, leading to worse nighttime vision between lighting fixtures, and cause a “veil of illuminance” beyond the lighting fixture. This leads to worse vision than if the light never existed at all, defeating the purpose of the lighting fixture. Most indoor lighting is equipped with shades to prevent glare, and most theater lighting is designed with shielding to prevent glare for audience members. Ideally, LED street and other exterior lighting should be tested in real-life installations, and visual acuity should be determined to ascertain best designs for optimal public safety. In a study of roadway lighting in 2016, there was no significant difference in roadway detection distance from LED fixtures of CCT 2100K, 3500K, or 6000K (Lewis and Gibbons 2016). Published studies thus far have not shown a decrease in traffic accidents associated with conversion to full-spectrum white LEDs (e.g., CCT >2700 K; Marchant 2020) A prudent approach to balance these human health and safety issues is to use the lowest CCT deemed acceptable; specify high-quality optics to ensure delivery of light only on desired surfaces instead of as glare; and avoid light trespass onto windows of any residential property.

N.2.3. Retinal damage from short wavelength blue light

Numerous studies over the past few years have raised concern that excess illumination, especially in the blue part of the spectrum, may affect human vision and promote retinal degeneration or accelerate some genetic diseases. Even low intensity blue light can cause retinal damage over time in animal models, and thus theoretically may accelerate the development of age-related macular degeneration (AMD), retinitis pigmentosa (RP), and certain genetic retinal diseases in humans (Walls 2011, Marquioni-Ramella 2015, Nowak 2014, Paskowitz 2006). Light pollution and especially blue illumination may have detrimental consequences on the retina and its physiology (Kanterman 2009, Pauley 2005). There are two main mechanisms of retinal damage: (a) ‘blue-light’ and (b) ‘visual pigment-mediated process’. Retinal light damage can be produced by low irradiance levels of white light rich in blue over a prolonged time (Behar-Cohen 2011, Wu 2006), or by more intense exposure to high irradiance with an action spectrum peaking at short wavelength of white light (Grimm 2001). Paradoxically, intermittent light exposure may cause greater visual cell damage than continuous light exposure (with the same light source and same total duration) (Organisciak 1989).

Free radical damage can occur when oxygen interacts with certain molecules, a process that can be initiated especially by blue light, and therefore, the retina is sensitive to such damage (Wu 2006). The retina has a system that protects cells and tissue(s) against oxidative stress, but these mechanisms can fail with age and then the pathologic symptoms of retinal degeneration begin (Siu 2008). ALAN from excess blue LED may potentially have negative consequences for retinal health, especially in older individuals where anti-oxidative stress mechanisms are less effective. In many human diseases such as AMD and RP, photoreceptor cells' death is the principal event of retinal degeneration and therefore it is prudent to consider that excessive exposure to natural or unnatural light may accelerate many of these (Grimm 2013).

N.2.4. Melatonin suppression

Melatonin is a hormone that humans naturally produce. It is not detectable during the day (even in dim light) and production peaks at night. With waning ambient light, and in the absence of electric lighting, humans begin the transition to nighttime physiology at about dusk; melatonin blood concentrations rise, body temperature drops, sleepiness grows, and hunger abates, along with several other responses. Melatonin supports night-time behaviour; this means that in humans it facilitates sleep initiation and sleep consolidation. The 24-hour melatonin profile marks the circadian rhythm and the habitual sleep-wake cycle (Czeisler, Shanahan et al. 1995, Dijk, Shanahan et al. 1997). People’s usual bedtime is measured to be about 2 hrs after melatonin onset (in dim light; see Duffy and Wright 2005).

These effects are interrupted by exposure to electric light, especially when it’s rich in short wavelengths. Light at night can suppress nocturnal melatonin production, disrupt the circadian system and compromise human sleep and health. For some of these responses a large interindividual variability has been reported (see Philips et al 2019). Recently, a new SI-compliant metric was established to quantify light for its stimulation of non-visual responses that are driven by intrinsically photosensitive retinal ganglion cells, ipRGCs: melanopic equivalent daylight illuminance (see international standard CIE S 026:2018). IpRGCs combine melanopsin-based photoreception with rod and cone signals, and the new metric has been demonstrated to be a good predictor for circadian responses to light, such as melatonin suppression and phase shifting (Brown 2020). The spectral sensitivities of the five photoreceptors (as defined in CIE S 026:2018) and the luminous efficiency function for photopic vision, V(l), are plotted in fig N.1.

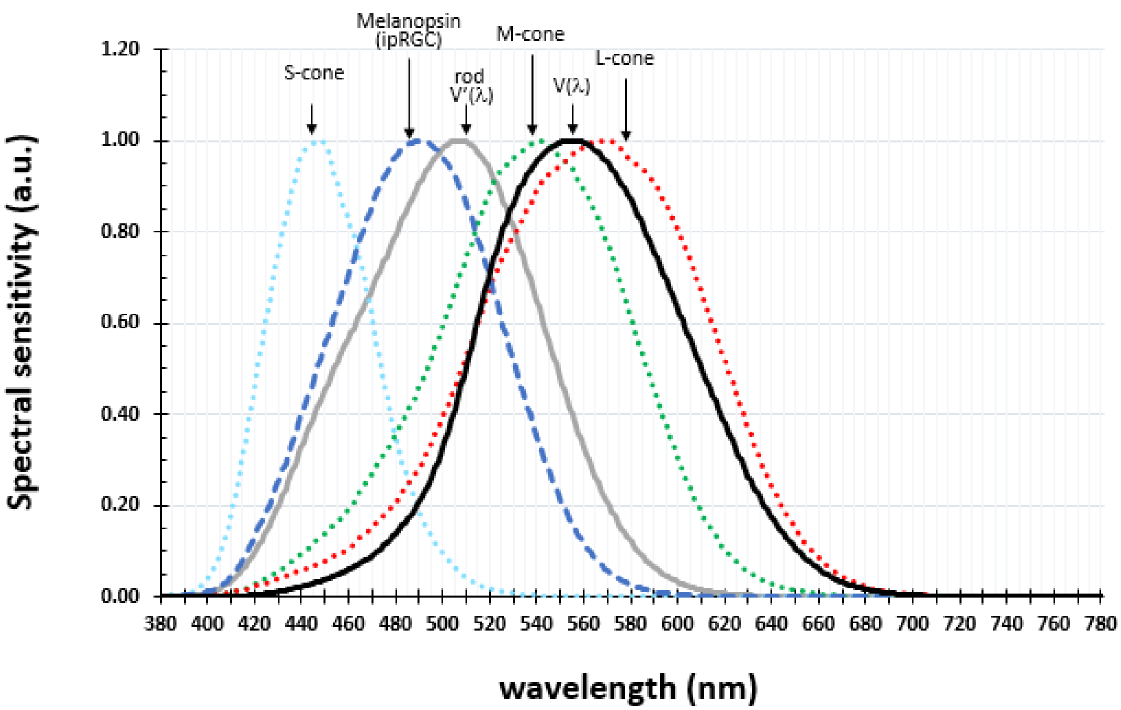

Figure N.1. The spectral sensitivities of the S-cone, M-cone, L-cone, rod and melanopsin-based (ipRGC) photoreceptor, as defined in CIE S026:2018. For comparison also the spectral luminous efficiency function for photopic vision, V(l), is given. The spectral sensitivity function for rods is also known as the spectral luminous efficiency function for scotopic vision, V'(l).

In general, the sleep-disruptive effects of evening/nighttime light are stronger when (i) the evening/nighttime light is more bright and more rich in short wavelengths (i.e., higher melanopsin activation), (ii) individuals have been exposed to less light during daytime, and/or (iii) individuals are less sleep deprived, i.e. more well-rested.

Melatonin is suppressed at very low light intensities, as little as 6 lx in sensitive humans, (Grubisic et al. 2019) although a large range in human sensitivity to this effect is observed, including a 50-fold variation between people in melatonin response to light exposure (Phillips et al. 2019). Children are more sensitive to disruption from light at night than adults (Nagare et al. 2019). Office workers exposed only to dim light during the day are more sensitive to disruption from light at night than those who work outside. Men are more sensitive to light at night, including decreased "long sleep" with increased exposure (Xiao et al. 2020).

Melatonin exerts a number of physiological cellular effects, and is suppressed by even low level lighting at night from outdoor lighting sources. (119) In addition, circadian responses that result from melatonin suppression are heavily dependent on the spectrum of light. As light is concentrated closer to the wavelengths of peak sensitivity for melanopsin, the intensity of light (measured in lx) required to suppress melatonin decreases (Grubisic et al. 2019). At 424 nm, the minimum illuminance for melatonin suppression is 0.1 lx (Souman et al. 2018). The relative impact of different lighting sources can be predicted using the melanopic response curve (Aubé et al. 2013, Longcore et al. 2018a). All full-spectrum LED sources have a greater potential circadian impact than HPS, including 2200 K (1.5 times HPS), 3200 K (2.5 times HPS), and 4300 K (3 times HPS).

Outdoor lighting is meant to increase overall safety of people and traffic, but, if poorly designed, can also compromise vision, safety, and public health. The study results on the effects of outdoor nighttime light on sleep find an association with satellite-measured outdoor lighting. For example, subjects in South Korea with higher exposure to light at night as measured by 2.7-km resolution satellite data (Defense Meteorological Satellite Program; DMSP) were 20% more likely to sleep less than 6 hours per night and on average slept 30 minutes less than subjects in areas with lower outdoor lighting levels (Koo et al. 2016). In a study in the United States, higher levels of outdoor lighting as measured by DMSP were significantly associated with reporting < 6 hours of sleep per night, an effect that remained in place even after accounting for noise and population density (Ohayon and Milesi 2016). In that study, people who lived in the brightest areas were more likely to go to bed later, wake up later, and sleep less. They also were more likely to report that they were dissatisfied with sleep quality or quantity and to be sleepy during the day. DMSP-measured light at night was negatively associated with restorative long wave sleep. Importantly, that study validated that brightness in bedrooms correlated positively with satellite-measured outdoor light (Ohayon and Milesi 2016).

Satellite-measured light at night was also associated with the use of more drugs for insomnia in a second South Korean study (Min and Min 2018). Residents living in the lowest two quartiles of light at night as measured by DMSP used significantly less insomnia medication, even after accounting for age, sex, population density, income, body mass index, smoking status, alcohol consumption, exercise, and psychiatric disease. Mean use of insomnia medication increased with each quartile of light exposure from lowest to highest for each of three insomnia medications (Min and Min 2018).

Most recently, a study of the NIH-AARP Diet and Health Study cohort in the United States investigated sleep and exposure to light at night as measured by the DMSP satellite (Xiao et al. 2020). The highest levels of light exposure associated with 16% (women) and 25% (men) increased probability of reporting short or very short sleep duration. Probability of reporting short or very short sleep increased from lowest to highest quintiles of light at night in models that adjusted for age, race, marital status, state of residency, smoking, alcohol, vigorous physical activity, TV viewing, and median home value, population density and poverty rate at census tract level (Xiao et al. 2020). The authors concluded that, “Taken together, these findings suggest that the prevalence of sleep deficiency is higher in places with higher levels of LAN [Light at Night]” (Xiao et al. 2020). It remains an open question whether indoor exposure to street lighting is of sufficient magnitude to affect circadian rhythms directly, but recent research investigating light spectrum and cancer risk suggests that the color of light outdoors in the vicinity of residences is an important risk factor (Garcia-Saenz et al. 2018).

While studies using remotely sensed data detect associations between sleep disturbance, circadian disruption, and associated diseases and light at night, others question the relationship between outdoor lighting and indoor exposure to light at night. Leaving aside the point that outdoor exposure to lighting can also contribute to circadian disruption, these studies focus on relationships between indoor and outdoor exposure. Recent work confirms the relationship between ground-level irradiance outdoors and satellite-based proxies for light at night. Using a dataset or 515 ground-based measurements of illumination from the upper hemisphere, Simons et al. (2020) showed that ground-based light exposure correlates highly with remotely-sensed light (VIIRS DNB annual composite) and even more with the New World Atlas of Artificial Night Sky Brightness (Falchi et al. 2016). This work conclusively establishes that satellite-measured light at night is a proxy for ambient light in the environment on the ground at night, as one would expect.

With that relationship now established (Simons et al. 2020), ongoing research is now pursuing individual-level studies of correlation between indoor light levels and satellite-measurements of light at night. In a more recent Dutch study, individual-level light exposure for children was measured indoors with a device that had a resolution of 0.1 lx (Huss et al. 2019). They found an influence of outdoor light on indoor light during the darkest time period with a correlation of 0.31. It should be noted, however, that 94% of the children in the study had curtains that controlled light entering the room. In a survey of lighting designers using their own light meters, Miller and Kinzey (2018) reported measurements in a number of different contexts within homes. At windows without drapes a maximum of 20 lx was reported, with a mean of 5 lx and median of 0.5 lx. All of those light levels are dramatically elevated above natural conditions: a full moon would produce 0.1–0.2 lx.

Experiments that involve exposures to light at night document illumination levels that affect health and sleep outcomes. Sleeping under 5 lx of 5779 K light caused more frequent arousals, more shallow sleep, and more REM sleep (at the expense of long wave deep sleep) (Cho et al. 2016). Light greater than 3 lx during the last hour of sleep was associated with weight gain in an elderly population (Obayashi et al. 2016). In another study of an elderly population, increased light at night and especially light at night > 5 lx was associated with 89% increased risk of depression (Obayashi et al. 2013). Further studies indicate that elevated illumination is associated with higher blood pressure as well, with associated excess deaths, at 3, 5, and 10 lx exposures (Obayashi et al. 2014). Metrics of sleep quality (efficiency) were also consistently lower with higher illumination at each category (3, 5, and 10 lx) (Obayashi et al. 2014).

Taken together, this research is consistent with a few different interpretations of the influence of outdoor lighting on human circadian rhythms and health outcomes. It is possible that the correlations between light at night and adverse health outcomes indicate instead variation in another factor, such as air pollution, as suggested by Huss et al. (2019). The robustness of sleep disruption correlations when controlling for population density, however, argues against that interpretation (Ohayon and Milesi 2016). Xiao et al. consider this question and conclude: "[I]t is also possible that the observed associations in our study population represent a true relationship, but primarily driven by individuals whose ALAN exposure was more heavily influenced by outdoor ALAN (e.g. individuals living in rooms facing bright streets and/or with insufficient window treatments to block out light, or individuals with a high amount of nighttime activities outside home)." Such an interpretation, that outdoor light can influence indoor sleeping environments and associated sleep and health outcomes, is consistent with the literature as it currently stands.

N.2.5. Endocrine Cancers (Breast, prostate)

Epidemiological studies are a critical component of the evidence required to assess whether or not light exposure at night (LAN) affects disease risk, including cancer. These studies are necessarily observational and can rarely provide direct causal understanding of the associations observed. Carefully designed and controlled basic laboratory studies in experimental animal models have the potential to provide the empirical support for a causal connection to light exposure at night and biological/health effects and to establish plausible mechanisms. One area of considerable study on the possible effects of nighttime light exposure involves cancer (Stevens et al 2014).

The majority of early studies in experimental models of either spontaneous or chemically-induced mammary carcinogenesis in mice and rats demonstrated an accelerated onset of mammary tumor development accompanied by increased tumor incidence in animals exposed to constant bright light during the night as compared with control animals maintained on a strict 12 hours light/12 hours dark cycle (Blask 1999 & 2003 & 2005,Beniashvili 2001 , Travlos 2001, Van den Heiligenberg 1999). Convincing studies have shown the ability of LAN to promote the growth progression and metabolism in human breast cancer xenografts. Nocturnal melatonin suppresses the growth of human breast cancer xenografts; the essential polyunsaturated fatty acid, linoleic acid, is necessary for the growth of such (ER-) tumors, and its metabolism can be used as a biomarker of cellular growth (Anisimov 2004). Exposure of rats with such cancer xenografts to increasing intensities of white light during the 12 hour dark phase of each daily cycle results in a dose-dependent suppression of peak nocturnal serum melatonin levels and a corresponding marked increase in tumor metabolism of linoleic acid and rate of tumor growth. Exposure to even the very dimmest intensity of light during the night (0.2 lx) suppressed the nocturnal peak of circulating melatonin by 65% and was associated with marked stimulation in the rates of tumor growth and linoleic acid metabolic activity (Blask 2003 &2005, Wu 2011).

The ability of light exposure at night to stimulate tumor growth (including dim exposures) has been replicated in rat hepatoma models as well (Dauchy 1997 & 1999, Van den Heiligenberg 1999). The reverse also is true; gradually restoring circulating melatonin by reducing initial exposure to light at night (24.5 lx) is accompanied by a marked reduction in tumor growth and linoleic acid metabolic activity to baseline rates in the breast cancer and hepatoma models (Dauchy 2011). The important role of melatonin as a nocturnal anticancer signal is further supported by the growth responses of human breast cancer xenografts perfused with human whole blood collected from young, healthy premenopausal female subjects exposed to complete darkness at night (e.g., high melatonin), compared with xenografts that were perfused with blood collected from the same subjects during the daytime (e.g., low melatonin; Blask 2005). The growth of xenografts perfused with blood collected during the dark was markedly reduced. Addition of a physiological nocturnal concentration of melatonin to blood collected from light-treated subjects restored the tumor inhibitory activity to a level comparable to that observed in the melatonin-rich blood collected at night during total darkness. Moreover, the addition of a melatonin receptor antagonist to the blood collected during darkness (i.e., high melatonin) eliminated the ability of the blood to inhibit the growth and metabolic activity of perfused tumors. Circadian disruption by chronic phase advancement (e.g., simulating jet lag) also increases cancer growth in laboratory animals (Filipski 2004 & 2005).

The preponderance of experimental evidence supports the hypothesis that high circulating levels of melatonin during the night not only provide a potent circadian anticancer signal to established cancer cells but help protect normal cells from the initiation of the carcinogenic process in the first place (Blask 2009 & 2011).

Melatonin exhibits antiproliferative and antioxidant properties, modulates both cellular and humoral responses, and regulates epigenetic responses (Brzezinski 1997, Korkmaz 2009, Reiter 2010). Melatonin also may play a role in cancer cell apoptosis and in inhibiting tumor angiogenesis (Sainz 2003, Lissoni 2001). While the experimental evidence from rodent cancer models links disruption of circadian rhythms and circulating melatonin concentrations (inversely) with progression of disease, the human evidence is indirect and based on epidemiological studies. Breast cancer has received the most study. The hypothesis that the increasing use of electricity to light the night might be related to the high and increasing breast cancer risk in the industrialized world and to mortality rates in the developing world was first articulated in 1987, and summarized by a comprehensive review by the American Medical Association (Stevens 1987; Stevens 2012; Stevens 2016). Potential pathways include suppression of the normal nocturnal rise in circulating melatonin and circadian gene function. (Hoffman 2010, Stevens 2009). Conceptually, this theory would predict that non-day shift work would raise risk, blind women would be at lower risk, reported sleep duration (as a surrogate for hours of dark) would be inversely associated with risk, and population nighttime light level would co-distribute with breast cancer incidence worldwide. All these effects have been seen and reported (Kloog & Stevens 2010). Based on studies of non-day shift occupation and cancer (mostly breast cancer), the International Agency for Research on Cancer (IARC) concluded that "shift-work that involves circadian disruption is probably carcinogenic to humans" (Recommendation Level 2A; IARC 2010). A detailed review of the individual studies supporting this conclusion is available (Straif 2007). A large case-control study of nurses in Norway found a significantly elevated risk in subjects with a history of regularly working five or more consecutive nights between days off, and another found that as the type of shift (e.g., evening, night, rotating) became more disruptive, the risk increased (Lie 2011, Stevens 2011, Hansen

2011). In the Nurses Health Study cohort, increased urinary excretion of melatonin metabolites also was associated with a lower risk of breast cancer (Schernhammer 2009).

Although shiftwork represents the most extreme example of exposure to light at night and circadian disruption, perturbation of circadian rhythms and the melatonin signal is also experienced by non shift workers with a normal sleep/wake-cycle. Anyone exposing themselves to light after dusk or before dawn is overriding the natural light-dark exposure pattern. After lights are out for bedtime, there is evidence that ambient background light from weak sources in the bedroom or outside light coming through the window could influence the circadian system. In the large and comprehensive study from the Harvard department of population medicine, the Nurses Health study II, which involved 110,000 women followed from 1989-2013, outdoor LAN was directly correlated with higher breast cancer levels in (James 2017). The researchers linked data from satellite images of Earth taken at nighttime to residential addresses for each study participant. The study also factored in detailed information on a variety of health and socioeconomic factors among participants. Women exposed to the highest levels of outdoor light at night—those in the top fifth—had an estimated 14% increased risk of breast cancer during the study period, as compared with women in the bottom fifth of exposure. As levels of outdoor light at night increased, so did breast cancer rates. There are now a number of studies that have shown such a link between cancer rates and outdoor lighting levels, including studies from Haim, Kloog, Portnov, and colleagues, who provided correlational data connecting satellite-measured light at night from the DMSP OLS system to breast and prostate cancer, indicating a connection between outdoor lighting levels and rates of these cancers (Li 2010,Rybnikova 2015, Kloog 2008-2011). Similar studies have reinforced these findings in different populations around the world (Bauer2013, Hurley 2014, Garcia-Saenz 2018). In addition, evidence also suggests that once breast cancer occurs, exposure to even dim LAN can accelerate the spread of the cancer (Anbalagan 2019), whereas melatonin has been shown to suppress breast cancer spread by blocking certain gene expression (Lopes 2016, Mao 2016). One negative study from Canada has been published (Ritonja, 2020), possibly explained by higher use of blackout shades for northern summer sleeping.

A number of other case-control studies have now reported an association of outdoor nighttime light level in the bedroom with breast cancer risk (Rybnikova 2015). Despite the difficulty of gathering reliable information on bedroom light level at night, the possibility that even a very low luminance over a long period of time might have an impact is important (Stothard 2017). The lowest level of light intensity that could, over a long time period, affect the circadian system has not been established. In the modern world, though, few people sleep in total darkness, so the potential risks may affect large percentages of the global population.

Light-at-night and circadian disruptions have been suggested to play a role in other cancers. Men who reported the highest level of exposure to indoor LAN were at greater risk of prostate cancer than men who reported no indoor illumination at night. Outdoor LAN in the blue-light spectrum, which is believed to be the most biologically relevant exposure, was also positively associated with prostate cancer (Garcia-Saenz 2018). Other possible associations include ovarian, colorectal, and non-Hodgkins lymphoma, but evidence comparable to that obtained for breast cancer has not yet been developed.

N.2.6. Other Health effects

The modern world is experiencing an epidemic of obesity and diabetes that may be influenced by lack of sleep, lack of dark, and/or circadian disruption, with strong evidence that chronic exposure to light at night increases risk of cancer, diabetes, obesity, and heart disease (Cappuccio 2010, Lunn 2017). Shift workers have a higher incidence of diabetes and obesity (Pietroiust 2010). Epidemiological studies also show associations of reported sleep duration and risk of obesity and diabetes (Gangwisch 2009). Circadian disruption may be a common mechanism for these outcomes and potential links between the circadian rhythm and metabolism (Pietroiusti 2010). In addition, incidence of cardiovascular disease and obesity increases from chronic sleep disruption or shiftwork and is associated with exposure to brighter light sources in the evening or night (Smolensky 2015).

Emerging evidence suggests that other chronic conditions also may be exacerbated by light at night exposure and ongoing disruption of circadian rhythms, including depression and mood disorders, gastrointestinal and digestive problems, cardiovascular effects, and reproductive functions (Obayashi 2018, Koo 2016, Motta 2012). Circadian rhythm and sleep are intimately related but are separate phenomena. Adequate daily sleep is required for maintenance of cognitive function and for a vast array of other capabilities that are only partially understood. Sleep is not required to synchronize the endogenous circadian rhythm, whereas a stable 24-hour light-dark cycle is required, and is adversely affected by outdoor LAN (Patel 2019, Xiao 2010, Ohayon 2016) and low daytime light exposures (Wright 2013).

A Stanford study of 15,863 people used the Defense Meteorological Satellite Program (DMSP) to measure how much outdoor light those people were exposed to at night. People living in urban areas of 500,000 people or more were exposed to nighttime lights that were three to six times more intense than people living in small towns and rural areas. The study showed that outdoor nighttime light affects sleep duration and was significantly associated with sleep disturbances. People living in more intense light areas were more likely to sleep less than six hours per night than people in less intense light areas, and have higher rates of depression (Keigo 2018). People living in more intense light areas were more likely to be dissatisfied with their sleep quantity or quality than people in less intense light areas, with 29 percent dissatisfied compared to 16 percent. It was recommended that people may want to consider room darkening shades, sleep masks or other options to reduce their exposure, though a better solution would be better engineered lighting taking human physiologic effects into consideration (Am. Academy Neuro, 2016). A large study involving 10,123 adolescents has shown sleep disturbance in highly lit urban areas compared to rural areas, leading to a marked increase in mood and anxiety disorders (JAMA 2020), and low level LAN had adverse effects persisted later as adolescents (Borniger 2014).

The epidemiological and laboratory research on sleep and health cannot entirely separate effects of sleep duration from duration of exposure to dark, because the sleep-wake cycle partitions light-dark exposure to the suprachiasmatic nucleus (SCN) and pineal gland (Djjk 2004). The distinction is important because a requirement for a daily and lengthy period of dark to maintain optimal circadian health has different implications than a requirement that one must be asleep during this entire period of dark; many individuals normally experience a wakeful episode in the middle of a dark night. Light during the night will disrupt circadian function as well as sleep, and the health consequences of short sleep and of chronic circadian disruption are being intensively investigated (Van Cauter 2008). Media use at night (i.e., televisions, computer monitors, cell phone screens) negatively affects the sleep patterns of children and adolescents and can suppress melatonin concentrations. The American Academy of Pediatrics recommends removing televisions and computers from bedrooms to assist in limiting total “screen time” on a daily basis (Garrison 2011). This action also may help in improving sleep patterns.

Understanding the neuroscience of circadian light perception can help optimize the design of electric lighting to minimize circadian disruption and improve visual effectiveness. White LED streetlights are currently being marketed worldwide in the name of energy efficiency and long-term cost savings, but such lights have a spectrum containing a strong spike at the wavelength that most effectively suppresses melatonin during the night. It is estimated that a blue rich LED lamp can be 5 times more powerful in influencing circadian physiology than a warmer lamp based on melatonin suppression not seen with dimmer, longer wavelength light (Koo 2016, Falchi 2011, Lucas 2014). Thus, white LED street lighting patterns could contribute to the risk of chronic disease in the populations of cities in which they have been installed.

N.3. Effects of Artificial Light at Night on Flora and Fauna

Approximately 30% of all vertebrates and over 60% of all invertebrates known today are nocturnal (Hölker et al. 2010b). Specifically, more than 60% of all known mammals are adjusted to the ecological niche of the night. Nocturnal animals adapted their behavior and sensory systems to the nocturnal low-light conditions and can be directly affected if these conditions are altered by ALAN. However, ALAN can also affect diurnal animals directly or indirectly (Knop et al. 2017, Kurvers et al. 2018). The duration and intensity of perceived daylight, the course of twilight, and the natural light during night, in particular moonlight provide signals for orientation and rhythms and thus represent important information for most organisms.

ALAN can have a range of lethal and sub-lethal effects on wildlife (Longcore & Rich 2004, Rich & Longcore 2006, Gaston et al. 2012, Gaston et al. 2013, Meyer & Sullivan 2013). Some wildlife species will avoid areas with additional lighting (Beier 1995, 2006, Stone et al. 2009, Stone et al. 2012), while some benefit from the presence of additional ALAN, which has consequences on food-webs and habitat use (Manfrin et al. 2018). The impact of ALAN on nocturnal organism level cascades into ecosystems and also affects day-active organisms and their ecological functions (Hölker et al. 2010a, Hölker et al. 2010b, Longcore 2010, Gaston et al. 2013; Bennie et al 2015).

Here we present the impact of ALAN on migration and habitat use, ecological functions, the timing and quantity of reproduction, and the immune system in various taxa. The impact of ALAN is a major risk factor for biodiversity and consequently global food supply. The impact threatens many endangered nocturnal taxon groups such as bats and amphibia (Hölker et al. 2010b), but it also threatens the habitat and ecological functions for non-endangered organisms including many insect species, wildflowers, small mammals, and birds. With noteworthy exceptions, environmental protection regulations in most nations hardly if at all consider ALAN as a detrimental ecological factor and thus mitigation is not widespread, notwithstanding guidance that is available to minimize those impacts.

N.3.1. Impacts on migration and habitat use

Nocturnal animals have evolved under dark natural night skies and some even navigate and migrate using the stars at night (Foster et al. 2018). Attraction, repulsion and disorientation are possible outcomes of encounters between wildlife and ALAN (Longcore & Rich 2004). The migratory movement of wild animals can be impaired by ALAN in both the horizontal and the vertical. Many migrating species are attracted to light and are held up on their migration routes by ALAN. Other species, however, avoid ALAN and are restricted to non-illuminated areas on their migration routes. The most well-known situation is the attraction and disorientation of sea turtle hatchlings on ocean beaches, which results in the death of the juvenile turtles that do not reach the ocean (McFarlane 1963). Research conclusively shows that ALAN can have an adverse impact on the foraging behavior of bat species, and exclude certain species from foraging routes or areas (Stone et al. 2009, Polak et al. 2011). Cabrera-Cruz et al. (2019) found that the difference in flight altitudes of nocturnally migrating birds between urban and non-urban areas was consistently higher over urban areas, suggesting that the effects of urbanization on wildlife extend into the aerosphere and are complex, stressing the need of understanding the influence of anthropogenic factors on various habitats in air and water not only on land.

Aquatic Organisms. The drift of aquatic insect larvae can be impaired in illuminated flowing waters (Henn et al. 2014; Perkin et al. 2014). Zooplankton and smaller fish use the protection of darkness to drift into higher layers of the water column at night time and descend during daylight hours. Direct ALAN or skyglow can suppress this diel vertical migration of zooplankton in urban lakes (Moore et al. 2000). Zooplankton in Arctic waters showed reaction to ALAN down to depths of 200 m (Berge et al. 2020) and was even disturbed by ship lights (Ludvigsen et al. 2018). Fish predation behavior and the occurrence of small and medium size fish species changed dramatically in coastal waters (Bolton et al. 2017) as well as daytime behavior of fish regarding habitat use in freshwater systems when exposed to ALAN (Kurvers et al. 2018). Illuminated overpass and crossing structures such as bridges and weirs impose barriers for migratory fish, as demonstrated for salmonid fish and eels that occasionally interrupt their migration at such structures (Cullen & McCarthy 2000; Lowe 1952; Nightingale et al. 2006). Even ALAN on the order of artificial skyglow can disrupt the nightly migrations undertaken by the crustacean amphipod *Talitrus saltator*, which is normally guided by the sky position of the moon (Torres et al. 2020).

Aquatic predator-prey relationships can also be influenced by ALAN as shown for pacific salmon (Mazur & Beauchamp, 2006), bullheads, juvenile red salmon (Tabor et al., 2004), yellowfin bream, leatherjackets (Bolton et al., 2017) as well as for seals (*Phoca vitulina*) (Yurk & Trites, 2000). The spawning of salmon larvae was observed to be delayed (Riley et al. 2016), resulting in fishes migrating in smaller groups and thus under higher predation risk.

Birds. Disruption of bird migration and fatalities were already reported more than 100 years ago at lighthouses (Squires and Hanson 1918) and later for floodlights of airport ceilometers (Howell et al. 1958). A study of the *Tribute in Light* installation in New York documented an increase from 500 birds within 0.5 km of the vertical light beams before they were turned on to 15,700 birds within 0.5 km 15 minutes after illumination (Van Doren et al. 2017). Upwards directed ALAN, measured by satellite, is associated with greater numbers of birds present during the day, especially in the fall when juveniles are migrating south (La Sorte et al. 2017). Birds can be attracted by urban ALAN and then end up disproportionately using urban habitats as compared to rural habitats with higher food availability (McLaren et al. 2018). The major bird migration routes cross highly light polluted areas. Many migrating birds traverse large expanses of land twice every year at night when ALAN illuminates the sky (Cabrera-Cruz et al. 2018). A helpful tool for future but also past research on nocturnal bird migration is weather radar, which can detect migrating songbird species.

Attraction at night is only the first hazard. Urban habitats and especially business districts are dangerous landing grounds, because they are susceptible to collisions with glass, which they do not perceive as a barrier (Klem 1990, Sheppard & Phillips 2015). The combination of ALAN followed by daytime glass exposure is a significant threat to songbirds during the already strenuous migratory period (Cabrera-Cruz et al. 2018). Numerous studies present the risk of coastal birds colliding with natural structures or buildings due to ALAN (Telfer et al. 1987; Rodriguez & Rodriguez 2009; Miles et al. 2010; Rodriguez et al. 2014, 2015) and how warm light spectra and regulated light intensities can reduce the fatal collisions (Rodriguez et al. 2017; Rebke et al. 2019). Lighting on communication towers is associated with significant annual bird fatalities correlated with lighting (Longcore et al. 2012, 2013, Gehring et al. 2009)

ALAN also affects habitat use and predator prey-relations in birds. Partridge are documented to roost closer to each other on darker nights and can see predators farther away on lighter nights (Tillmann 2009). An experimental study of the effect of streetlights (20 lx) on breeding bird density shows a negative impact (De Molenaar et al. 2006). The adverse effects of these lights (decreased density of Black-tailed Godwit nests) were experienced up to 300 m (984 ft) from these lights, extending into areas with negligible increased illumination, which means that the adverse impact results from the light being visible, rather than the amount of light incident on the sensitive receptor.

Insects. Many families of insects are attracted to lights, including moths, lacewings, beetles, bugs, caddisflies, crane flies, midges, hoverflies, wasps, and bush crickets (Sustek 1999, Kolligs 2000, Eisenbeis 2006, Frank 2006, Longcore et al. 2015). Female mayflies, performing their upstream compensatory flight, are attracted upward toward bridge lamplight and to concrete surfaces that appear as water surfaces due to light polarization (Szaz et al. 2015).

Any lamp with significant emissions at ultraviolet or blue wavelengths is highly attractive to insects (Eisenbeis 2006, Frank 2006, van Langevelde et al. 2011, Barghini and de Medeiros 2012) and insects attracted to lights are subject to increased predation from a variety of predators, including bats, birds, skunks, toads, and spiders (Blake et al. 1994, Frank 2006). Moths, having a key role in the ecosystem as pollinators, are particularly attracted to lights (Macgregor et al. 2015, Macgregor et al. 2017, Knop et al 2017) and are often killed in collisions with lights or by becoming trapped in housings (Frank 1988, 2006). Short of death, this attraction removes native insects from their natural environments (Meyer and Sullivan 2013) in what Eisenbeis (2006) calls the “vacuum cleaner effect”.

Bats. The responses of different bat species to lighting are complex (Rydell 2006, Voigt et al. 2018). Some faster-flying and more maneuverable species can be attracted towards ALAN sources in exploiting the high prey abundance. Slower and less maneuverable species will avoid lights, essentially being repulsed by their presence (Stone et al. 2009, Stone et al. 2012, Stone et al. 2015). Light at the entrance of a roost can keep bat species in general from emerging for their nightly foraging (Boldogh et al. 2007). The attraction and avoidance of ALAN is species dependent and associated with their seasonal and daily behaviour such as root emergence, drinking and foraging or resting. For most ecological needs in almost all bat species ALAN is a disturbing factor (Voigt et al. 2018).

ALAN that spills on commuting routes or flyways can significantly reduce the habitat use for many bat species. The behavior of light-sensitive bats can be impaired within the radius of up to 50 m distance to the light source, even if the illuminance level is as low as 1 lx (Azam et al. 2018, Pauwels et al. 2019). Some species of bats avoid artificial lights to reduce predation risk (Stone et al. 2009, Polak et al. 2011). Hale et al. (2015) observed that the success to cross depends on light intensity and width of the non-illuminated gap. The study presents a common urban bat (*Pipistrellus pipistrellus*) selecting dark crossing roots at gaps, e.g. at trees. The avoidance of lit passages can lead especially to disturbed drinking behavior for many bat species (Russo et al. 2017, Voigt et al. 2018). The illumination of roosts or the entrance to it can cause the bats to abandon roosts in the worst case (Stone et al. 2015b). When migrating, some species, e.g., *Pipistrellus* spp. can be attracted especially to white and green lights (Spoelstra et al. 2017) and become distracted by phototaxis from their migration routes (Voigt et al. 2017). Azam et al. (2016) judge the effects of ALAN on bat populations as being more impacting on the occurrence and the activity of bats than increasing imperviousness of the land through development. In Sweden, bat occurrence was observed at illuminated and non-illuminated churches. Bat colonies had decreased significantly in frequency from 61% in 1980s to 38% by 2016, especially at sites where churches were lit from all directions, leaving no dark corridor for the bats to leave and return to the roost. In contrast, in churches that were not lit, no colony decrease was observed after 25+ years (Rydell et al. 2017).

Non-flying mammals. The presence of permanent outdoor lighting can erode landscape connectivity for wildlife species (Stone et al. 2009). The existence of the lights themselves, shielded or not, is sufficient to influence wildlife movement (Beier 1995, 2006). This phenomenon was illustrated by a radio telemetry study of young mountain lions in Orange County, California (Beier 1995):

> "Overnight monitoring showed that dispersers especially avoided night-lights in conjunction with open terrain. On M12's initial encounter with a well-lit sand factory and adjacent sand pits, he took 2 hours and 4 attempts to select a route that skirted the facility, after which he rested on a ridgetop for 2 hours. During 2 nights in the Arroyo Trabuco, M8 explored several small side canyons lacking woody vegetation. He followed each canyon to the ridgetop, where city lights were visible 300–800 m west. He stopped at each canyon ridgetop for 15–60 minutes before returning to the arroyo, without moving >100 m into the grasslands west of the ridgeline in view of the city lights."

Further data on the use of underpasses and the influence of lighting on landscape connectivity have been reported. An experimental evaluation of underpass use by wildlife found that for mule deer, even nearby lights affected movement compared with a reference period (Bliss-Ketchum et al. 2016). Small mammals respond to illumination in their foraging activities. For example, artificial light of about 0.1 lx reduced the activity, movement, or food consumption of a cross-section of rodent species (Clarke 1983, Brillhart and Kaufman 1991, Vasquez 1994, Falkenberg and Clarke 1998, Kramer and Birney 2001). This phenomenon has been shown in natural (in addition to laboratory) conditions (Kotler 1984, Bliss-Ketchum et al. 2016, Wang and Shier 2017, Wang and Shier 2018, Hoffmann et al. 2019).

The driving force behind patterns of activity and foraging by animals influenced by ALAN is presumably predation. Additional ALAN might increase success of visually foraging predators, thereby increasing risk to their prey, with one critical exception: prey species with a communal predator defence, such as schooling or flocking, have decreased risk of predation with additional light. Evidence for this general pattern continues to accrue. A general review of nocturnal foraging suggests that night is a refuge with decreased overall predation on birds and mammals, and that foraging groups are larger at night, especially for clades that are not strictly nocturnal (Beauchamp 2007). Songbirds that were experimentally relocated moved back to their home ranges at night, a result that is most consistent with predator avoidance (Mukhin et al. 2009). Predator-prey systems are tightly tied into lunar cycles, with many relationships affected by lunar phase (Williams 1936, Sutherland & Predavec 1999, Topping et al. 1999, Riou and Hamer 2008, Upham and Hafner 2013). Even within species, variation in color interacts with the lunar cycle to affect foraging success. White-morph Barn Owls have an advantage foraging during the full moon because the light reflecting off their white feathers triggers their rodent prey to freeze in place, while Barn Owls with darker colored feathers do not have this advantage (San-Jose et al. 2019).

Lit habitats often get lost for the use by nocturnal wildlife and often these areas also are not populated with day-active organisms (Longland 1994; Rotics et al. 2011; LeTallec et al. 2013; Ciach et al. 2019). Illuminated areas thus can become “blind ecological spots”, which can become vulnerable to invasive species, better adapted to anthropogenic disturbances. This also includes vegetation, because the avoidance of habitat by frugivores (i.e. frugivore bats) results also in a reduction of seed dispersal into illuminated habitat (Lewanzik and Voigt 2014).

N.3.2 Impacts on ecological functions

Habitat which is not used by wildlife may lack important ecological functions. For example, when illuminating areas in the Alps, the nocturnal pollination of a thistle species was disturbed (Knop et al. 2017). The reduced pollination led to reduced numbers of day-active pollinators as with the thistle an important food source was declined. Thus ALAN has an impact on both pollination and the availability of food.

Pollination. As described earlier, the high attraction of ALAN on moths has a rather high impact on the nocturnal pollination activity. Affected are mainly wildflowers. Furthermore, nocturnal pollinators were observed to carry pollen from a reduced number of plants when exposed to streetlight, indicating less pollination activity on wildflowers (Macgregor et al. 2017). Their ecological necessity is today not yet fully understood, but studies like for example Knop et al. (2017) present a rather high significance function on the stability of biodiversity and functioning of ecosystem networks (Fontaine et al. 2005).

Water quality. The lack of migration in aquatic zooplankton (Moore et al. 2000) paired with the observation of altered periphyton growth and changed phytoplankton community structures in freshwater bodies (Grubisic et al. 2017, 2018; Poulin et al. 2014) could potentially trigger algae blooms and significantly decrease the water quality in freshwater systems.

Consumption of carcasses. ALAN can significantly impact the food-webs in disrupting predator-prey relations. The oversaturation of insect prey at ALAN sources and beneath can increase the number of scavengers such as spiders, Harvestmen and snails (Davies et al. 2012; Manfrin et al.2018; van Grunsven et al. 2018). The scavengers can even get picky as for example spiders were observed to rather consume terrestrial food sources although more aquatic species are attracted to lights at riparian areas (Manfrin et al. 2018).

Food sources and predator prey relations. The massive attraction of insects to ALAN sources leads to declined food sources for many organisms, an effect which can cascade into higher levels of the food-web. Bats, which in natural conditions rather catch beetles, will consume more moths (Cravens et al. 2017), which in turn leads to decreased nocturnal pollination.

N.3.3. Impacts on reproduction

The rhythm of light and dark is an important Zeitgeber. The timing for pairing and reproduction relies on the circadian, lunar and seasonal rhythms of light. Hormone metabolism is triggered by the signal of light. ALAN can suppress the metabolism of melatonin, which is important for the circadian metabolism and hormones which trigger the circadian and seasonal timing including the signal for reproduction (Grubisic et al. 2019). The lack of the natural light signal can expand the timing of birth in mammals (Le Tallec et al. 2013; Robert et al. 2015) in birds (de Young et al; 2016, Dominoni et al. 2013; Ouyang et al. 2017), amphibians (Baker & Richardson 2006) and fishes (Brüning et al. 2016a, b).

Mammals. The reproductive state is determined by the trend of the day length and not its absolute length (Gerlach & Aurich 2000). When natural light conditions are polluted by ALAN this signal can become blurred, and thus the seasonal changes (LeTallec et al. 2013).

Birds. ALAN affects diurnal species substantially as well. It affects the timing of dawn and dusk song, seasonality of reproduction, mate choices, and can extend activities of diurnal species into the night (Stracey et al. 2014). Birds that sing earliest are responding to increases in illumination so faint that they are undetectable by humans (Thomas et al. 2002). This is true for impacts across species, where diurnal species are affected in numerous ways by an altered nighttime environment (Miller 2006, Kempenaers et al. 2010, Titulaer et al. 2012, Dominoni et al. 2013a, Dominoni et al. 2013b, Da Silva et al. 2014, Dominoni et al. 2014, Zhang et al. 2014, Da Silva et al. 2015).

The research on the effects of ambient and artificial lighting on bird reproduction goes back to the 1920s (Rawson 1923, Rowan 1938). Research shows an earlier start to seasonal breeding of birds in urban (lit) environments than rural (dark) environments (Havlin 1964, Lack 1965). Light of 0.3 lx can move reproductive seasonality of songbirds by a month and cause irregular molt progression (Dominoni et al. 2013a, Dominoni et al. 2013b). Timing of the dawn song and lay date in a songbird have been shown to be associated with proximity to streetlights. Further affecting mate choice, which has implications for fitness (Kempenaers et al. 2010). A songbird (Tree Sparrow *Passer montanus*) exposed at night time to 6 lx in the laboratory secreted luteinizing hormones earlier than controls. This effect was observed also with urban birds exposed to 3–5 lx night lighting (Zhang et al. 2014).

Plants. ALAN affects the perception of seasonal change by plants and their associated physiological responses. Exposure to ALAN is associated with earlier budburst in plants, in a pattern that cannot be explained by the greater temperatures in cities (ffrench-Constant et al. 2016). Trees exposed to nearby lights have long been observed to hold on to their leaves later in the fall (Briggs 2006, Škvareninová et al. 2017, Massetti 2018) and prevent seed set in plants cued to shorter daylengths (Palmer et al. 2017). In wildflowers a decline in the quality of pollination was measured (Knop et al. 2017; Macgregor et al. 2017) as well as a negative impact especially of blue-rich white LED streetlights on seed production of wild flowers (Macgregor et al. 2019).

Insects. With an estimated 6-10 million species, insects represent more than half and potentially 90% of known living organisms (Novotny et al 2002; Chapman 2006). These include the order Lepidoptera, the great majority of which are nocturnal moths, as well as 23 other orders. Population trends in insects have been observed to decline under long time exposure to ALAN (van Grunsven et al. 2019), and some researchers point to ALAN as a significant driver of the observed overall precipitous population of insects worldwide (Owens 2020). The pheromone production of single female moths exposed to streetlights was observed to be reduced in quality and quantity (van Geffen et al. 2014). The number of visits to flowers by pollinating insects at night was observed in a Swiss study to decline by 62% in the presence of ALAN (Knop et al 2017). Artificial light at night also affects the visual communication required for reproduction of species such as the bioluminescence in fireflies, contributing to the decline of fireflies and other organisms that rely on bioluminescent communication (Lloyd 2006, Hagen and Viviani 2009, Viviani et al. 2010, Bird and Parker 2014, Owens 2018). A Brazilian study documented lower species richness of fireflies in areas of 0.2 lx and greater (even from sodium vapour lamps, which are otherwise considered to be more wildlife friendly), except for those few species that naturally fly at greater illumination (Hagen and Viviani 2009).

N.3.4. Immune responses

Studies on the physiological effects of ALAN on mammals are numerous, partly because of the implications for understanding human health (e.g., Zubidat et al. 2007, Zubidat et al. 2010). As a whole, they show that artificial light at levels far less intense than previously assumed are able to entrain circadian rhythms and influence physiological functions such as immune response (Bedrosian et al. 2011). For example, extremely dim light is sufficient to entrain rhythms in mice, and can be done without phase shifting or reducing production of melatonin (other physiological indicators of light influence) (Butler and Silver 2011). For shorter wavelengths (blue and green) entrainment takes place at 10^{-3} lx. Much greater intensity, 0.4 lx, is needed for red light to entrain rhythms (Butler and Silver 2011). This research is consistent with recently documented differences in mice behaviour for exposure to 20 lx vs. 1 lx at night (Shuboni and Yan 2010). Mice that were exposed to dim (5 lx) light at night consumed the same amount of food as those under dark controls, but gained weight as a result of the shift in time of consumption (Fonken et al. 2010).

Birds (*Parus major*) roosting in the white light were much more active at night and present a higher probability of malaria infection (Quyang et al. 2017). Saini et al. (2019) found that chronic ALAN exposure significantly increased bactericidal activity and that this elevation in immune performance manifested at different developmental time points in male and female quails. ALAN intensities of 0.5 to 5 lx, significantly increased cell proliferation in the ventricular brain zone and decreased the neuronal densities in two brain regions suggesting neuronal death (Moaraf et al. 2020).

Plants “anticipate” the dawn with a synchronized circadian clock and increase immune defence at the time of day when infection is most likely (Wang et al. 2011). The timing of resistance (R)-gene mediated defences in *Arabidopsis* to downy mildew is tied to the circadian system such that defences are greatest before dawn, when the mildew normally disperses its spores (Wang et al. 2011). Preliminary experiments show that carbon assimilation is lower in trees exposed to continuous night lighting, compared with controls in a “stereotypical urban setting” (Skaf et al. 2010). Some plants might use light-triggered circadian rhythms to synchronize expression of anti-herbivory compounds with periods of peak herbivory, leading to increased loss from herbivory in out-of-phase plants (Goodspeed et al. 2012). The importance of circadian rhythms in plants, for all functions from disease response and flowering time to seed germination, and the potential for disruption by night lighting, has not been explored widely (Resco et al. 2009, Bennie et al. 2016). Adverse effects on ornamental plants and agricultural plant production have been observed in forms of decreased stomatal movements (Kwak et al. 2018), shifted community compositions (Bennie et al. 2016), accumulation of superoxide radicals (Kwak et al. 2017), triggered stress responses (Nitschke et al. 2016; Meravi et al. 2020), soybean maturation delay (Palmer et al. 2017) and changed photo-physiology (Kwak et al. 2018; Meravi et al. 2020).

N.3.5. Impacts on biodiversity and food supply

Summing up, the impact of direct ALAN and skyglow is a major factor for the decline of habitat for nocturnal wildlife, declining ecological functions and reproduction, consequently leading to loss of biodiversity as sensitive organisms can lack food sources and habitat. The impact on the hormone systems of many organisms makes the ecosystem vulnerable because many individuals lack sufficient immune response against stress factors such as anthropogenic pollutants and disturbances.

The stress response of trees implies that trees can be weakened by ALAN, which might be critical as trees are an important factor in balancing CO_2-emissions. The direct impact of ALAN on crops indicates that ALAN has direct impacts on food production. Especially the impact of ALAN on primal states of the food webs, as described earlier, like changes in periphyton communities and insects are important to be studied in more detail, as the effects will cascade into higher levels of food webs. Paired with weakened organisms and ecological function, we face unpredictable changes in ecosystems. Unlike to temperature, which has changed dramatically in history of earth, are the alterations of the brightness of the nightscapes a new physical experience on which we lack knowledge about responses and adaptation of organisms. Considering the growing stress factors like increasing temperature, changing climate, pollutants such as plastics and heavy metals and overpopulation we might want to decrease anthropogenic stressors where possible and light pollution is one anthropogenic factor that could be regulated and reduced easily.

N.3.6. Biodiversity strategy and gaps in protection against adverse effects of ALAN

The global biodiversity strategy and regulations for the protection of nature are important regulating decision makers and other stakeholders. For example the EU biodiversity strategy claims[10]: "Biodiversity is essential for life. Nature provides us with food, health and medicines, materials, recreation, and wellbeing. A healthy ecosystem filters our air and water, helps keep the climate in balance, converts waste back into resources, pollinates and fertilises crops and much more. Nature also provides for businesses: half of the world's Gross Domestic Product (GDP), €40 trillion, depends on nature. We are losing nature like never before because of unsustainable human activities. The global population of wild species has fallen by 60% over the last 40 years. 1 million species are at risk of extinction." However, the strategy hardly considers the effects of ALAN on biodiversity and ecosystem services.

Neither ALAN nor light pollution is considered in the Global Assessment Report on Biodiversity and Ecosystem Services by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IBPES) and the summary for policymakers.

Schroer et al. (2019) discuss protection gaps for adverse effects of ALAN in European environmental protection regulations. While protection is predominantly provided for species with special protection status that reveal avoidance behaviour of artificially lit landscapes and associated habitat loss, adverse effects on species and landscapes without special protection status are often unaddressed by existing regulations. Legislative shortcomings are caused by difficulties in proving adverse effects on the population level, detecting lighting malpractice, and applying the law to ALAN-related situations. To protect flora and fauna from impairments nature conservation law and immission control law provisions apply, although substantial shortcomings remain.

a. The protection of habitats is spatially limited and even within its application it requires an individual impact assessment. However, assessments for lighting systems are so far not subject to approval procedures.

b. The protection of specially protected species requires an adverse effect such as the injury, death, or avoidance behavior of a specimen, excluding most of the adverse effects of ALAN.

c. Most provisions require either a significant increase in killing risks or a significant decline of a local population. Both criteria are in ALAN-related situations difficult to assess.

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[10] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/actions-being-taken-eu/eu-biodiversity-strategy-2030_en

In the United States, light pollution's impacts on flora and fauna are not well regulated. It is possible that they are considered as an impact in the preparation of assessments under the National Environmental Policy Act, but the professional practice of doing so is underdeveloped, leaving concerns to be raised by the public. Direct impacts of ALAN on organisms can also be regulated under the federal Endangered Species Act. At the state level, some states have laws that require environmental review as well, but they too do not have a well-developed practice of considering the ecological impacts of ALAN. The U.S. National Park Service has published a guidance document on management approaches to minimize ecological effects of ALAN on protected lands (Longcore and Rich 2017). The U.S. Bureau of Land Management is developing a set of best management practices for light pollution that will inform decision-making on its vast holdings.

N.4 Geographical and territorial impacts of light pollution

Light pollution is pollution, and should be treated as such. Artificial light at night introduces into the atmosphere a huge number of particles (photons) that should not be there during nighttime, and that give rise to detrimental consequences either by its own direct effects (e.g. by directly activating key physiological processes or distorting predator-prey relationships) or by reducing the spatial and temporal contrast of the natural night light cycles (e.g., erasing the monthly rhythm of natural illumination associated with the Moon).

Light pollution displays the characteristics of any classical form of pollution. It has, like any other kind of pollution, specific spatial and temporal features. Spatially, light pollution is a form of pollution with an intermediate range of spread. Unlike greenhouse gas emissions, which are incorporated into the global circulation of the planetary atmosphere, or unlike very local episodes of contamination such as heavy metal spills, light pollution sources affect wildlife in an area with a typical size of several hundreds of km around the emission points. Photons know no borders (Bará and Lima, 2018), and political and administrative territorial divisions do not prevent their propagation beyond the particular area from where they were emitted. Artificial light can distort natural wildlife by (i) increasing the levels of local illumination (irradiance on ground, due either to the direct radiance of the sources or to the increased skyglow produced by atmospheric scattering), and (ii) by the direct visibility of the source radiance itself, propagated along the line of sight. The direct radiance from the sources is not reduced by geometrical propagation factors (it does not decrease with the square of distance); it is reduced only by intrinsic attenuation processes (scattering plus absorption in the atmosphere). The high transparency of the terrestrial atmosphere allows the direct radiance to propagate with slight attenuation across long distances (~100 km) and in consequence artificial lights on the horizon can act as an extremely powerful distracting factor for those life forms highly dependent on visual processes – especially migratory birds, since at their altitude of flight a wider area of territory is visible.

Temporally, light pollution emissions present an extremely short characteristic time scale. Once the light emitting sources are switched off, in a fraction of a second all photons have been absorbed or have escaped towards outer space, and the light pollution source becomes inactivated. Importantly, though, the environmental effects produced before the switch-off can last for long periods of time, an issue deserving deeper research.

A key feature is that any linear indicator of the level of deterioration of the natural night (artificial sky brightness, horizontal irradiance in any biologically relevant spectral band, direct radiance from sources in the horizon...) depends linearly on the amount of emissions of the neighboring territories, up to several hundreds of km away. Non-linear indicators (e.g. the maximum brightness of the night sky) depend on the emissions in a non-linear but monotonically increasing way. Thus, in order to keep the deterioration levels below admissible thresholds for critical effects on biodiversity, it is necessary to keep within definite limits the total emissions from the surrounding territory. Each particular location (city district, village, industrial or agricultural installation) contributes to deterioration of the linear indicators proportionally to its absolute emissions. Overall emissions and the deterioration of the nocturnal environment are inextricably linked and no remediation or control of unwanted light pollution effects can be expected if the overall emissions are not kept at bay (Falchi and Bará, 2020).

The impact of city and industrial light domes covers large portions of the surrounding territory. Even when light sources are correctly installed, adjusted, and shielded, the sky receives a part of their direct emission and another contribution from the reflection on the surfaces they light (Narisadam & Schreuder, 2004). The light is scattered in different directions by the atmosphere, creating a diffuse artificial glow (sky glow). Light emissions set in almost vertical directions run a distance approximately equal to the atmospheric thickness (typically considered as 8 km). Therefore, vertical light emissions do not generate a large contribution to sky glow because they do not suffer much atmospheric scattering. Conversely, lighting emissions in almost horizontal elevations contribute significantly to artificial sky glow because these emissions can run large distances (of more than 100km), having a much greater probability of being scattered by the atmosphere (Narisadam & Schreuder, 2004). The dominant scattering process is Rayleigh scattering, which has an inverse dependence to the fourth power of wavelength: this means that 450nm (blue) emissions are scattered in the atmosphere three times more than emissions in 589nm (yellow - amber) and six times more than in 700nm (red). Therefore, blue emissions contribute much more intensely to artificial sky glow (Luginbuhl et al., 2009). Such scattering is responsible for the blue color of the day sky. At night, the scattering of artificial blue light by atmospheric molecules is the major cause of the substantial increase of the glow of the night sky. Only a small amount of blue light is needed to have a noticeable effect in the sky.

As discussed above, melatonin is present in an enormous variety of species, adopting multiple biological functions: antioxidant protection (which started in unicellular organisms), environmental tolerance in fungi and plants, immunomodulation and chemical expression of darkness in vertebrates, regulation of seasonal reproduction photoperiodic mammals (Grubisic et al., 2019). The Melatonin Suppression Index (MSI) shows the potential exposure to different temperature color indices of light. The MSI confirms that the blue part of the spectrum present in LEDs ranging from 2,200K to higher CCT has the potential to produce enormous impacts on the surrounding territory, for both wildlife and humans. Fig. N.2 shows models of MSI under two different assumptions of LED streelighting: PC Amber, with zero blue light content, and CCT 5000K, with 50% blue light content.

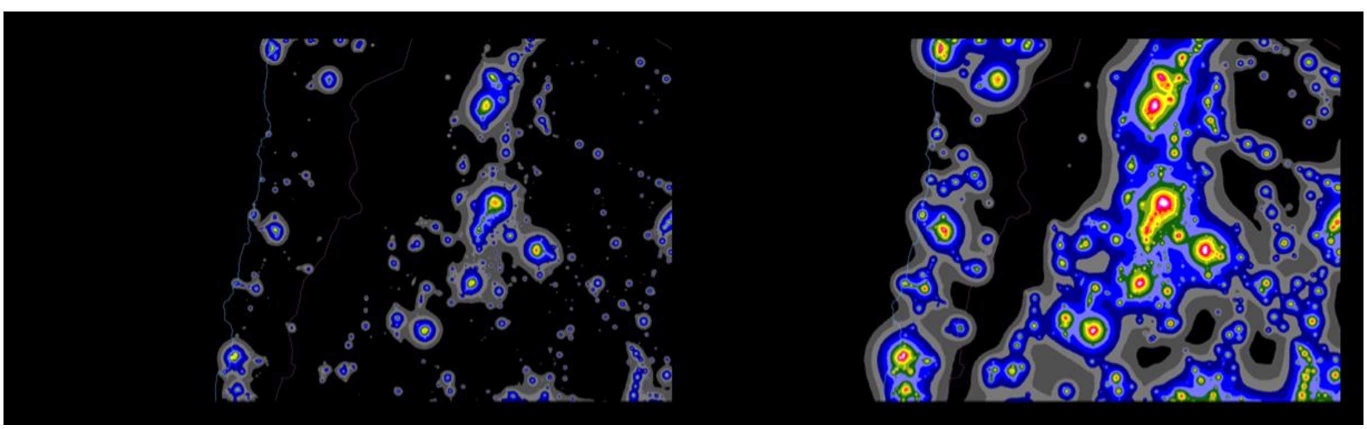

Figure N.2: Melatonin Suppression Index (MSI) model for region of La Serena / Antofagasta, Chile. Left: Assuming PC Amber LEDs (0% blue light content). Right: Assuming 5000K CCT LEDs (50% blue light content).

The polarization of light in the atmosphere is relevant for multiple animals and insects, as it generates a pattern in the sky that allows them to orient and navigate. The light reflected by the Moon is also polarized (Kyba et al., 2011), although its contribution is not well understood (Jones et al., 2013). Despite the fact that the brightness of the Moon is >100,000 times less significant than sunlight, it is indeed used by a great variety of nocturnal species to navigate (Kyba el al., 2011). The zodiacal light also presents polarization (Noll et al., 2012). The polarization of Rayleigh scattering does not affect the integrated scattering of light in the atmosphere (Noll et al., 2012), and anthropogenic light pollution is not polarized, so when added to the natural light, it diminishes the total polarization, affecting the orientation capacities of many nocturnal species over the territory (Kyba et al., 2011).

Linear projects, such as highways, can fragment ecosystems, potentially making them non-viable to many species of fauna by their physical obstacles and risk of being killed by motor vehicles. Similarly, light acts as a physical barrier that can fragment ecosystems, limiting the ability of fauna to move freely for foraging, reproduction, and migration.

N.5. Recommendations

The preceding sections demonstrated that the biological environment can be affected by ALAN in many ways. Since there is a large variety of affected organisms (i.e. humans and many other species), regulatory initiatives should ideally cover all adverse effects in a holistic and sustainable approach. This section summarizes the proposed guidelines for the mitigation of the adverse effects of ALAN on humans and other species.

This general proposal should enable adoption, adaptation and implementation of environmentally friendly lighting for countries, regions, municipalities, and communities. The strategy can be summarized in the four pillars of the efficient lighting scheme: “The right light, at the right place, at the right amount, for the right duration.” The following recommendations aim to cover most of the environmental aspects of obtrusive light. It should be noted that the order of presentation does not reflect the significance of each recommendation.

N5.1. Areas to be illuminated

Governing bodies (e.g. countries, states, counties, etc.) should define the decision criteria whether an area must or is allowed to be illuminated. To minimize environmental impact, unnecessary illumination should be prevented and enforced by a local ordinance, while new outdoor lighting installations should be adequately justified.

Master planning of the outdoor night-time environment should include strategies for maintaining dark areas dark and reducing lighting in currently over-illuminated areas. Planning of the outdoor lighting should prevent, restrict, and counteract damages or inconveniences to human health and the natural environment from artificial lighting at night.

Maximum admissible values of the indicators of deterioration of the nighttime environment (e.g. maximum horizontal irradiance at ground level on sensitive biological bands) must be explicitly specified for each zone of the territory (including urban, suburbs, rural, and wilderness areas).

Zoning must be preferentially defined not in terms of the emissions allowed in each kind of zone (types of lamps, ULOR, etc), but in terms of the maximum allowable values of the deterioration indicators that must be enforced in each zone, independently from where the light sources are located within the zone. The technical characteristics of the sources and the absolute amount of emissions of each patch of the territory must be monitored and kept under control in order to warrant compliance with the environmental indicators of all surrounding and even distant zones, independently of where they are located.

The authorization of new lighting installations must be done (or the reductions thereof must be enforced) in a coordinated way, encompassing all territories that contribute to the deterioration of the nighttime environment of any given place, and not only those located in its immediate vicinity.

Territorial emission quotas should be established that provide some margin for authorizing increases of the light emissions if the indicators of deterioration of the nighttime environment have not surpassed the critical levels, or conversely, if the critical levels have been surpassed, that prohibit further lighting and/or require active remediation from the intervening administrations, either by reducing the absolute emissions or by redistributing them geographically to ensure compliance.

N5.2. Definition of ALAN-free areas and ecosystems

In an extension of the previous recommendation, environmental sensitive areas, wilderness areas, ecosystems and relevant areas can be characterized as ALAN-free zones. The zoning system defined by the CIE (Zones E0 and E1) can be adopted for these areas. Further development of outdoor lighting in such areas should be prohibited or restricted by national legislation.

N5.3. Illumination levels for outdoor areas

For areas that are determined to need outdoor lighting, the appropriate lighting class (minimum and maximum requirements) should be selected according to the relevant document (e.g. CIE 115 for road lighting). If no relevant document applies, lighting should be designed based on functionally based requirement and scientific evidence-based knowledge. Over-illumination should be avoided. The maintained average illumination levels shall not exceed the targeted value.

The goal for any wilderness area should be to return the brightness value of the night sky to a natural dark value of 22 mag/arcsec^2.

N5.4. Lighting control and adaptive lighting

Lighting control should deliver the right amount of light for the right amount of time. All new and renovated outdoor lighting installations should incorporate means of control of luminous flux. Lighting control systems should be added to existing installations when feasible. Lighting installations should be controlled through the hours of darkness using a predefined schedule or, preferable, adaptively using sensors and human intervention techniques. In certain lighting systems, lighting control can also alter the spectral distribution of emitted light during specific periods of time. Lighting levels should be reduced to the absolute minimum level where and when no or few users are present in the relevant area. Dimming or switching outdoor lighting off is recommended mainly for rural areas and certain urban areas (e.g. shopping centres, sport centres, industrial areas not active at night).

N5.5. Light distribution and orientation

Efficient and environmentally conscious lighting design is strongly recommended. Light should be distributed only to the area targeted for illumination. Spill light and in general waste of luminous flux delivered to the surroundings should be avoided. Appropriate lighting equipment should be used for each application.

Temporary lighting installations (for example aesthetic lighting) should ensure there is no negative environmental impact.

Outdoor lighting should be designed in a way to disturb ecosystems as little as possible regardless of the spatial scale, ensuring that species whose orientation and navigation are based on visibility of the stars, moon, Milky Way, and polarization of natural light at night (e.g. migrating birds, sea turtles, etc.) are not negatively affected.

N5.6. Intrusive light

Light entering indoor living areas should be minimized and ideally eliminated. Intrusive light can be mitigated by the following techniques.

- Efficient lighting design of public outdoor lighting near residential buildings, with mounting height of luminaires as low as possible and luminaire shielding to prevent light trespass beyond the intended subject.
- Adaptive control of lighting levels to absolute minimum according to the relevant lighting class with respect to curfew hours.
- Minimization of façade lighting and switching off after curfew hours.
- Minimization of colorful and dynamic lighting (colour facades, illuminated signs, advertisements, etc.) near residential buildings and switching off of such lighting after curfew hours.
- Control of obtrusive light from distant light sources of high intensity (e.g. stadium, park, industrial facility, etc.) by proper lighting design and luminaire shielding.

N5.7. Glare control in roads and outdoor working places

Glare levels should be controlled and reduced below the maximum recommendations (i.e. CIE 115 for road lighting, CIE S 015 and ISO/CIE 8995-3 for outdoor areas, etc.). Relevant glare control should be applied for colourful and dynamic outdoor lighting.

N5.8. Spectral content of the emitted light

The spectral content of the emitted light, especially the content in the region of blue, should be carefully selected for the intended application to minimize negative impacts on the surrounding environment. Residential areas should be illuminated with sources having the minimum amount of blue emission possible (CCT no higher than 3000K and/or spectral power distribution less than 1% in the range 380-500nm, with CCT <2200K strongly preferred) combined with dimming control. Tunable white luminaires, with variable CCT (e.g. 2200K-3000K) and variable luminous flux, can be used for residential and other urban areas (parks, squares) in case there is a demonstrated need for neutral white during certain periods. Environmentally sensitive areas should be illuminated only with sources with minimal spectral content in blue (e.g. amber LED) to avoid disturbance of the surrounding ecosystems.

N5.9. Modulated light in color façades and illuminated signs

Dynamically modulated color facades such as LED billboards are strongly discouraged, especially in residential areas. Their luminous intensity should be reduced to a level that prevents the glare to humans, and does not affect the relative groups of natural species. All illuminated facades and media advertisements should be switched off after curfew. The modulation frequency should be minimized to avoid disturbance to humans and natural species.

N5.10. Light measurements, obtrusive light and skyglow monitoring measurements

Obtrusive light and sky glow that affect humans and the environment should be carefully assessed and monitored, via measurements and monitoring. A holistic assessment for urban, suburban, rural and ecological reserves should be followed. Commissioning of lighting installations is recommended to avoid over-illumination or bad practices. Obtrusive light measurements and sky glow monitoring should be implemented in national or local regulations. Mitigation and possibly restoration measures should be applied when scientifically justified thresholds are exceeded.

N5.11. Urgent research topics

Interdisciplinary research among lighting, medical, and environmental research communities is urgently needed in the following fields and should be encouraged.

- Effects of artificial light at night on human health
- Effects of artificial light at night on flora and fauna
- Effects of artificial light at night on visibility levels and public safety
- Thresholds for impacts of artificial light at night on humans and natural species
- Measurement and assessment of ecological effects of artificial light at night

- Studies on impact of new technologies including adaptive lighting, and other characteristics of light such as light modulation (flicker) and glare.

Studies should use the correct and appropriate light quantities and metrics, which in many cases are not properly used.

N5.12. Strategic targets

- Establish specific regulations for outdoor lighting within each country.
- Establish an accreditation system for outdoor lighting installations.
- Ensure that new installations and renovations follow the relevant regulations
- Review and revise lighting legislation to consider negative environmental effects of ALAN.
- Review the requirements for illuminating roads and highways.
- Minimize the negative effect of outdoor lighting on human health and natural species.
- Restore and protect affected existing ecosystems by implementing environmentally conscious lighting technology.
- Promote lighting education to research communities new to studying the influence of light on human, and biological systems.
- Develop a scale of ecological classes of dark skies (e.g. the Bortle Dark Sky Scale) or adapt the scale of the World Atlas of Light Pollution (Falchi et. al., 2016) to show the differential impact of light over ecosystems and species across the territory.

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Appendix 1. The excessive and improper use of colorful and dynamic lighting

More and more LED flood lighting and landscape functional lighting are used/applied outdoors either in the downtown city center or even in the urban area all over the world in order to attract more tourists or to serve for illumination purposes or for advertisement purposes. The correct usage and proper installation of LED luminaires could bring positive effects and result, however, if they are used in the excessive and improper way, they may possibly bring a new source of light pollution that may affect astronomy observation, ecological system, floras and faunas, wildlife mating and birds migrating. The problem is becoming more severe when the urban city planners found out they are not able to divide distinctive districts into residential, workings and commercial areas. Hence the excessive usage of LED media facades in the shopping area may cause light intrusion into the resident area through the window, and that may cause sleep disorder, bringing negative emotional impact. Analyzing the satellite data of outdoor night lighting in Korea provided by the National Environmental Information Center of Korea and the Korean Community Health Survey data, it was found that night outdoor lighting was significantly related to depression symptoms and suicidal behaviors of Korean adults. In 2018, CIE released an international standard **CIE S026/E:2018 CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light on non-visual effects.** There is strong scientific evidence that light is not only essential for vision but also achieves important biological effects relevant for human health, performance and well-being that are not dependent on visual images. These effects depend on the spectral power distribution, the spatial distribution, the timing and the duration of the light exposure. They also depend on person-specific parameters such as an individual’s circadian phase and history of light exposure. Light is the main synchronizer of the human biological clock. It can shift the phase of the circadian rhythm and determines the timing of the sleep/wake cycle. Light can cause acute suppression of the nocturnal release of melatonin. There are also reports that light can increase heart rate, improve alertness, alleviate seasonal and non-seasonal depression, influence thermoregulation, and it can affect the electroencephalogram (EEG) spectrum. Exposure to light elicits fast responses (i.e. in the range of milliseconds and seconds) in the pupillary reflex or in brain activity recommending proper lighting at the appropriate time. However, because this type of light pollution (due to colorful and dynamic lighting) is still relatively new, there is still a lack of quantitative assessment and scientific research on the influence of that and how to quantify them. The excessive usage of outdoor lighting in mountains and also more and more lighting shows and parks are created can affect the circadian effects of trees, plant physiology and plant ecosystem, it may have an effect in the form of delaying the growth and defoliation period of these plants. Similar adverse impacts of night lighting can affect animal physiology and activity (disturb feeding, reproduction and orientation. Again, because we are dealing with new source of colorful and dynamic light source, more study and scientific research should be carried out in order to make quantitative assessment of the negative effects. The excessive light emitted from the media screen also can produce glare that may influence the actual safety (disability glare) and the comfort (discomfort glare) of the pedestrians.It can also divert the attention of the drivers, through creation of the glare and distractions, that compromise traffic safety. In September 2018, A new TC named **TC4-58 Obtrusive Light from Colourful and Dynamic Lighting and its Limitation** was established to provide guidelines for the implementation and usage of colorful and dynamic lighting in outdoor applications aiming at limitation of obtrusive light with respect to astronomical observations, humans and night-time environment and to develop metrics for obtrusive light from colorful and dynamic lighting systems and to propose suitable methods for limitation or prevention of obtrusive light from such systems.

Figure xx: The excessive usage of colorful lighting may affect astronomy observation, ecological system, flora and fauna, wildlife mating and birds migrating.

Appendix 2. Summary of research methods and the applied artificial light at night regime

Table 1: Summary of the research method of the referred articles and the applied artificial light at night regime. (Reviews are excluded)

Publication	Method	ALAN example
Baker & Richardson 2006	In situ experiment	Flashlight, illuminating frogs in an area of 1m² at 52-120 lx
Berge et al. 2020	In-situ monitoring	Lights used were normal working lights representative for any ship operating in the dark
Bolton et al. 2017	In-situ monitoring	Array of 4050 lm warm white LED spotlights installed under a wharf in 45°. Less intense than normal harbour illumination.
Brüning et al. 2018a	Laboratory experiment	1 lx, fluorescent bulbs
Brüning et al. 2018b	Field experiment	Experimental streetlight: 13.3 to 16.5 lx at the water surface and 6.8–8.5 lx at 50 cm depth

Cabrera-Cruz et al. 2018; 2019	Modell of Birds of the World geodatabase to obtain geospatial data characterizing the presence, origin and seasonality of 10,423 bird species around the world Data from nine weather surveillance radars in the eastern United States to estimate altitudes at five quantiles of the vertical distribution of birds migrating at night over urban and non-urban areas during five consecutive spring and autumn migration seasons.	Light pollution map: mosaic of six geotiff tiles from the Earth Observation Group (EOG) at NOAA National Geophysical Data Center to create a complete dataset of ALAN for the entire world
Cathey & Campbell 1975	In situ monitoring	Streetlight
Ciach & Fröhlich 2019	In-situ monitoring city of Krakow (PL)	Urban light pollution
Cravens et al. 2018	Field experiment	Experimental lights: 50-W LED, producing 4,200 lm at 5,500 K at 3 m height
Davies et al. 2012	Field experiment	High-pressure sodium streetlights

De Young et al. 2017	Laboratory experiment	Nighttime: 0-5 lx
Dominoni et al. 2013	Laboratory experiment	Daytime: 250-1250 lx Nighttime: 0.3 lx vs 0.0001 lx
Grubisic et al. 2017,2018	Artificial streamside flumes on a sub-alpine stream.	White LED stripes 20 lx
Henn et al. 2014	Field experiment	1482 lx; standard error (SE) = 533] intensely illuminated a 1 × 4 m area and were placed 1 m upstream of the drift net
Knop et al. 2017	Field experiment	experimental streetlight
Kwak et al. 2017;2018	Experimental set upr	3 years exposure of 1, 3 and 50 µmol m^{-2} s^{-1}
LeTallec et al. 2013	Cage experiments	light intensity: 24.2+/-0.9 nmol photons.s^{-1}.m^{-2} corresponding to a high pressure sodium lamp streetlight located 50 m in front of the cages and positioned 8 m above the ground

Longland 1994	Laboratory foraging arena	0.5 to 0.4 lx dark control, 5.5 lx illuminated patches
Macgregor et al. 2017	In situ monitoring	Streetlight: 2.3 lx (range 0.2–12.1 lx) vs 0.1 lx at the ground
Macgregor et al. 2019	Field experiment	Streetlight HPS vs. cold white LED, full vs. part night lighting
Manfrin et al. 2018	Field experiment	Experimental streetlight
Masetti 2018	In situ monitoring	Streetlight
Matzke et al 1936	In situ monitoring	Streetlight
Meravi et al. 2018	In situ monitoring	Leaves close to streetlight receiving 340–360 lx
Nitschke et al. 2016	Laboratory experiment	8 h light/16 h dark short day cycle vs. extended cycles of 32h, light intensities of 120 to 170 µmol m^{-2} s^{-1}, using a combination of Philips SON-T Agros,400W, and Philips Master HPI-T Plus, 400 W/645 lamps

Oyang et al. 2017	Field experiment	Experimental streetlight: 8.2 +/- 0.3 SEM lx at ground level beneath the light posts
Palmer et al. 2017	In-situ monitoring	Streetlight: 4.000K LED vs. HPS
Perkin et al. 2014	Artificial indoor flume	416 to 0 lx
Riley et al. 2015	Laboratory experiment	8, 4, 2 and 1 lx vs 0.1 lx
Robert et al. 2015	In situ monitoring	Marine base illumination vs bushland
Rotics et al. 2011	Field enclosure experiments	Approximately 2 lx, similar to light pollution measured about 40 m from an illuminated road junction in the study area. 70-watt yellow metal halide lamps at 3 m height.
Torres et al. 2020	In-situ experiment	Experimental streetlight: 0.2 lx diffused, cool-white LED light
Van Grunsven et al. 2018	Field experiment	Experimental streetlight