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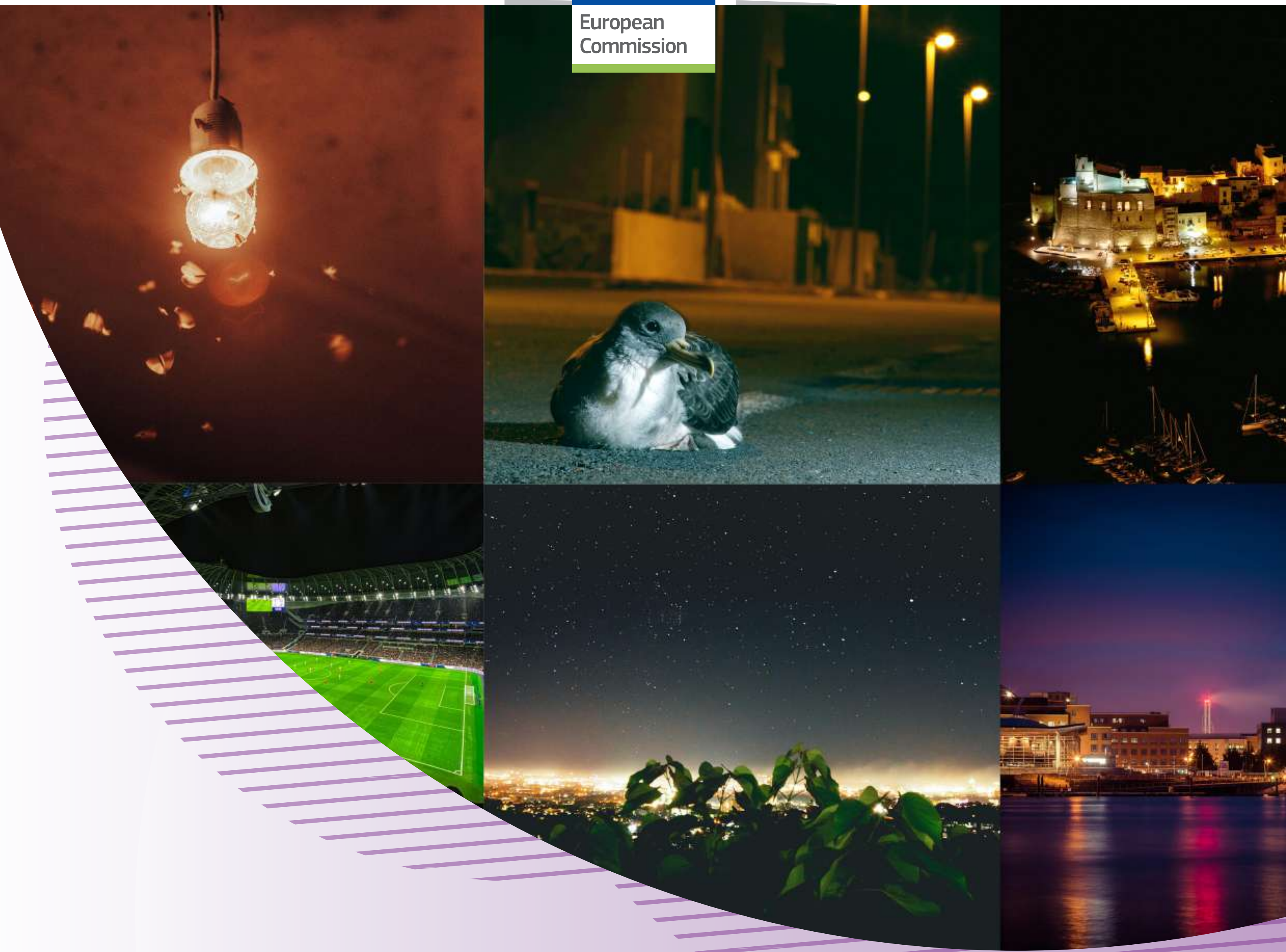

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FUTURE BRIEF:
Light Pollution: Mitigation measures for environmental protection

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Light Pollution: Mitigation measures for environmental protection

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Science for Environment Policy
Future Brief 28:

Light Pollution: Mitigation measures for environmental protection

Contents

Artificial lighting can cause light pollution, which is recognised as one of the most complex environmental degradation forms of the 21st century. Despite the need for night-time lighting, light pollution presents a severe problem for the environment and humankind. It can have adverse effects on people, astronomy and wildlife health, and results in inefficient use of energy and other environmental harm (e.g. carbon dioxide emissions, global warming), crime and disorder.

Katja Emen, Faculty of Criminal Justice and Security; University of Maribor. Slovenia, 2021

1. Introduction

The growing world population, coupled with increasing urbanisation, has led to increased use of artificial lighting inside buildings, but also outdoors at night-time. Light pollution occurs when the presence of artificial light produced by human activities adversely affects the natural environment and the health and well-being of living organisms, including humans.

Lighting that causes light pollution is often referred to by the umbrella acronym 'ALAN', referring to artificial light at night[1]. For most of human history we have used candles to light our way with sunset and sunrise marking the decreases and increases in our activity levels. However, the advent of electrical outdoor lighting has changed these activity patterns. Although this has led to many benefits, it also means that for most people the night sky is no longer dark, and they cannot see the Milky Way (Smith *et al.*, 2023).

ALAN has largely increased overtime due to industrialisation, urbanisation and population growth. However, the recent focus on energy efficiency to tackle climate change, as well as to lower the rising cost of energy, has led to technologies and behaviour changes by consumers that also lower light pollution (Jägerbrand and Spoelstra, 2023). LED technology for example, is more energy efficient and when used correctly can lead to less light pollution than older light sources; however, the colour emitted, necessity, timing, positioning and shielding should all be considered carefully.

1 Please note that 'artificial light at night', is still the same type of 'natural light' as during the day i.e. photons, but the light source is electric, and it is this source that is artificial.

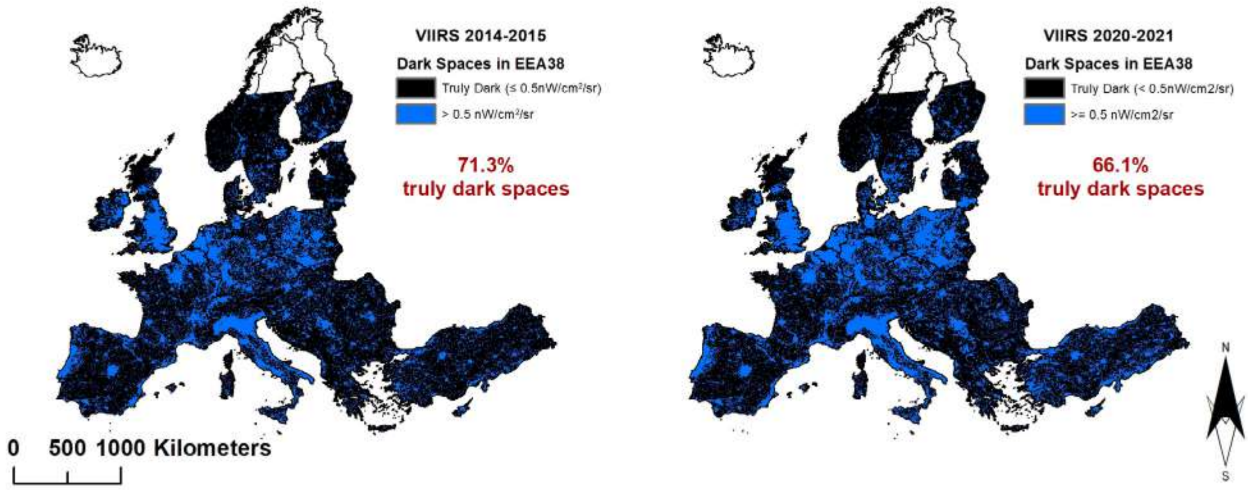


Figure 1: Maps depicting truly dark spaces in the EU-38 in 2014–2015, on the left-hand side (71.3%), versus in 2020–2021 (66.1%). These show an approximate loss of 5% of truly dark spaces across Europe in six years. This image is created from remote sensing imagery by the VIIRS Satellite. Black denotes 'truly dark' spaces which, in this image, is suggested to be European land surface with light emissions below or equal to 0.5 nW/cm^2/sr (nanowatts per square centimetre per steradian) of radiance. Blue denotes European land surface where light emissions are higher than 0.5 nW/cm^2/sr. Exclusion of Northern region depicted in white due to confounding effect of Aurora lights (Widmer *et al.,* 2022). Source: European Topic Centre on Human Health and Environment on behalf of EEA, 2022.

The principle focus of this brief is the environmental impact of artificial light at night. However, ALAN can also affect human health, with evidence that exposure to light at night can lower melatonin production, resulting in sleep deprivation, fatigue, headaches, stress, anxiety and other health problems. Some studies also show a correlation between reduced melatonin levels and cancer.

Humans are adapted to being active during the day, so our visual system requires greater luminance than species adapted to being active at night. Light pollution occurs as an unwanted side effect of people using lighting to be safely active outdoors at night. There is some evidence that inadequate lighting can contribute to people feeling anxious due to fear of attack, physically hurting themselves due to poor visual perception, or being less physically active i.e. avoiding walking at night. In focusing on environmental impacts on non-human flora and fauna primarily, we are not ignoring human concerns, as mitigating for the negative impacts of ALAN for biodiversity, will benefit people both indirectly and directly.

ALAN disrupts ecosystems, interferes with wildlife behaviour and migration patterns, can impact human health, and obscures our view of the night sky. To address these concerns, this report aims to introduce various mitigation measures that can be implemented to protect the environment from light pollution.

To provide some essential background knowledge this brief will present an initial overview of the types of light pollution and some of their impacts on wildlife, and ecosystems. This will be followed by a brief exploration of ways to measure light pollution when investigating ALAN at different scales in the environment.

As with many emerging environmental threats, the research evidence on the impacts of ALAN on different groups of organisms is still in its infancy, however, there is sufficient evidence to suggest it may have some quite significant detrimental impacts on biodiversity and human health. A consideration regarding application of the precautionary principle will be provided at the outset.

The majority of this report will explore multiscale transdisciplinary approaches to protect the environment from ALAN. This will firstly introduce innovative technological and practical adaptions of lighting design, to mitigate negative impacts on the environment. Management interventions and best practice approaches to mitigate impacts will be presented in the second half of chapter 2.

Mitigation measures can be introduced at different levels (stakeholders), across different sizes of spatial area, and for different times of the year/night to systematically deal with light pollution and its consequences. The concept of 'Dark Infrastructure' to be used alongside, in conjunction with, or as an add-on to existing blue and green infrastructure is presented. Dark infrastructure creates dark corridors, enabling movement of photo-sensitive species through an area of continuous darkness.

Legislative approaches are an important aspect of strategies and measures to manage the ecological impact of ALAN, alongside technical and practical adaptations used in cross cutting approaches at species, taxa, or area/ecosystem scale (see Table 1) (Jägerbrand and Bouroussis, 2021(a); Rodrigo-Comino *et al.*, 2021; Morgan-Taylor, 2023).

In this report we will focus on categories 3 (adaption to lighting design to mitigate ALAN) and 4 (measures targeted at certain sensitive habitats or taxa) from table 1, as well as discussing some category 2 current mitigation efforts undertaken by local government and communities in towns and cities. Legislative approaches to ALAN can be reviewed in a recent report by Widmer *et al.*, 2022, with an emphasis placed on identifying appropriate thresholds levels of ALAN for regulatory purposes (Widmer *et al.*, 2022). However, it must be remembered that none of these measures will work in isolation and they need to be implemented in combination, strategically and with stakeholder input.

Table 1: Division in groups for measures for reducing the adverse effects of ALAN, adapted from Jägerbrand and Bouroussis (2021a)

Category	Examples of recommendations
1. Recommendations for legislation at national or international levels	Classification of ALAN-free zones, limits of upward emitted light over geographical areas, legislation limiting the negative impact of ALAN.
2. Recommendations for practical schemes at local government level in cities, towns and villages.	Combining measures to reduce energy use and limit ALAN by integrating smarter lighting design, for example, sensors that turn on lights in car parks, or on pathways in parks only when people approach. Retrofitting shielded luminaires to limit light spill. Using timers to reduce unnecessary light at times when it isn't needed. Sustainable lighting to reduce energy costs and CO_2 output whilst minimising impact of ALAN.
3. Recommendations for technical and practical adaptations of the lighting design	Precise lighting design: spectral power distribution, lighting control and adaptive lighting concepts, light distribution and orientation.
4. Recommendations for sensitive species, taxa, or ecosystems	Measures for reducing impacts on sensitive species and habitats, identifying species and groups that are sensitive and suggesting management of sensitive areas to avoid the impact of ALAN.

A range of inspirational case studies of successful use of mitigation measures to ameliorate negative impacts of ALAN on biodiversity will be provided in this brief. With examples of successful mitigation measures used for more photo-sensitive nocturnal and twilight active species, and taxa impacted by ALAN, such as migratory birds, turtle hatchlings, bats and nocturnal insects. More widespread use of such mitigation measures, through partnerships that enable comprehensive strategies to be implemented, would contribute considerably to mitigating the present upward trend of light pollution overtime and the inherent negative impacts.

Night image of Paris, France, from the International Space Station by NASA Wikimedia Commons CC By 4.0.

Pursuing zero pollution, including in relation to harmful chemicals, in order to achieve a toxic-free environment, including for air, water and soil, as well as in relation to light and noise pollution, and protecting the health and wellbeing of people, animals and ecosystems from environment-related risks and negative impacts

Light pollution in the 8th Environment Action Programme's priority objectives

2. Multi-scale transdisciplinary approaches to protect the environment from artificial light at night (ALAN)

The impact of artificial light on the environment is multifaceted and complex. Although there is consensus from the scientific community that ALAN is an issue that needs to be addressed, the scientific sources behind this consensus are diverse in their disciplines and their approaches to study.

Studies can focus on different impacts of light pollution (e.g. astronomical, ecological and human health) (Jägerbrand, 2022) and on different types of light that can contribute to light pollution, such as skyglow and spill light (see box 1) (CIE, 2020). Research in this area uses distinct methods or approaches to measure impacts (e.g. remote sensing techniques, surveys, laboratory analysis, modelling tools) and considers different scales in time and space (Rodrigo-Comino *et al.*, 2021; Kocifaj *et al.*, 2023).

Box 1: Description of different types of light pollution

(International Dark Sky Association - https://www.darksky.org/light-pollution/;
International Commission on Illumination (CIE) - https://cie.co.at/eilvterm/17-29-185):

- **Glare** – *excessive brightness (luminance) that causes visual discomfort or a reduction in the ability to see objects (known to effect humans, paucity of research on other species).*
- **Skyglow** – *brightening of the night sky over inhabited areas from reflected light scattered by the atmosphere.*
- **Clutter** – *bright, confusing and excessive groupings of light sources (known to effect humans; paucity of research on other species).*
- **Reflected light** - *reflected light from nearby surfaces is spread in different directions around the lighting installation.*
- **Spill light** - *light emitted outside the area that a lighting installation is designed to illuminate, onto adjacent areas where it is unnecessary.*

Skyglow from urban area lighting up the night sky.
Source: https://www.pexels.com/photo/green-leafed-plants-under-starry-night-1676073/

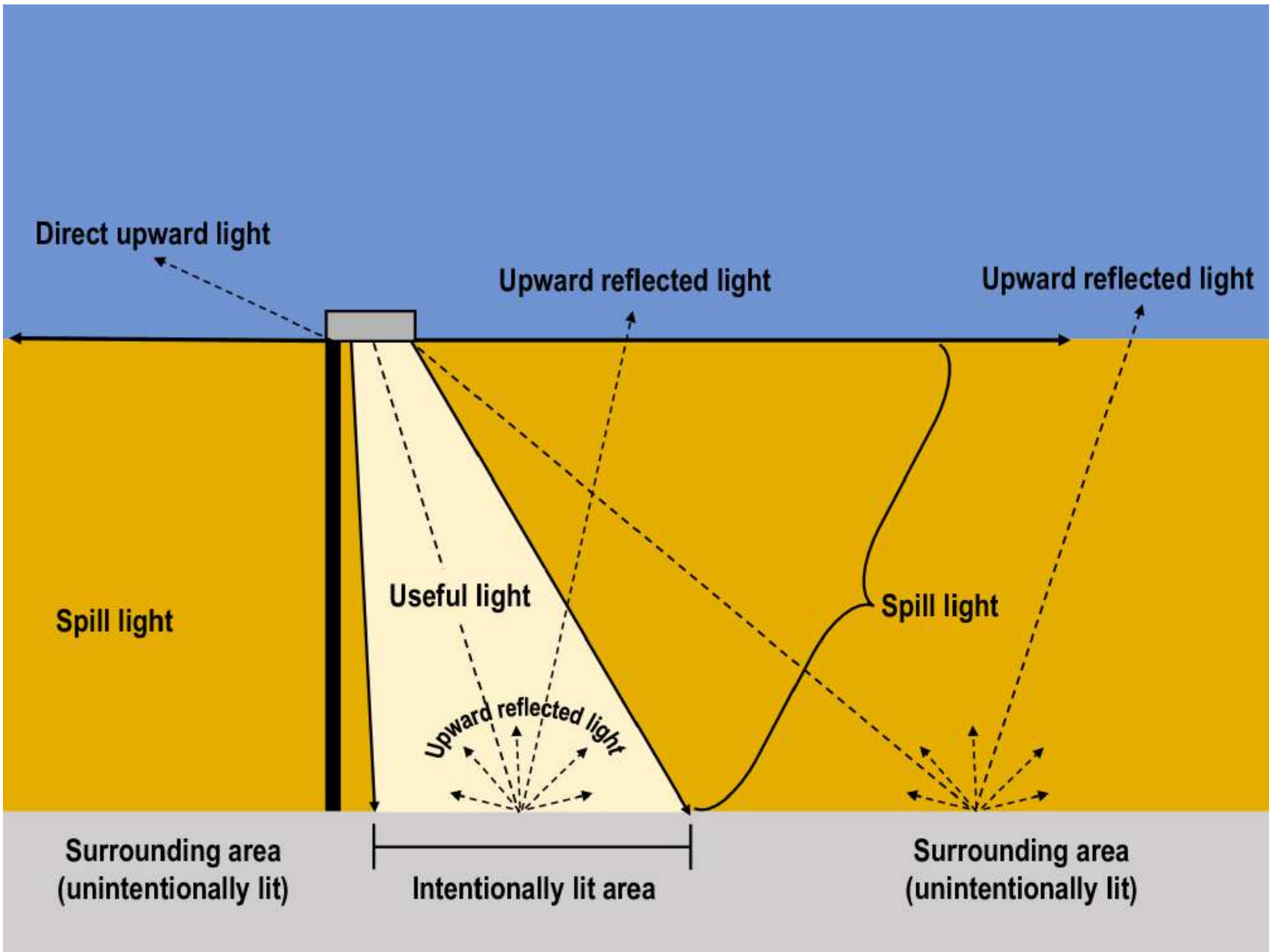


Figure 2: Types of obtrusive light. Spill light is the light emitted by a lighting installation that falls beyond the intentionally lit area. Source: Annika Jägerbrand

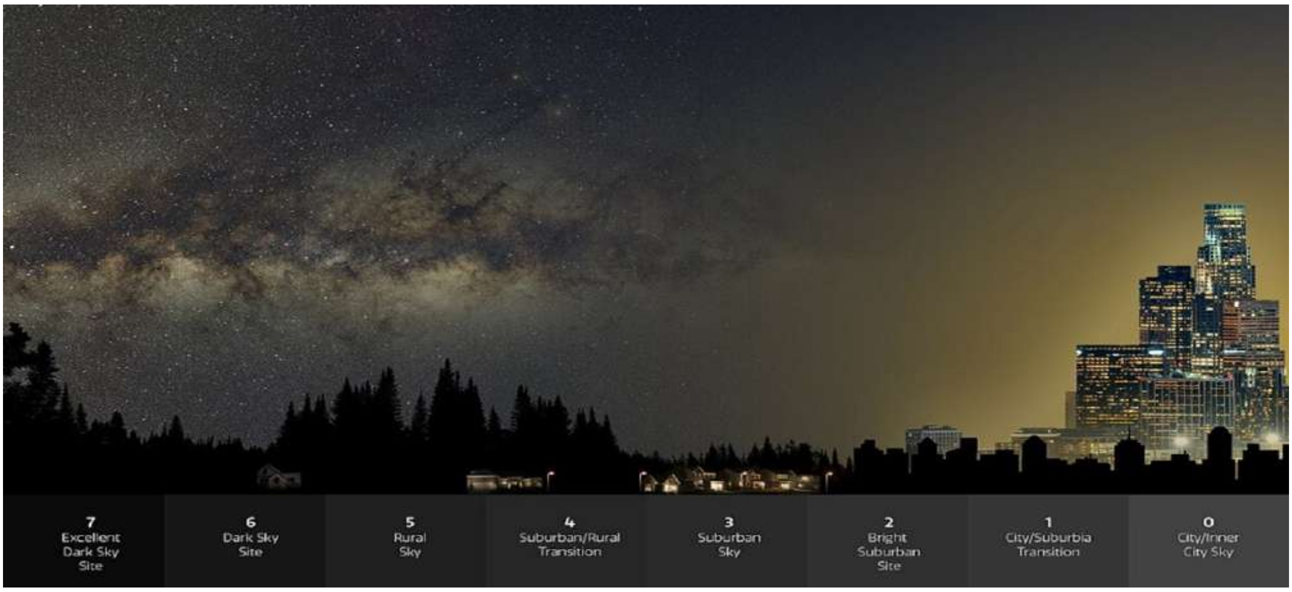


Figure 3. Infographic illustrating the impact of light pollution on our ability to see stars and other objects in the night sky. The numeric scale is similar to that used by citizen scientists on the 'Globe at Night' project, run by the National Science Foundation's NOIRLab (National Optical-Infrared Astronomy Research Laboratory), which concludes that stars are disappearing from human sight at an astonishing rate. Source: NOIRLab/NSF/AURA, P. Marenfeld, CC BY 4.0 <https://creativecommons.org/licenses/by/4.0>, via Wikimedia Commons.

In addition to this, those involved in decision-making have different perspectives, depending on whether they are scientific or industry experts, policymakers or the public. Within these groups there are differing priorities, such as ecological protection, protection of astronomical observations from Earth, energy efficiency and public safety – all of which consider different measures of impact (Jägerbrand, 2022).

This complexity makes it challenging to mitigate for and prevent the impacts of ALAN, as there are a range of possible qualities to consider, measure and limit. It also necessitates interdisciplinary and joint efforts to develop and implement solutions. Experts from lighting, medical, and environmental research communities need to collaborate across relevant fields (United Nations Office for Outer Space Affairs, 2021).

These collaborations have produced initiatives and techniques to manage light pollution that span across technical innovation, regional, national and international initiatives and approaches focused on species or ecosystems (Widmer *et al.*, 2022). For example, the recent 'responsible outdoor lighting at night' (ROLAN) manifesto came out of the ROLAN conference that was organised by the ILLUME research group from the Gdansk University of Technology, and the Society of Light and Lighting (SLL). It provides 10 core principles for external illumination, with easy-to-follow actions to minimise the impact of outdoor night-time lighting and make the stars visible again, and has been adopted by the International association of lighting designers (IALD) and the Illuminating Engineering Society IES, showing dark sky protection is underway (International Dark-Sky Association, 2023; Zielinska-Dabkowska, *et al.*, 2023). However, the implementation of these new approaches remains low, (Rodrigo-Comino *et al.*, 2021) and tends to consider only one or a few aspects of ALAN and their impacts in isolation. There is a need for more evaluation and greater knowledge sharing to develop multifaceted solutions to this complex problem.

2.1. Applying the precautionary principle to ALAN

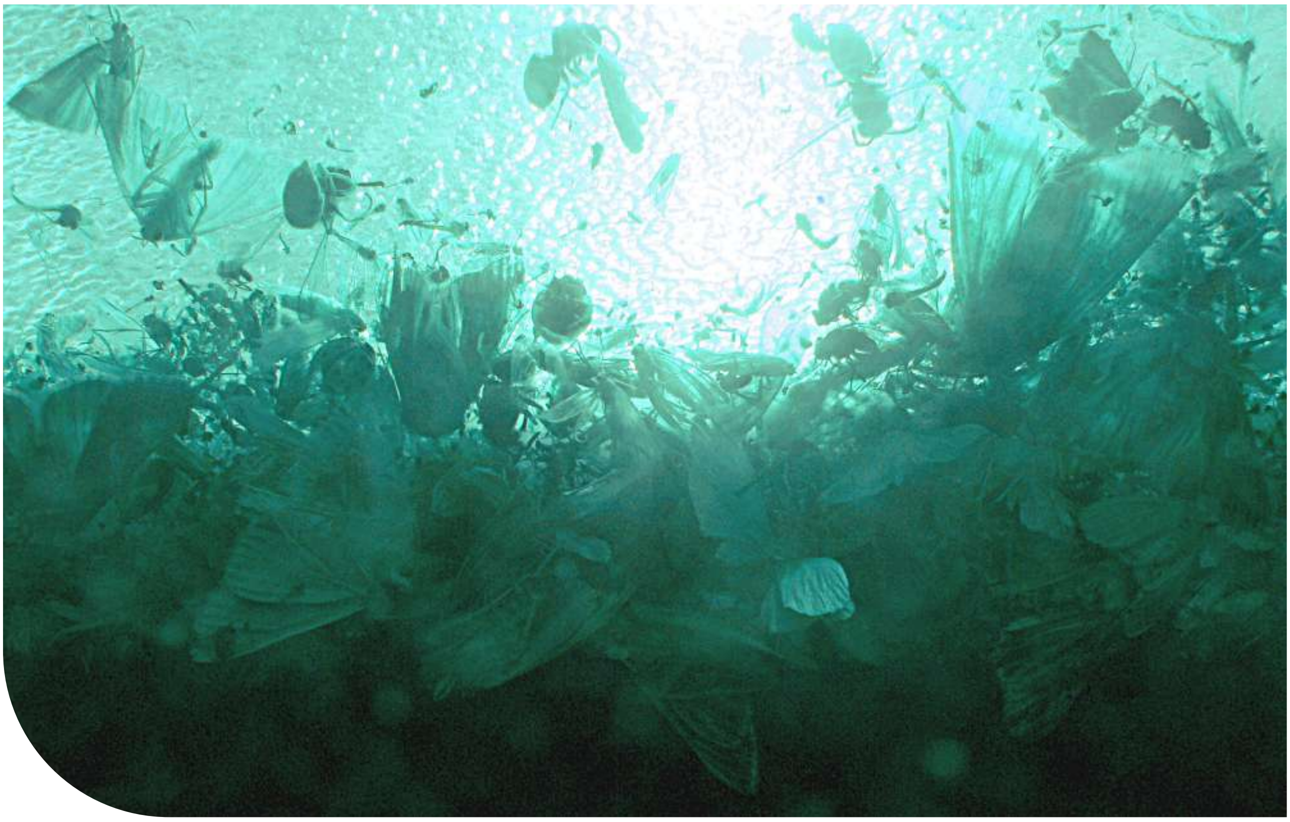
There is a paucity of empirical data on the effects of ALAN, and there is much to learn about the relationships between impact and light levels, spectral content and directionality. Consequently, it has been recommended that precautionary methods are implemented to avoid and mitigate for light pollution in protected areas (Commonwealth of Australia, 2020; Jägerbrand and Bouroussis, 2021b).

The precautionary principle has four central components: taking preventive action in the face of uncertainty; shifting the burden of proof to the proponents of an activity; exploring a wide range of alternatives to possibly harmful actions; and increasing public participation in decision making (Science for Environment Policy, 2017; Kriebel *et. al.*, 2001).

To translate the precautionary principle into approaches to reduce ALAN, organisations and experts working in this area have proposed simple rules. For example, the 'UK Dark Skies at Night Partnership' (UKDSP) is a collaborative forum of UK dark-sky places, including those with International Dark-Sky Association designations; the Commission for Dark Skies; the Countryside Charity (CPRE); the Institution of Lighting Professionals and the Society of Light and Lighting. The UKDSP has drafted a 'Dark Sky Standard' with its strategy having four pillars at its core described as "The right light, at the right place, at the right amount, for the right duration" (United Nations Office for Outer Space Affairs, 2021; UKDSP, 2021), where the expression "right light" relates to an adequate visual performance for humans, while meeting the goals for environmental and health protection.

Similarly, Clanton formulated an approach to reducing light pollution which involves (i) using lights only when necessary; (ii) employing the lowest illuminance as possible; and (iii) minimising the light shed skywards (Clanton, 2014).

National light pollution guidelines in Australia suggest that the starting point for all lighting designs should be natural darkness, and that artificial light should only be added for specific and defined purposes, and only in the required location, and for the specified duration of human use (Commonwealth of Australia, 2020).



Dead insects trapped after being attracted by light in a lighting box hidden in the soil near a public monument. This is an example of an ecological trap caused by light pollution. Source: Lamiot, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons

2.2. Technological and practical adaptations of lighting design

Some researchers have argued that older installations of night-time lighting systems in the United States are inefficient, overly brilliant, improperly directed and shielded; some being entirely unnecessary (Nguyen and Gupta, 2022). Unshielded light fixtures can direct more than half of their illumination upward or laterally, resulting in only 40% of the light illuminating the ground (Nguyen and Gupta, 2022). In some parts of the world nearly a third of outdoor lighting is projected to be wasted as a result of this poor design.

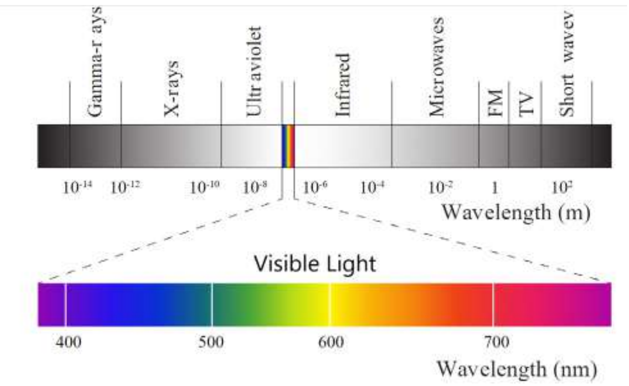
There have been huge technological and innovative advances in lighting design that have improved energy efficiency, aesthetics and functionality. This has happened both for outdoor and indoor lighting, and with both positive and negative consequences for the environment in terms of light pollution. Technology in this field continues to progress and is becoming increasingly informed by research into the impacts of ALAN. The ultimate goal is that lighting can continue to fulfil its purpose, while minimising or eliminating environmental harm.

Table 2: Different general approaches to adapting lighting design

Focus of adaptation	How it works
Modifying the light source	Changing colour, intensity
Changing the direction of light and shielding light	Using shielding or other approaches to prevent light from falling where it is not intended or needed
Limitation of upward and downward light	Reducing amount of light going upwards, particularly to reduce skyglow
Lighting control and scheduling	Scheduling light to be present only at times when it is needed
Smart, intelligent and nano approaches	Using IT solutions that connect light to customer needs through Internet of Things

2.2.1. Type of light source

As a response to the climate crisis and energy prices, contemporary lighting strategies are focusing on energy-efficient systems with low carbon output. As a result, many countries are transitioning to white light emitting diodes (LED), which are more sustainable than sodium vapour lights as they require less energy, however, they have negative impacts on many living organisms. These white LEDs have a higher output of shorter wavelengths, emitting light in the blue part of the spectrum (Widmer *et al.*, 2022). Unfiltered white light LEDs can have a more negative ecological impact on certain species relative to lights with other colour spectra. So, it is important to use these light sources carefully, after consideration of the need for ALAN, and where possible use lower intensity LEDS with a lower blue content when possible. Blue wavelengths affect the circadian rhythms of humans, insects and other vertebrates, largely because many organisms perceive shorter wavelengths of light, i.e. blue light, better than they can perceive light of longer wavelengths, meaning that the impacts of light pollution will be greater for blue light compared to longer wavelengths (Jägerbrand and Bouroussis, 2021b).



Overview of the type and colour of the different wavelengths. Source: Tom Gaimann, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons

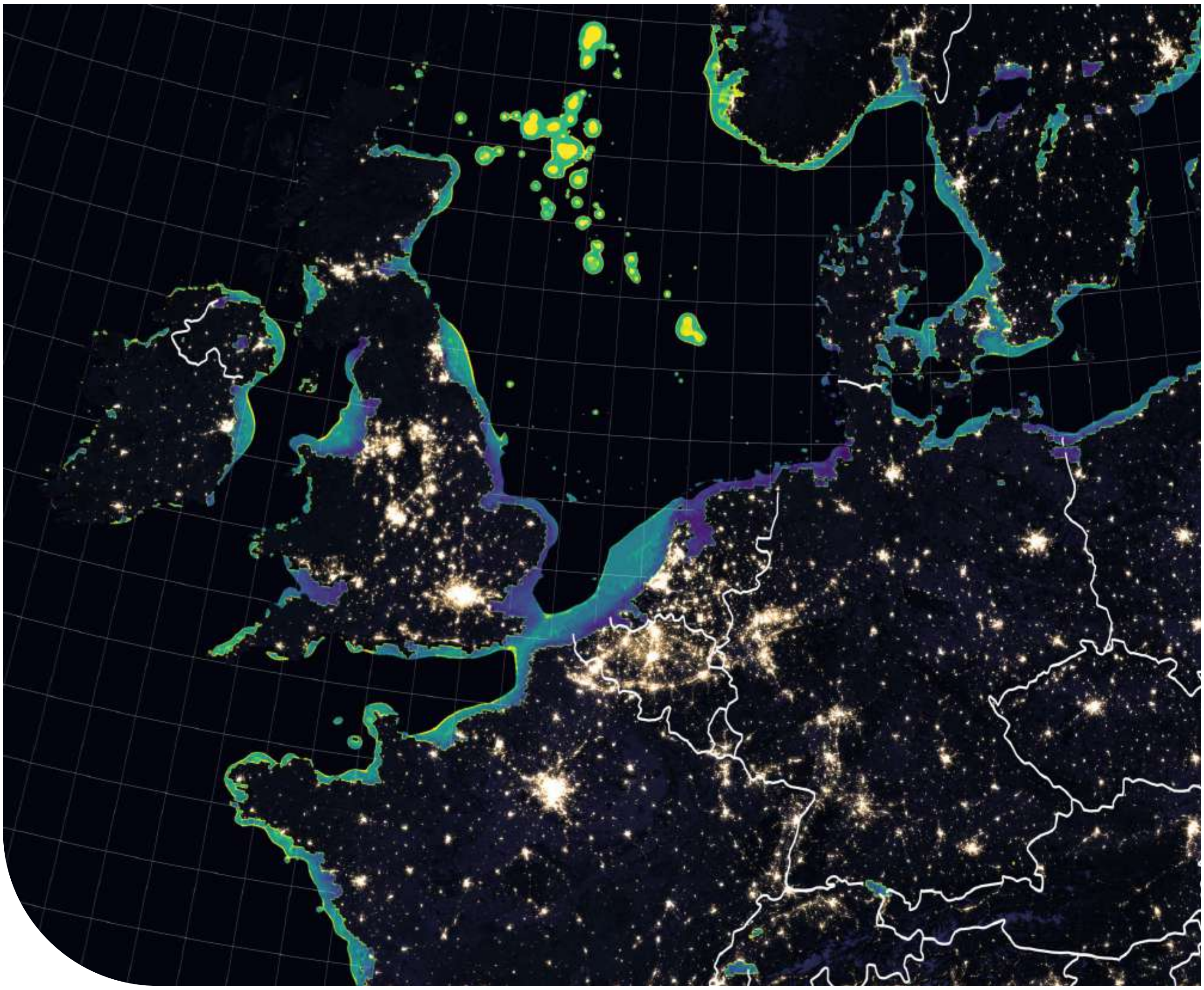


Figure 4. Offshore oil and gas rigs and wind farms in the North Sea shine brightly on the water, as does the glow of coastal cities in, for example, the United Kingdom (landmass at left) and Norway (upper right). In April, the region's waters are clear enough that the artificial light can penetrate from 1 metre depth (dark blue in the picture) to 30 metres depth (yellow in the picture). Source: NASA Earth Observatory images by Joshua Stevens, using data courtesy of Smyth, T.J., *et al.* (2021).

Approaches to minimise and avoid blue content of light have been recommended and implemented. These include filtering out wavelengths in the blue region or using yellow, green or amber LEDs.

In the case of coastal installations, it has been suggested that using red artificial light at night might be favourable to most marine organisms as this light wave colour weakens quickly in water and so doesn't penetrate very far (Davies *et al.*, 2020). Most marine species are not sensitive to this wavelength of light, as they have evolved in its absence, however, there are other considerations regarding red light use at sea, such as whether this colour of light would still serve its function for humans.

Box 2: Do red coloured LED lights in street lamps, cause less impact on wildlife than other LED colours?

Figure 5: Green light, white light, and red-light treatments in a natural area in the Netherlands – part of an experiment by Kamiel Spoelstra, of the Netherlands Institute of Ecology, to examine the impact of different spectra across multiple taxa, including birds, bats, and insects. Source: Photographs by Kamiel Spoelstra / NIOO-KNAW

Kamel Spoelstra and colleagues have been running ALAN experiments in the Netherlands since 2010, examining the impacts of different colours of street lamp lights on wildlife, including bats, insects, mice, voles and birds. They noted that the least impactful colour of LED light was red light, where bat frequency and behaviour largely mimicked that of the dark control areas.

In contrast, white and green light was found to be an 'ecological trap' for moths and other nocturnal insect species, i.e. the light offers a seemingly attractive habitat for these species, but in reality compromises their survival. In this case the moths and insects were attracted to the lights, and then eaten by non-light-shy bat species, such as the common pipistrelle (*Pipistrellus pipistrellus*), which took advantage of the abundance of prey. This created a situation where the insects were initially flying much higher near the lights, but over time this abundance fell to below that noted at dark or red-light lamp posts. Most bat species do not perceive red light as well as blue light, explaining the reduced impact of red light on their behaviour (Spoelstra *et al.*, 2017).

However, more recent studies examining the impacts of colour spectra of ALAN on bat flight behaviour along ecological corridors and during migration, found some species of bats are impacted by both red and white spectra. For example, when red or white light was placed on one side of a hedgerow, one bat species, the lesser horseshoe bat, *Rhinolophus hipposideros*, was found to detour and fly along the other side, seeking shelter among vegetation (Zeale *et al.*, 2018). This highlights the issue that red light is not a perfect solution, but also that vegetation and orientation of street lighting can help mitigate the impacts of ALAN when lighting is unavoidable (Barré *et al.*, 2021; Barré *et al.*, 2023).

So, when a protected light-sensitive bat species is present, such as the rare lesser horseshoe bat, the use of light at night needs to be considered more carefully and mitigation measures put in place, or, ideally, no light used at all. In the UK the latest guidelines for developers, issued by the Institution of Lighting Professionals and the Bat Conservation Trust, suggest maintaining dark corridors in any developments near to lesser horseshoe bat foraging or roosting sites, with shielded red lighting near these corridors (ILP/BCT, 2023).

Recent advances in tuneable white technology, and other combined sources with various spectra, offer the flexibility of using application-specific light sources together with spectrum control over time. Tuneable liquid lenses, for example, have enabled the development of luminaires with changeable beam patterns, focus and colour temperature (Nguyen and Gupta, 2022). Researchers have also developed, white light emitting diodes (WLEDs) that have the same intensity as traditional LEDs but provide a more diffuse light with less glare and hardly any blue component. These WLEDs use layers of organic fluorescent dyes to perform spectral conversion, rather than phosphor, and enable accurate colour perception compared with natural light (Menéndez-Velázquez *et al.*, 2022).

There is a large variability in photoreceptors, photobiological processes and light-related behavioural responses across the bio-environment. Although reducing blue content is expected to be helpful in many cases, there is no best spectrum for all applications, since different colours of light may affect species in different ways (Longcore, 2023; UN Office for Outer Space Affairs, 2020). Despite this uncertainty, the consensus at present for minimising the impact of ALAN on terrestrial species, when the light cannot be removed completely is to use amber or red lights, with little or no blue. However, as there are some exceptions to this warmer colour change for some organisms (e.g. horseshoe bats), as discussed in Box 2, it is important to consider the specific qualities of the environment with regard to species present, and the functional need of humans inhabiting the space to ensure their safety.

Researchers have developed an index based on standard spectral emission curves for new and established outdoor lighting, alongside the spectral response curves of certain organisms – which is a way to map their responses over different wavelengths. This index provides a tool to assess the potential impact of lights, in terms of how well the light is perceived by organisms, if at all. The approach can be updated with new information about both the spectral responses of organisms, and the emissions of light sources, and could potentially be used to help inform choice about new lighting products (Longcore *et al.*, 2018).

There is however, further work to be undertaken to investigate the effect that light intensity has in combination with spectral output, and research is ongoing to note if this has an impact, and if so, what this is. Therefore, future adjustment to the index may be required as new research data becomes available.

The level of light exposure from artificial light sources at night is the most critical factor – if a light appears brighter, i.e. has greater illuminance, it will be emitting more light into the environment. So, when installing lights, the important factor is not only the amount of blue light that is emitted, but also how bright it is – or its illuminance. If selecting an amber light source – as this has less negative ecological impacts than a blue light source –it also needs to be of low brightness or illuminance. Ultimately, the critical factor is the level of light exposure (brightness, or illuminance) for species or environments – shown by recent research that investigated the impact of light colour versus light intensity on glow-worm mate choice. The intensity of light interfered more with mate choice than the colour of the light (Van de Broeck, *et al.*, 2021).

When choosing light sources in the presence of certain species, such as migratory bird species, turtle hatchlings, or bats, the overarching guidance is to choose a light source from the warmer end of the colour spectrum, i.e. yellow/amber/red, with most or all of the blue light removed. The International Convention on the Conservation of Migratory Species of Wild Animals (CMS) provides more specific guidance on this. However, this can be summarised as allowing high or low-pressure sodium lights, and, in some instances, filtered LEDs or metal halides which remove the red wavelength of light. Luminaires which should not be installed when these light-sensitive species are present, are those containing blue light such as metal halide, white LED, Halogen, mercury vapour, white fluorescent (CMS, 2023; Department of Climate Change, Energy, the Environment and Water, 2023).

However, in the presence of these species, and as a default position for any new light installation externally, these luminaires should only be installed when there is a human safety need for artificial light.

2.2.2. Direction of light and shielding

The direction of light is an important aspect that can affect if, and how, light pollution impacts the environment. The concept of spill light (see box 1) describes light falling where it is not intended, or needed, and there are techniques to reduce or eliminate this.

Special optics is the primary modern solution for ensuring only the intended area is lit, with designed optics that can be very accurately focused, for example to shine only on a certain spot, or along roads rather than across them (Wänström Lindh and Jägerbrand, 2021). By using these types of optical designed solutions there is very little wasted light, and so less wasted energy.

However, when it comes to improving existing light installations, retro-fitting luminaires with physical barriers known as shields can be useful in mitigating light spill as this blocks light from spilling beyond certain angles. There are different levels of shielding to enable the approach to be tailored to the situation, starting with sharp shielding that doesn't allow any luminous flux above or below the horizon, and less than 1 per cent of the total luminous flux between 80 and 90 degrees of the nadir (see figure 7).

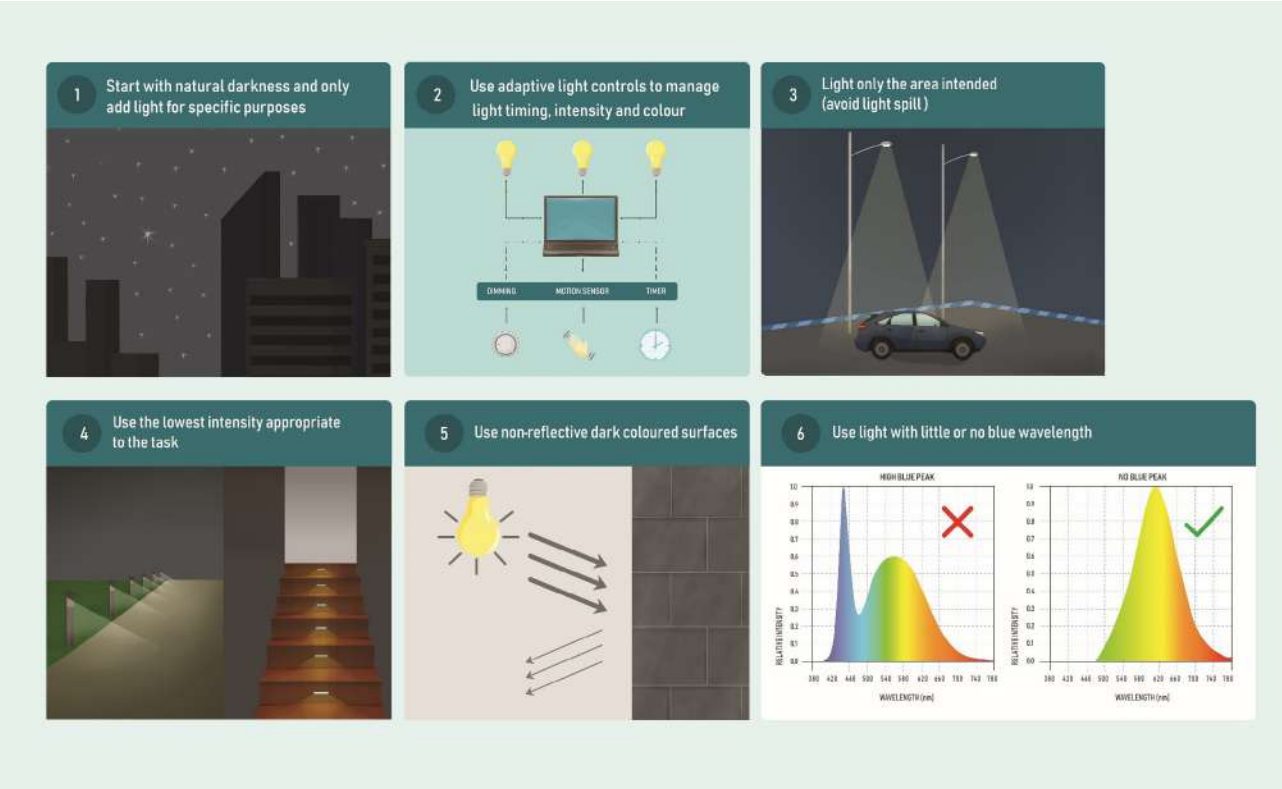


Figure 6. Lights should be directed towards the area intended to be lit, and shielded to further avoid lighting anything but the target area or object. Additional measures to ameliorate impacts of ALAN are warmer coloured luminaires, of lower intensity and set to only come on at required times. Source: DCCEEW 2023, National Light Pollution Guidelines for Wildlife, Department of Climate Change, Energy, the Environment and Water, Canberra, May. CC BY 4.0.

Image depicting road lighting on a rural street with some shielding of the luminaire. Lights should be directed towards the area intended to be lit, and shielded to further avoid lighting anything but the target area or object. Additional measures to ameliorate impacts of ALAN are warmer coloured luminaires, of lower intensity and set to only come on at required times. Source: Shutterstock, photo by Amy Johansson

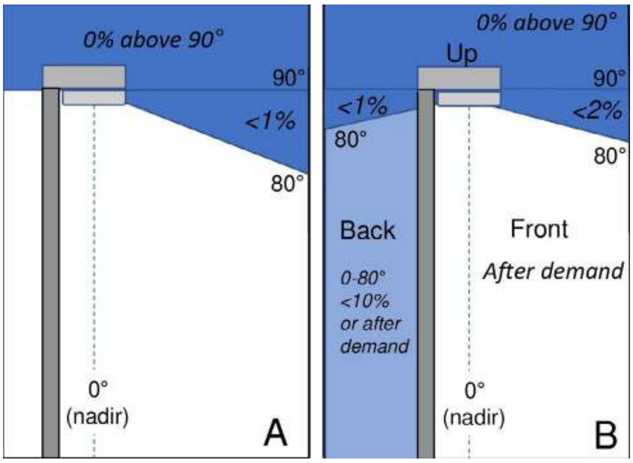


Figure 7: Example of shielding of luminaires to reduce ecological light pollution in protected areas: (A) sharp cut-off, SCO (B) BUG system (not to scale). Source: Jägerbrand and Bouroussis, 2021b

Another approach is the BUG system that allows stricter and more detailed shielding. The acronym stands for backlight, uplight and glare (see figure 7 and box 3) It is recommended to keep uplight as close to zero as technically possible and backlight as low as possible in protected areas to prevent light pollution and skyglow.

In the European Union, lighting accounts for 14% of total energy consumption; of that, approximately 14.7% is outdoor stationary lighting, which are mainly streetlights. Globally, almost one-fifth of all electricity produced is used for lighting, of which approximately 8% is outdoor stationary lighting

Source: De Almeida *et al.*, 2014

A: Road lighting 	B: Bridge lighting 	C: Aesthetic lighting 	D: Façade lighting 	E: Sky glow 
Examples of affected taxa				
Bats Insects Amphibians Mammals Birds Spiders	Fish Birds Bats Amphibians Insects	Insects Bats Birds Spiders	Bats Insects Mammals Birds Spiders	Fish Insects Shellfish Bats Turtles
Examples of mitigation measures				
• Luminaire shielding • Improved optics • Adaptive lighting • Physical barriers	• Restrict spill light outside of bridge • Adaptive lighting	• Remove aesthetic lighting from trees • Time-schedule for winter use	• Replace with downward light • Bat presence: remove or do not use lighting • Adaptive lighting	• Prevention of upward light via luminaire shielding or improved optics • Adaptive lighting

Figure 8: Examples of outdoor lighting installations, affected biodiversity groups, and some potential mitigation measures.

Photo A, depicts road lighting which can affect terrestrial species due to light spill.

Photo B, shows bridge lighting spilling onto the harbour waters below, affecting terrestrial and aquatic species.

Photo C, aesthetic lighting on trees affect species living in them and those that forage on them. This lighting should be removed or time restricted.

Photo D, upward façade lighting can affect several terrestrial species including bats, and it should be removed or replaced with downward lighting.

Photo E, skyglow. Source: Figure adapted from Jägerbrand and Spoelstra 2023.

Photo sources: A: Night Highway Light Streetlights Plumes Headlights Stock Photo 1979678945 | Shutterstock ; B: Chris Gin from Auckland, New Zealand, CC BY 2.0 <https://creativecommons.org/licenses/by/2.0>, via Wikimedia Commons; C: https://www.shutterstock.com/image-photo/illuminated-trees-houses-summer-party-holiday-1763294753; D: Shashank Verma, Poland, A Hotel Building with Lights at Night · Free Stock Photo (pexels.com); E: City Night Stock Photo 695937 | Shutterstock

Box 3: BUG (Firstlight Technologies)

The BUG rating considers **B**acklight, **U**plight, and **G**lare. BUG was developed by the Illuminating Engineering Society (IES) and the International Dark Sky Association to better explain how light can be measured. The BUG rating of a luminaire relates to how much light a light fixture produces. Overall, the lower the BUG rating, the fewer light problems (and light pollution) the fixture will cause.

- **Backlight** – this is the light that is spilled from behind the fixture into areas where it is unwanted.
- **Uplight** – this is the resulting light spill above the top of the fixture. Uplight contributes greatly to light pollution and sky glow and is generally not "dark-sky friendly."
- **Glare** – light glare is the amount of front light in the forward zones and happens when the light is too strong or concentrated. Glare is a safety issue as well as a light issue near adjacent properties.

Consideration should also be given to blocking light spill from internal light sources. This could include black-out blinds or shutters for transparent portions of a building, including sky lights (Commonwealth of Australia, 2020). This type of shielding can be performed by fixtures or structures that are not specifically designed for this purpose, such as shutters and blinds. However, this can mean they do not always effectively reduce ecological harm of ALAN, for example, in the Bonn Post Tower Germany, the shutters only attenuate but do not prevent pollution from emergency lighting on the floors, as they were designed first and foremost as sunshades rather than specifically for shielding (Korner, von Maravic and Haupt, 2022).

House in a forest, showing non-intentional lighting of the surrounding vegetation outside of the building, as windows without blinds spill light outwards. Source: https://www.pexels.com/photo/a-house-in-the-forest-12712629/

2.2.3. Limitation on upward (or downward) light

Skyglow occurs when the night sky is brightened, often from the lighting in cities. It can impact natural environments several kilometres, or tens of kilometres away from densely populated city centres. For example, in rural areas skyglow is often visible from adjacent urban environments or cities and can be perceived by certain species (Jägerbrand and Bouroussis, 2021; Rodriguez *et al.*, 2022. Many photo-sensitive species, such as birds, amphibians, insects (i.e.) and bats, in areas without high levels of direct ALAN, can still be affected by skyglow. However, for aerial species it can be difficult to distinguish the effects of skyglow from the impacts of directly emitted light. A recent European study found that skyglow from coastal cities that are low and close to the sea surface, exposes seafloor habitats to high levels of light pollution (Davies *et al.*, 2020).

Illuminated City Buildings near Water at Night, Cardiff, Wales. Source: Duncan Richardson, https://www.pexels.com/photo/illuminated-city-buildings-near-water-at-night-16510048/

Various approaches have been used in street-lighting planning to reduce energy consumption and glare, which causes discomfort for humans (see box 1). These approaches can work with specific measures and define a limit or threshold which should not be breached. For example, the edge illuminance ratio (EIR) represents the ratio of the level of light inside the carriageway edge, compared to the light outside the edge, and is used for roads with an adjacent footpath or a cycleway to ensure light levels do not negatively impact those on the footpath/cycleway. Whilst limiting luminous intensity – or the quantity of light per solid angle – can reduce energy consumption. Putting these limits in place leads to a more precise lighting design for roads which, in turn, helps limit the impact of light pollution on the environment. These are good examples of when technical management of light enables multiple benefits, in this case greater energy efficiency, reduced glare and less skyglow (Jägerbrand and Bouroussis, 2021a).

A more direct approach to reducing skyglow is to work with measures of upward light ratio (ULR), upward light output ratio (ULOR) or upward flux ratio (UFR)[2]. These measures provide different representations of the level of light that is directed upwards into the sky, and limiting them can prevent or reduce the level of skyglow. For example, The International Commission on Illumination (CIE) recommends maximum ULR values for luminaires for different environmental zones (Commission Internationale de l'Eclairage, 2017) (see section 2.4.2), and ULOR has been used in road lighting procurement in the EU with a recommendation for 0% ULOR for any lights (Donatello, *et al.*, 2019).

Light can also be reflected upwards from highly polished, shiny or light- coloured surfaces such as white painted infrastructure, polished marble or white sand, and this can contribute to sky glow. For light reflected from surfaces beneath the luminaire or from the surroundings then it is more suitable to manage the UFR for limitation of skyglow and light pollution. Measures to limit this type of upward light can be quite straightforward, such as alternatives to painting storage tanks with white paint (Commonwealth of Australia, 2020).

There are also options for management through the structure of the light or luminaire itself, where upward tilting light can be limited using appropriate optics, reflectors and lenses (Jägerbrand and Bouroussis, 2022).

2.2.4. Lighting control and adaptive lighting

The scheduling of lighting to dim, or switch off, can prevent or lessen the negative impact of ALAN on species which are nocturnal or crepuscular (active primarily in twilight and dawn), by creating dark times. The use of a schedule alongside programmable lighting systems is known as adaptive lighting.

The time at when lighting should be dimmed or switched off, and for how long, will depend on which species are a priority, and which part of the day/night this species is active during the year. Measures of this type have been shown to reduce ALAN, but the real assessment of success lies in whether they reduce the ecological impact.

For example, part-night lighting has proved insufficient to avoid impacting light-averse bats (Azam, *et al.*, 2015), because their foraging time can be reduced even if lighting is dimmed during part of the dark time period. The time when many nocturnal species are most active is twilight, which is when human demand for light peaks. However, dedicated lighting has proven successful in some specific situations, for example, thousands of trapped migratory birds are released from the National 9/11 Museums' 'tribute in light', by the intermittent switching off of the lighting rig (Van Doren, *et al.*, 2017).

Dimming may have an even smaller impact on light-aversive bat species depending on the illuminance level (Rowse, *et al.*, 2015), yet it may be effective regarding other less light sensitive nocturnal species. Very few studies have combined dimming and part-night lighting to better understand the thresholds of avoidance or attraction for photo-sensitive species (Jägerbrand and Bouroussis, 2021b). One three-year field experiment assessed several lighting strategies of LEDs on previously unlit grassland ecosystems, and one of these was a combination of dimming by 50%, and switching off lights between midnight and 04.00 (Davies, *et al.*, 2017). Out of the four strategies this combination of dimming and part-night lighting did show the most promise in terms of fewest taxa affected, but the numbers of two common species were still reduced.

However, the installation of dimmable lighting may be considered prudent in most scenarios, given that light intensity is important for most nocturnal species, but threshold data is largely absent at present. Dimmable lighting allows levels to be adjusted lower (or higher) after installation, as more research data becomes available on the ecological impacts of ALAN on resident species (Jägerbrand and Spoelstra, 2023). In a small

2 More detail on ratios can be found here: https://link.springer.com/chapter/10.1007/978-3-319-11466-8_16

study of two streets in peri-urban Switzerland, researchers found that installing street lighting that dimmed when traffic was not present reduced light levels by 35%, overall. This regime, compared to full light, resulted in lower insect numbers and reduced bat activity (Bolliger *et al.*, 2020).

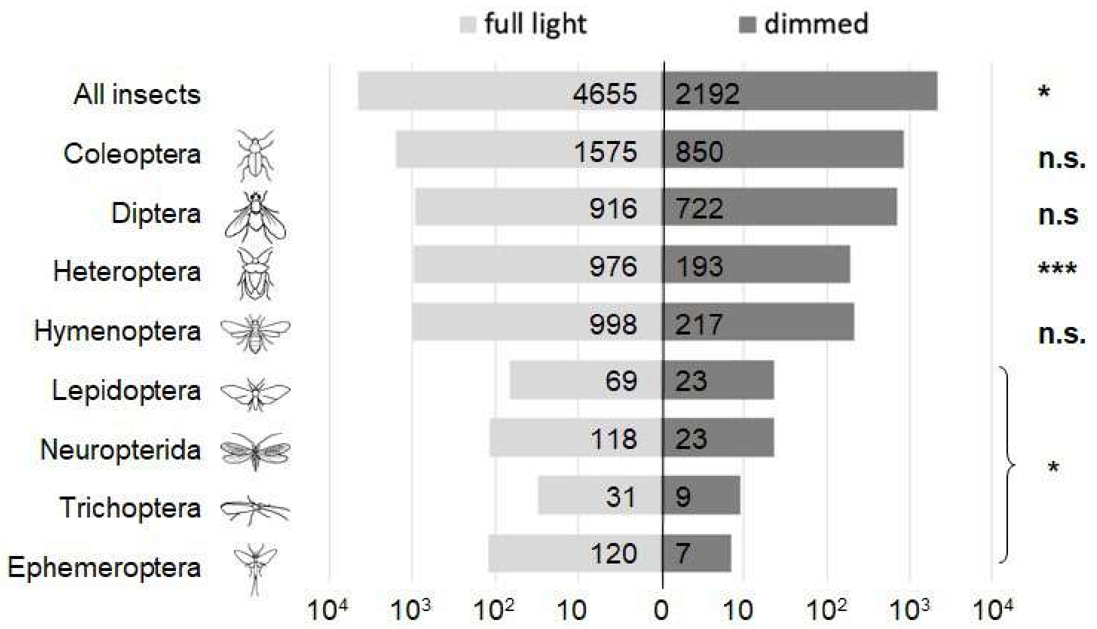


Figure 9. Number of insects caught in a trap – total and per group – according to two different lighting regimes, full light versus dimmed. Overall there was a significant difference, with more than double the number of insects caught when full light was used versus dimmed lighting. Source: Bolliger *et al.*, 2020 in Basic and Applied Ecology.

Consequently, the recommended best-practice precautionary measures for photo-sensitive species are to switch off lighting or implement dimming and/or part-night schedules starting as early as possible. Further research is needed to fine tune these approaches so that they work more effectively and without affecting other functions of lighting (Jägerbrand and Bouroussis, 2021b).

2.2.5. Adaptive lighting: Smart, intelligent and nano approaches

Intelligent lighting has been proposed as part of smart energy and city concepts. This consists of dynamic lighting management backed up by IT tools that can adjust the brightness of lamps independently using data from vehicles and/or walkers in the region.

It can be applied to achieve solutions to multiple problems such as improving viewing experience, preventing visual disturbances, lowering energy consumption and resisting impacts of light pollution (Nguyen and Gupta, 2022). Central to this are sensors that can detect reduced light intensity (light-dependent resistors, LDR) and passive infrared (PIR) motion detectors that can detect the location of objects.

Modern technology offers several solutions for controlling the switching off and dimming of lighting installations. Luminaires can be dimmed automatically via scheduled profiles or using inputs from field sensors. Motion, presence, traffic and other sensors can also provide an additional level of smartness to help adapt lighting levels according to variable conditions. In LED luminaires, drivers can also be pre-programmed to follow a specific profile throughout the year without adding significant costs to the equipment itself.

Manufacturers also now produce solutions that allow lighting to be linked to customer demands through the Internet of Things (IoT), which uses the Internet to link physical objects with gadgets, such as household appliances and industrial machinery. When equipped with sensors and communication networks these gadgets can provide important data for individual services and monitoring. Research has shown the benefits of IoT systems to reduce light pollution through a real-time pollution surveillance network (Nguyen and Gupta, 2022). Looking to the future, relevant innovations and technologies that are currently in development, for example autonomous vehicles, could incorporate night-time lighting into their design at the early stages (see box 4).

In the USA, approximately 30% of outdoor lighting is considered to be "wasted," estimated to cost upwards of 7 billion US dollars per year. Furthermore, eliminating this excess lighting could have the same reduction in CO_2 emissions as removing ~ 9.5 million cars from the road.

Source: Gallaway, *et al.*, 2010

An estimate of the excess and wasted night-time lighting in the European Union puts the costs at over 5 billion euros per year

Source: Morgan-Taylor, 2014.

Box 4: Autonomous vehicles and light pollution (Stone, Santoni de Sio and Vermaas, 2020)

Autonomous vehicles are currently still a technology in development. The design of both the vehicles and the surrounding infrastructure are open-ended. Researchers have proposed that night-time lighting should be a priority consideration for autonomous vehicles during their development phase, and that if designed correctly they could enable a reduction in light pollution and a better balance of lighting and darkness. For example, the AI system of self-driving cars could be designed to incorporate controls to quickly and efficiently adjust the amount of light needed from headlights, altering it dynamically depending on the level of light needed. If all cars were able to apply this technology, it could result in significantly reduced light emissions (Eliot, 2022).

By taking a design for values approach, considerations around dark skies and ALAN reduction can be incorporated into this technology during its development phase. Lighting strategies for vehicles could be replaced with alternative technologies that bring some darkness back into landscapes. Alongside the possibility of extra smart lighting within a new AI technology, there are multiple ways in which driverless cars can be implemented that could aim to minimise ALAN. For example, two hypothetical scenarios explored by Stone, *et al.* (2020) are one in which automated cars drop their passengers off and then find parking in unlit lots, and another in which highways no longer require lighting except for emergencies and at exit ramps. Both of these scenarios could reduce ALAN but would require behavioural change and development of trust in these new technologies and their approaches (Brandon, 2019).

The use of IoT and smart systems enables production of large monitoring datasets. Working with these AI techniques have broad potential in the lighting industry to improve the illumination in the buildings, reduce energy usage and give light the same quality as sunshine through machine learning approaches.

Nanomaterials are also opening up new possibilities. At the nanoscale, materials can become better conductors for heat, or reflect light, whilst others change colour or become stronger. Working at a nanoscale, researchers have used flexible carbon-based sheets to improve the luminosity and efficacy of LEDs, developing new forms of lighting known as organic LEDs. Semiconductors made from nano-material phosphorus are being used to make LEDs that convert blue light into a warmer shade of white – this is done by producing a false sensation of brightness from the use of green light, creating LEDs that are not so dominated by blue wavelengths (Nguyen and Gupta, 2022)

2.3. Thresholds of artificial light to eliminate environmental harm

In order to mitigate the impacts of ALAN on the environment for all types of locations or species, it is useful to establish a threshold on a type of light measurement, that reduces or eliminates any environmental harm. Once this threshold has been identified, often based on research insight into the level of 'toxicity' from light that can be tolerated, then designers and decision-makers should consider this as an upper limit on the amount of artificial light. Thresholds can then be used to set up zones where these limits cannot be breached (Commonwealth of Australia, 2020).

Thresholds are used to manage all forms of pollution, and most well-known pollutants have been studied extensively for many decades to establish their toxicity, and dose-effect responses on organisms, humans and the environment.

Such evidence-based knowledge is crucial to establish threshold values, but in lighting research there is presently a lack of high-quality, controlled evidence-based research on dose-effect responses (Jägerbrand, 2022; Jägerbrand and Spoelstra 2023). There are a few controlled studies on individual species that incorporate more than one light level in their experiments, for example a recent study on the greater wax moth (*Galleria mellonella* L.) to 14 different light intensities (Jägerbrand, A. *et al.*, 2023).

Collaborations between researchers of ALAN's environmental impacts and lighting designers should be fostered to identify relevant issues that guide future research. Supporting evidence-based lighting design approaches and technological solutions, including light sources, lighting controls, luminaire design and appropriate measurement methods will enable the identification of thresholds and application of appropriate mitigation to benefit environmental health (Zielinska-Dabkowska *et al.*, 2023).

Thresholds differ according to the species, the variable that defines the threshold and the function or behaviour that is disrupted so their identification may not always be practical. For example, a study on the impact of light pollution from the Bonn post tower showed that even faint, but exposed light sources, attract and disorientate migratory birds, concluding that it was not possible to define an intensity level that was low enough not to produce this effect (Korner, von Maravic and Haupt, 2022).

As migration is not a constant activity, this finding suggests that the best approach to reduce negative impacts on migratory birds may be to switch off lights at those times when birds are migrating. A novel approach to this is to forecast or predict the numbers of migratory birds in a specific city from a range of ecological variables, and on those days when the levels are high to implement 'Lights out Action Alerts'.

The Colorado State University AeroEco Lab has created alert maps for the US states and cities of relative migration intensity. These maps have four levels: no alert, low, medium, and high. A high alert is a night that will see a large amount of migration activity and these events account for only 10% of the nights in a season but account for 51% of the total seasonal movement[3]. A similar approach was taken by 'World Migratory Bird Day 2022'[4] which adopted the theme of "Dim the Lights for Birds at Night" to raise awareness of this as an approach in this area.

The debate around thresholds and measures becomes more complex when considered at the regional or global scale using larger datasets and modelling techniques. European research has modelled changes of European light emissions using satellite data (Widmer *et al.*, 2022) by considering two thresholds of radiance: 2 nW/cm^2sr, at which at least a low ecological impact can be expected, and of 0.5 $nW/cm^2/sr$, which is the lowest light level of light emissions that can be measured by satellite monitoring. However, 0.5 $nW/cm^2/sr$ is the natural luminance of the night sky without artificial light, and not the generally accepted threshold for a truly dark sky. However, this satellite data only models light emitted upwards, not light emitted downwards, effecting species below streetlights, for example.

Decreasing light intensity is essential to prevent negative impacts of ALAN on highly photosensitive nocturnal species which are sensitive even to low light levels. Due to the problematic nature of identifying threshold light intensity levels, it may be prudent to keep light levels below lower moonlight levels whenever possible ranging from 0.05 to 0.1lux (Jägerbrand and Spoelstra 2023).

A different, but conceptually similar approach to light thresholds, is to consider optimal levels for different functions for humans (e.g. to enable visibility for safety, enhancing aesthetics of cultural sites) with a limit placed on the maximum use above this level. The main aim of these is to not use more light than necessary to achieve the function required for human use, and so avoid ecological impacts as far as possible. In the case of the function of improving visibility, these levels are based on human visual capabilities and can vary for different groups, for example older persons (>65 years) will have more difficulty detecting obstacles at very low illuminance values (0.2lux). There are other functions to be considered, such as improving energy efficiency, so that the use of illumination levels for functions can enable the ALAN management to be more tailored to the needs of the community.

3 The Colorado State University AeroEco Lab has created alert maps: https://aeroecolab.com/uslights
4 World migratory bird day 2023, May 13th and October 14th: Water #WMBD2023 | World Migratory Bird Day

Box 5: Units of light – common measurement terms – for further standardised technical details refer to the CIE website[5]

(Source: https://www.lumitex.com/blog/light-measurement#1 and e-ILV | CIE)

Illuminance *is the amount of luminous flux per unit area (or luminous emittance) and is measured in lux where one lux is equal to one lumen per square meter –* ***lm per m²***.

Luminous intensity *is the quantity of light that is emitted in unit time in a definitive direction. It is measured in* ***Candela (cd)*** *which is unit of luminous intensity per unit time per unit solid angle where 1 lumen = 1 candela x steradian (the SI unit of solid angle).*

Luminous Flux *is the amount of energy a light emits over time, which is weighted to the spectral sensitivity of human vision, measured in* ***lumens (lm).***

Luminance *is the intensity of light from a surface per unit area in a given direction measured as* ***cd per m²***.

Radiance *is the radiant flux emitted, reflected, transmitted or received by a given surface, per unit solid angle per unit projected area and is measured in* ***watts per square metre per steradian W/m²/sr***. *Radiance is useful because it indicates how much of the power emitted, reflected, transmitted or received by a surface when looking at that surface from a specified angle of view.*

5 CIE ILV, offers standardised (technical) definitions for light and lighting for lighting professionals and researchers: https://cie.co.at/e-ilv

There are numerous ways to measure and assess light dependent on what you are studying (see box 5). The regulations of different countries vary in how they plan and measure light, the type of lighting installations for which limits are defined, or the allowed area for which light needs to be controlled/managed.

For example, France has included strict metrics in its policy regulating outdoor lighting, where light emissions are measured in illuminance, and three thresholds have been identified depending on the level of urbanity. Whereas in Korea light is measured in luminance, and the areas depend on the number of photo-sensitive species that inhabit the area. Croatia uses a similar zone system to Korea, and combines it with illuminance similar to France (Widmer *et al.*, 2022).

Some countries have implemented recommendations on the colour, or spectral properties of the light sources (referred to as CCT, or colour corrected temperature), e.g. France, below or equal to 3000K for exterior lighting, below or equal 2400K for natural areas and sites for astronomical observations. The recommendation for a lower CCT is based on the assumption that this correlates with a reduced amount of blue light.

Comparison of correlated colour temperature (CCT) of five lamps (indoor compact fluorescent light bulbs). From left (warmer yellow) to right (cooler blue): 2700K, 3500K, 4100K, 5500K, 6500KCFL. The warmer yellow lower CCT light, is suggested for exterior lighting due to the lower amount of blue light – known to be harmful to many nocturnal species. Source: User: Splarka, Public domain, via Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Color_temperature_comparison_of_5_CFLs.jpg

2.3.1. Lighting measurements and assessment

Appropriate instrumentation and methods are needed to make the initial assessment of where ALAN needs to be managed, to establish the thresholds to manage it and to monitor the effectiveness of these initiatives. These measurements do not work in isolation with developments requiring input from lighting designers and contextual information regarding the local habitat and any light-sensitive species present from ecological surveys.

When new outdoor lighting installations are being established, light levels should be measured during the construction, operation and maintenance periods. This enables designers to adjust the lighting design, to meet design requirements whilst also identifying any obtrusive lights for removal or mitigation. Monitoring the variation of sky glow in the long term is also important, to assess the increase or the restoration of the brightness level towards the set target (Jägerbrand and Bouroussis, 2021a).

Currently there are many possible ways to measure light and its impact on the environment and there is no universally accepted metric or approach to measurement. Due to the variety of species that may be affected by artificial light the task of measurement is challenging and needs to consider their light exposure, location, field of view and spectral sensitivity. Measurements in the field are typically performed at night or at twilight, under various weather conditions, and can be done at a particular time, multiple sets of times or long-term monitoring.

Measuring ecological light pollution at smaller scales on the ground requires different measurement techniques, depending on the light source and the species or ecosystem of concern. The measurement device chosen needs to account for the specific animal's eyes, and the sensitivity of the measurement device. Light traps can be used to observe ground-based wildlife, whereas drones might be used to simulate the positioning of flying animals, to gain for example, a migratory bird's eye perspective of ALAN (Kocifaj, Wallner and Barentine, 2023).

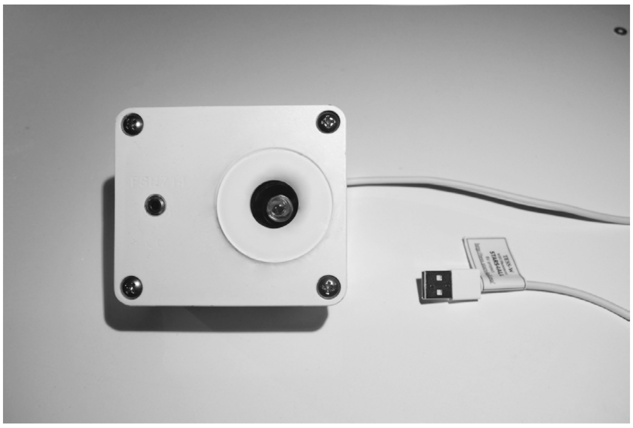
The dominant quality of light that is measured is horizontal illuminance. This means that the most used instrument is a hand-held illuminance meter or luxmeter that measures the amount of light that falls on an area. These meters are designed to match the human's eye spectral sensitivity, which limits their applicability for species with very different sensitivities (Jägerbrand and Bouroussis, 2021b). Although it is important to strive for more standardised light measurement to better understand the impacts of ALAN, it must also be remembered that due to complexity of ecosystems and the environment, ecological impacts cannot be anticipated or assessed by the measurement of light alone. The positioning of light, how it sits within the immediate environment and other indirect effects it may have such as attracting predators, must be considered.

Guidelines for documenting and reporting light pollution of ecological and environmental relevance encompass a comprehensive approach that involves assessing both the ambient light pollution in the environment and the specific light exposure experienced by the organism that is being studied. To document light pollution accurately, it is essential to measure illuminance and/or luminance levels at multiple locations in various directions, while also considering spectral distribution. Additionally, providing a detailed description of light in three dimensions enhances the repeatability of the assessment. When evaluating the light exposure of species, it becomes crucial to measure light where individual organisms perceive it and in relevant directions. Furthermore, it is advisable to express these measurements in units of biological significance, such as radiance, to ensure that the assessment aligns with the biological relevance for living organisms.

Box 6: STARS4ALL project (Source: https://stars4all.eu/)

The European Union/European Commission supported 'STARS4ALL' – a project to encourage investigations and collaborative infrastructure in Europe for fostering dark skies –as part of the Horizon 2020 Programme between 2016 and 2018. Among the breakthroughs was the Dark Sky Meter app, that monitors sky luminance and exchanges data with researchers all over the world. Another technology developed was the TESS-W photometer, capable of measuring and providing a continual assessment of the night sky illumination – for light pollution investigations.

The STARS4ALL Foundation Is a hub for the results of this project, sharing data among the TESS photometer network and providing open data form this to the public.



TESS-W

Tess W photometer, a device which can be used to measure night sky illumination. Source: https://tess.stars4all.eu/faqs/. Photo of the left by Lucía García and photo of the right by Alexis Mancilla

Remote sensing is also used, mainly wideband radiance and red/green/blue maps from the International Space Station. This provides valuable data on spatial distribution of illuminated areas and an estimation of illuminance levels, but the information concerns only direct or reflected upward radiance, without an indication of the 3-D propagation of light.

Skyglow measurement tends to use two dominant techniques – the Sky Quality Meter or the commercial RGB imaging cameras, but there is no standardisation in their units.

One of the research priorities in this field is to establish a more standardised way to describe ALAN, define thresholds and monitor measures to reduce its negative impact (see Chapter 3 for more exploration).

2.4. Management interventions and best practice for mitigating ALAN impacts on the environment

Alongside technical solutions around light, and light installations, there are a range of management interventions that work at a systemic level to address the impact of ALAN. These implement the technical approaches alone, or in combination, in a way that best addresses the specific challenges posed by ALAN in a region, or for a species or ecosystem. These can include integrated measures, outlined in lighting masterplans to protect against ALAN in local planning aiding efficient infrastructure design. ALAN focussed management interventions can also seek to define geographical lighting zones, or identify species and ecosystems that require specific protection. These emerging mitigation interventions often dovetail into existing environmental management interventions, aimed at climate change, biodiversity degradation and carbon reduction.

2.4.1. Lighting masterplan and efficient design

A lighting masterplan is a strategic document that acts as a framework for subsequent design decisions on public lighting, particularly in cities. It serves a number of purposes in terms of defining the aesthetic and functional lighting criteria, and increasing the efficiency and quality of city lighting, with the ultimate goal of securing a comfortable, and well-structured lit environment.

The lighting masterplan should be integrated into urban development sustainability studies, and include the minimisation of the potential negative impacts on the environment (Jägerbrand and Bouroussis, 2021a). This masterplan should include details of what is needed to implement efficient lighting design techniques, including the appropriate equipment, optics, lenses, and other relevant technologies. The masterplan should also work at the macro level, defining those areas that need more protection from ALAN with environmental lighting zones (see section 2.4.2) and areas that need more visibility for safety (Zielinska-Dabkowska, 2016).,

The aim of the masterplan is to serve the lighting needs in an optimised way, by creating a holistic picture of the area that details the technical solutions at the local level (Jägerbrand and Bouroussis, 2021a).

Box 7: Road lighting planning and decision-making for government roads in Sweden

The Swedish Transport Administration has established a decision-making process to assess the need for comprehensive environmental analysis, and the implementation of light pollution mitigation measures along roads under its jurisdiction.

Generally, road lighting or decorative lighting should be avoided outside urban areas, except for road lighting in complex situations.

Some fundamental requirements, including those to be introduced in 2024, encompass:

- Luminaires must have flat glass;
- The maximum correlated colour temperature should not exceed 3000K (i.e. yellow, warm white light);
- Criteria for reducing light pollution via upward light ratio (ULR);
- Requirements for luminaire efficiency (lm/W);
- Limits on over-illuminated roads, allowing a maximum of 20% excess light above minimum requirements;
- Standard night-time light reductions for all luminaires, operating at 60% and 40% of full effect during night-time;
- Mandates for presence-controlled pedestrian and bicycle paths, when applicable;
- Mandatory deactivation of all decorative lighting at 10pm;
- No lighting permitted at wildlife passages, with exceptions made for multi-use overpasses and underpasses.

Rather than universally applying the precautionary principle in all environments, the Swedish Transport Administration has devised a lighting planning tool. When deciding to construct a new road or renovating an existing one, designers are required to employ this tool. The tool incorporates Geographic Information System (GIS) data, highlighting areas of ecological significance. The GIS data is sourced from various databases, and specific criteria are established to determine the ecological importance of an area.

In cases where planned lighting intersects with a designated nature value area (within a distance of ≤ 50 m from the road*), this serves as an indicator that standard lighting should potentially be avoided. This situation necessitates a more comprehensive analysis, to be conducted by an ecologically competent individual from the Swedish Transport Administration.

Following the analysis, a decision can be reached to determine whether the lighting has an impact on the local fauna. If such an impact is identified, additional measures and actions are required.

Additional actions to be taken in the presence of a nature value area:

- implementing night time curfews during specific times and seasons as needed;
- opting for correlated colour temperatures below 3000K;
- minimizing spill light and employing shielding techniques;
- installing physical barrier such as planks or lightproof fabric;
- exploring measures to reduce speed or other solutions to enhance traffic safety, thereby reducing the reliance on road lighting.

Below is an image from the lighting planning tool displaying a planned road intersecting a nature value area, specifically a swamp forest (Figure 10).

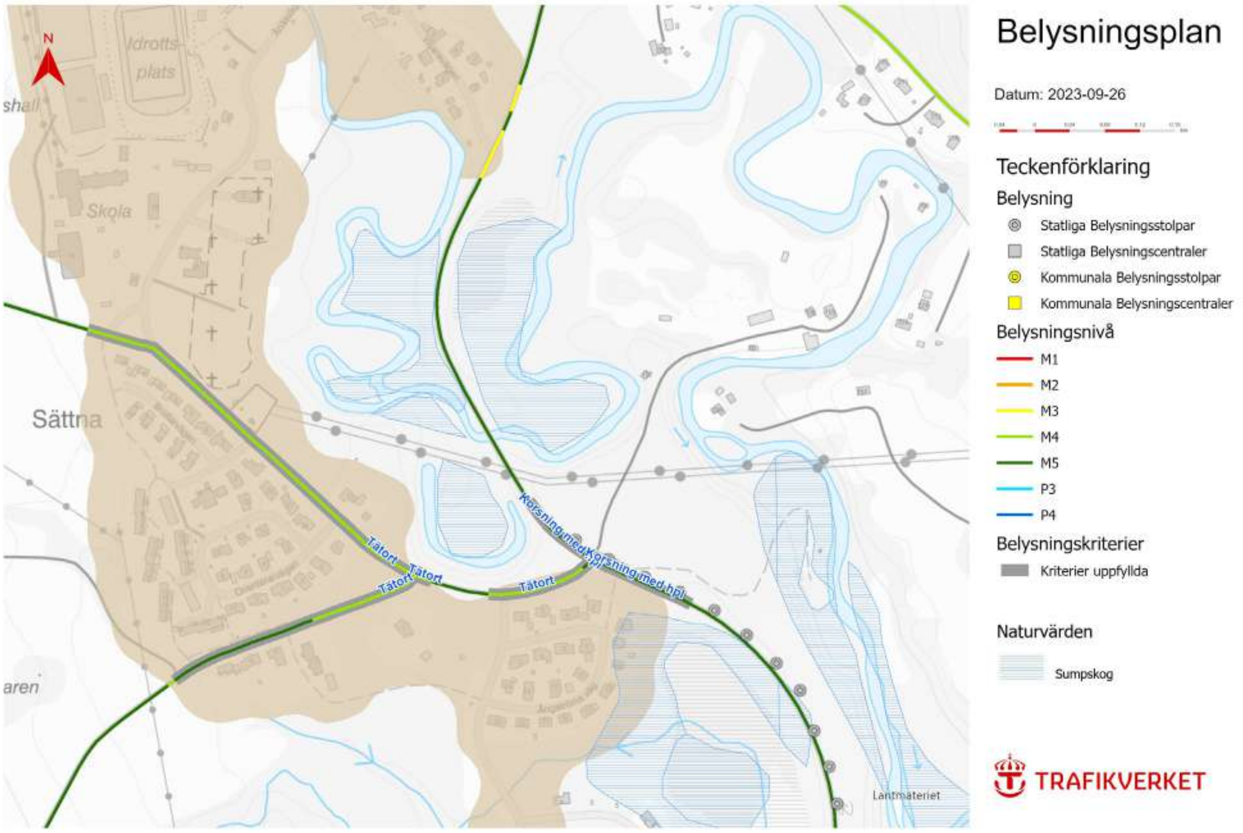


Figure 10. A picture depicting the light planning tool showing a planned road intersecting a nature value area. Green lines enclosed in grey represent roads with a requirement for lighting. The blue dashed area represents swamp forest, designated as a nature value area requiring special consideration in road lighting planning. © Petter Hafdell, using GIS software

2.4.2. Environmental lighting zones

The use of specified zones within which there is a maximum admissible level of a pollutant, is a well-recognised method to limit environmental harm. This has been adopted within the field of light pollution where types of zones are described according to the desired level of lighting, and then caps on light emissions are determined for these zone types. The aim of these environmental lighting zones is to help stop further deterioration of areas that need protection.

Not only can zones enable protection of specific areas, but it can also classify larger land areas into zones of different character. This macroscale overview can help inform which areas should be prioritised in strategic work with natural environments, or to gain insight into which natural environments should be protected from future light pollution (Jägerbrand and Bouroussis, 2021b).

There are several benefits to dividing an area into zones. Firstly, it is easier to work at the landscape level when incorporating nature conservation into a planning process. Also, the use of environmental lighting zones in the urban planning process, will quickly identify lighting needs for a range of areas and functions (Jägerbrand and Bouroussis, 2021b).

A number of lighting zone classification schemes have been proposed, with the most well-known including: the European based CIE (Commission Internationale de l'Eclairage, 2017), the North American based IESNA-IDA (International Dark-Sky Association and Illuminating Engineering Society, 2011), and the RASC dark sky protection program (Royal Astronomical Society of Canada, 2018).

The CIE environmental lighting zones are based on the ambient brightness of the environment and are divided into zones from E0 to E4, ranging from intrinsically dark to high district brightness (see table 3). The IESNA-IDA Model Lighting Ordinance uses lighting zones (LZ-0 to LZ-4) and recommends lighting design and use within the lighting zones.

Table 3: Environmental lighting zones and examples of areas, please note sky quality meter (SQM) depicts luminance – or the light given off by a surface – in magnitudes per square arc second. Source: adapted from Jägerbrand and Bouroussis, 2021b; lighting zones source:CIE 150:2017; SQM values souce: Institute of Lighting Professionals, 2021.

Zone	Lighting Environment	Surrounding area	Examples
E0	Intrinsically Dark (SQM 20.5+)	Protected	UNESCO Starlight reserves, IDA Dark sky places. Astronomical observable dark skies.
E1	Dark (SQM 20-20.5)	Natural	Relatively uninhabited rural areas. Areas of outstanding natural beauty. IDA buffer zones.
E2	Low district brightness (SQM ~15-20)	Rural	Sparsely inhabited rural areas, villages, or relatively dark outer suburban areas.
E3	Medium district brightness	Suburban	Well inhabited rural and urban settlements, small town centres or urban locations.
E4	High district brightness	Urban	City, and town centres with high levels of night-time activities.

In the case of skyglow, which impacts large areas, and can extend far from the source itself, limitation measures can extend beyond the country or regional limits. An intergovernmental understanding and common actions might be useful in long-term strategies for skyglow limitation, (Institution of Lighting Professionals, 2021). Currently to prevent skyglow, the Institution of Lighting Professionals (ILP) recommends maximum values for levels of light directed upwards into the sky (ULR or ULOR) for the different CIE zones, and in the case of ULOR it also categorises it according to the type of installation.

Based on the recommendations of the ILP, an area to be lit lying close to the boundary of two zones should be subjected to the limitation standard applicable to the most rigorous zone (Institution of Lighting Professionals, 2021).

Zoning approaches to light pollution can also be embedded in existing networks of projected areas. For example, the EU already has a network of protected areas in Natura 2000, and the Habitats Directive requires Member States to take the necessary measures to avoid significant disturbance of protected species in these sites, which, where relevant, is applicable to light pollution.

In the context of environmental management in protected natural areas, employing more than five environmental lighting zones can prove advantageous. This approach facilitates the identification of areas characterised by the highest light levels. Using too few zones may result in a situation where numerous areas fall within each of the three pertinent environmental lighting zones (E0 - E2) (Jägerbrand, Brutemark, and Andersson, 2023).

2.4.3. Definition of ALAN-free areas and ecosystems

ALAN-free areas should be defined to enable the implementation of the strictest limits on the spectrum, shielding and total amount of illumination, even inside cities. Examples of areas that should be ALAN-free are environmentally sensitive areas or ecosystems, intrinsically dark areas, nature reserves and habitats with endangered species in need of protection (Jägerbrand and Bouroussis, 2021a). For example, the Czech Republic has identified four regions with pristine night skies - Bystřická, Manětínská, Jizerská and Beskydská - that need to be protected (Widmer *et al.*, 2022).

The goal of ALAN-free areas is to retain or restore the night sky luminance, and the ambient lighting to natural levels. Even if this might not be possible everywhere, it is important to protect the environment from further deterioration, and to implement adaptation measures to stop the direct impacts of ALAN. The zoning system defined by the CIE (2017) for the zones E0 and E1 can initially be adopted for these areas. Protected or sensitive areas may require extra protection, including connectiveness of dark zones between areas, and buffer zones around the protected area, with restrictions on outdoor lighting, if there is a risk of ecological impact from light (Jägerbrand and Bouroussis, 2021a; Institution of Lighting Professionals, 2021).

Aurora Borealis in Sutherland, UK. The dark skies of North West Scotland enable the aurora borealis to be clearly seen.
Source: Andrew Tryon, CC BY-SA 2.0 <https://creativecommons.org/licenses/by-sa/2.0>, via Wikimedia Commons

Box 8: The International Dark-Sky Places (IDSP) program.

This was established by the IDA in 2001 to recognize and protect areas with extraordinary night-time features for future generations, as well as encourage awareness of the issues involved. It encourages cities, parks, and conserved places all across the world to preserve and protect dark locations by promoting smart lighting policy, and public awareness. It does not specifically aim to protect species from the impact of ALAN. Candidates must go through a rigorous application process that includes demonstrating strong community support for dark sky protection. The program **offers five certification categories**. As of January 2023, there are 201 certified Dark Sky Places in the world. These include 115 Parks, 38 Communities, 20 Reserves, 16 Sanctuaries, 6 Urban Night Sky Places, and 6 Dark Sky Friendly Developments of Distinction.

https://www.darksky.org/our-work/conservation/idsp/

Box 9: Lighting Protocol for Dark Sky Parks

International guidance on artificial light at night mitigation measures, for within a designated 'Dark Sky Park', have been developed in association with the International Dark-Sky Association. Based on the guidance, the measures apply to all property and structures within a dark sky preserve and are designed to limit glare and adverse ecological impacts of artificial lighting throughout dark sky parks (DSP) – providing technical specifications for acceptable illumination levels for navigating safely within the park. Suggestions are also made regarding lighting policies that could be applied to urban areas beyond the park boundaries, to protect the DSP from deterioration from nearby light pollution (RASC and Dick, 2020).

- **Signage should not use active lighting**. Instead, retro reflective materials should be used with signs mounted less than 1m off the ground so people using flashlights after dark can see them.
- **Only full cut-off (FCO) fixtures should be used**. Existing lights should be shielded or replaced with FCO fixtures to prevent light from shining beyond the immediate area that requires illumination.
- **Illumination level produced by fixtures should be as low as is practical**. For vehicles this is suggested as 3 lux, or 0.3fc for large parking areas with high traffic density, where speed limits are in effect. Whereas with pedestrians only 1 lux or 0.1fc is needed. Lower light wattages can be used as it is assumed that pedestrians will have flashlights and cars will have headlights. These lights serve as markers, phosphorescent markers can also be used.
- **Structures and barriers (such as trees or shrubs) should be used to confine illumination to the immediate area**.
- **All light sources should be turned off within 2-hours of sunset**, automatic timers should be used to avoid the need for staff to turn off lights.
- **Indoor lighting should be prevented from shining through exterior windows** by using curtains within 30 minutes of sunset – if indoor lighting is still necessary.
- **All light fixtures should emit a minimum of UV and blue light, with white lights not used at all**. Sodium lamps, incandescent lamps and amber LEDs may be used, but UV lights should not be used at all as they attract flying insects.

2.4.4. Dark infrastructure

Green and blue infrastructure policies have been developed globally based on the concept of ecological networks, recognising that within fragmented landscapes a set of suitable interconnected habitats need to be preserved to support biodiversity, and deliver a wide range of ecosystem services.

Research has shown that ALAN is present in all of the major habitat categories, which includes terrestrial, aerial, aquatic, wetlands and marine areas (Sordello *et al.*, 2022), but currently nature conservation policies around blue and green infrastructure have limited consideration of the adverse effects of ALAN. A good example of where it has been considered is the resolution adopted by the International Convention on the Conservation of Migratory Species of Wild Animals (CMS), which recognises that ALAN is an emerging issue for wildlife. Recently the CMS launched a new online guide to help cities around the world reduce the impacts of light pollution on wildlife (Nunny, 2021). The guide offers facts, case studies, information resources, and a checklist for cities to reduce the harmful effects of artificial lighting on wild animals (Nunny, 2021; Cities with nature, 2023)[6].

Researchers and planners have proposed that darkness quality should be integrated within blue and green infrastructure to implement a dark infrastructure. The result would be an ecological network – formed by cores connected by corridors – in which darkness is an additional quality that needs to be managed, with the goal of preserving and restoring an ecological network with a level of darkness that is as natural as possible, and that enables maintenance of biodiversity.

To use this framework dark infrastructure must be identified, preserved and restored at different landscape levels, to enable ecological continuities where the night and its rhythms remain as natural as possible. Researchers have proposed a four-step process for this which must be implemented across different administrative and ecological levels, bringing together top down planning schemes and bottom up insights from local inhabitants (Sordello *et al.*, 2022). The four steps are outlined in figure 10.

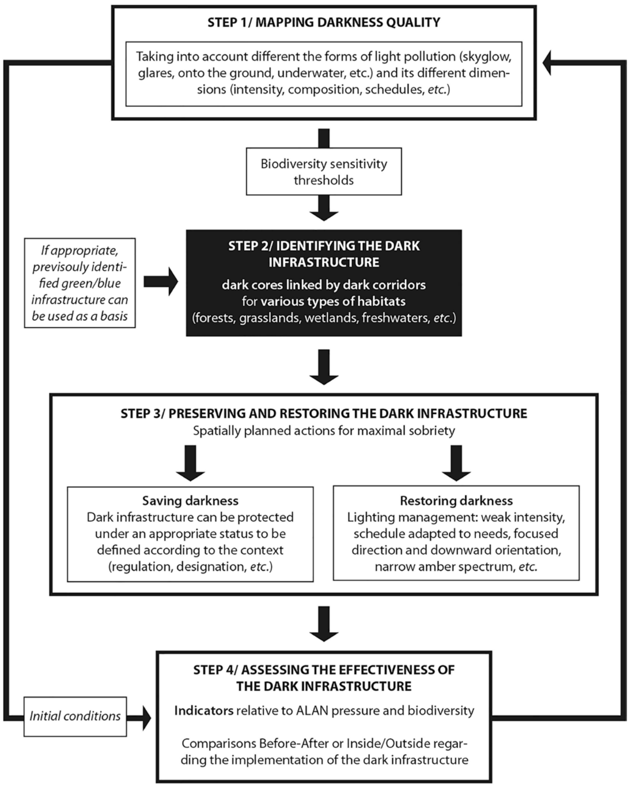


Figure 11: Four steps to implement dark infrastructure (Sordello *et al.*, 2022). Source: © 2022 Romain Sordello, Samuel Busson, Jérémie H. Cornuau, Philippe Deverchère, Baptiste Faure, Adrien Guetté, Franz Hölker, Christian Kerbiriou, Thierry Lengagne, Isabelle Le Viol, Travis Longcore, Pascal Moeschler, Jessica Ranzoni, Nicolas Ray, Yorick Reyjol *et al.* Published with license by Elsevier B.V. Available via CC BY 4.0

- The first step of **mapping** involves depicting the spatial distribution of darkness quality. It can use a range of indicators including satellite images, field data, light measurements and aerial photography that gives a bird's eye view of the landscape. The pros and cons of each data source depend on the scale: national, regional, municipal, neighbourhood.
- The second step of **identification** signposts the use of thresholds to limit ALAN and enable dark infrastructure. Once the cut-off threshold is chosen there are two options for implementation: either accounting for ALAN in existing green or blue infrastructure, or integrating ALAN in the design of new green or blue infrastructure (see box 10 for examples).

6 'Curb light pollution in your city' available at: https://citieswithnature.org/curb-light-pollution-in-your-city/

- The third step of **preservation and restoration** includes the technical and management approaches that have been covered in this brief, and highlights that light pollution must be reduced without losing comfort and function for human activities – a concept referred to as 'sobriety'[7].
- Finally, in its fourth step the framework outlines the importance of **assessing effectiveness of dark infrastructure**, and monitoring this to provide feedback into mapping of darkness quality. Monitoring should include indicators of light pollution, and those related to biodiversity, such as species richness and abundance – as well as measures of functional and structural connectivity (see section 2.4.6).

Box 10: Examples of dark infrastructure implemented in Europe (Sordello *et al.*, 2022)

After a cut-off threshold is chosen for what constitutes a dark infrastructure, Sordello *et al.* (2022) suggest two approaches to implement dark infrastructure.

- **Taking an existing green/blue infrastructure and considering ALAN within its boundaries:** In a region in the Geneva basin in Switzerland, dark infrastructure has been created by intersecting low ALAN areas with the existing green infrastructure. This was done by an automated method that extracted light sources from high-resolution aerial photography taken at night. Using this data, researchers modelled the visibility of these light sources from any location within 1 km radius to give an estimate of the level of ALAN (Ranzoni *et al.*, 2019). Although the analysis does not consider data from direct lighting measurements, it allows for a first large-scale mapping of the night-time continuum and highlights the areas benefiting from very low light pollution. The areas with low levels that were intersected with green infrastructure were considered to be dark infrastructure, requiring protection of darkness quality.

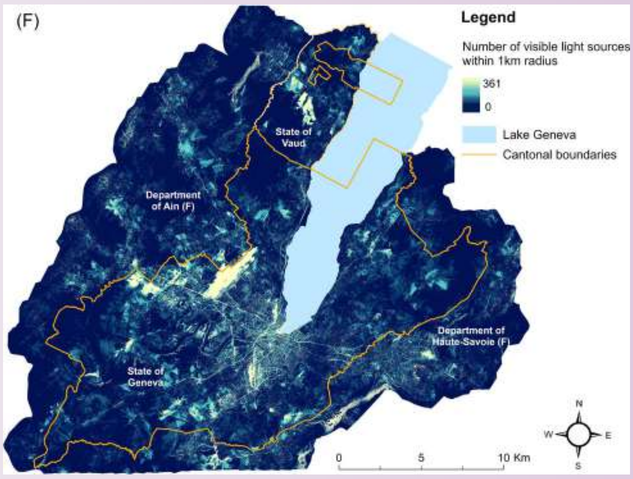


Figure 12: Raster map showing visibility of light sources of the Geneva basin. Source: Sordello *et al.*, 2022.Published with license by Elsevier B.V. Available via CC BY 4.0

- **Integrating ALAN in the design of a new green or blue infrastructure from the outset:** In Douai, France, a dark infrastructure was identified from scratch – this was done by establishing a bat activity map for different groups of bats, using 80 bat sound recorders during two nights. The map set out a hierarchy of activity levels to identify the areas of highest bat activity, which then formed the dark infrastructure. It was not translated into cores and corridors but into a set of dark ecological continuities. The three shades of blue on the map are related to the intensity of bat activity, where the darkest blue has the most intense bat activity and is a priority for further actions of preservation and restoration.

7 Aim for sobriety with regard to lighting, by lighting only when strictly necessary, by questioning the need for lighting in advance and by seeking alternatives as a priority

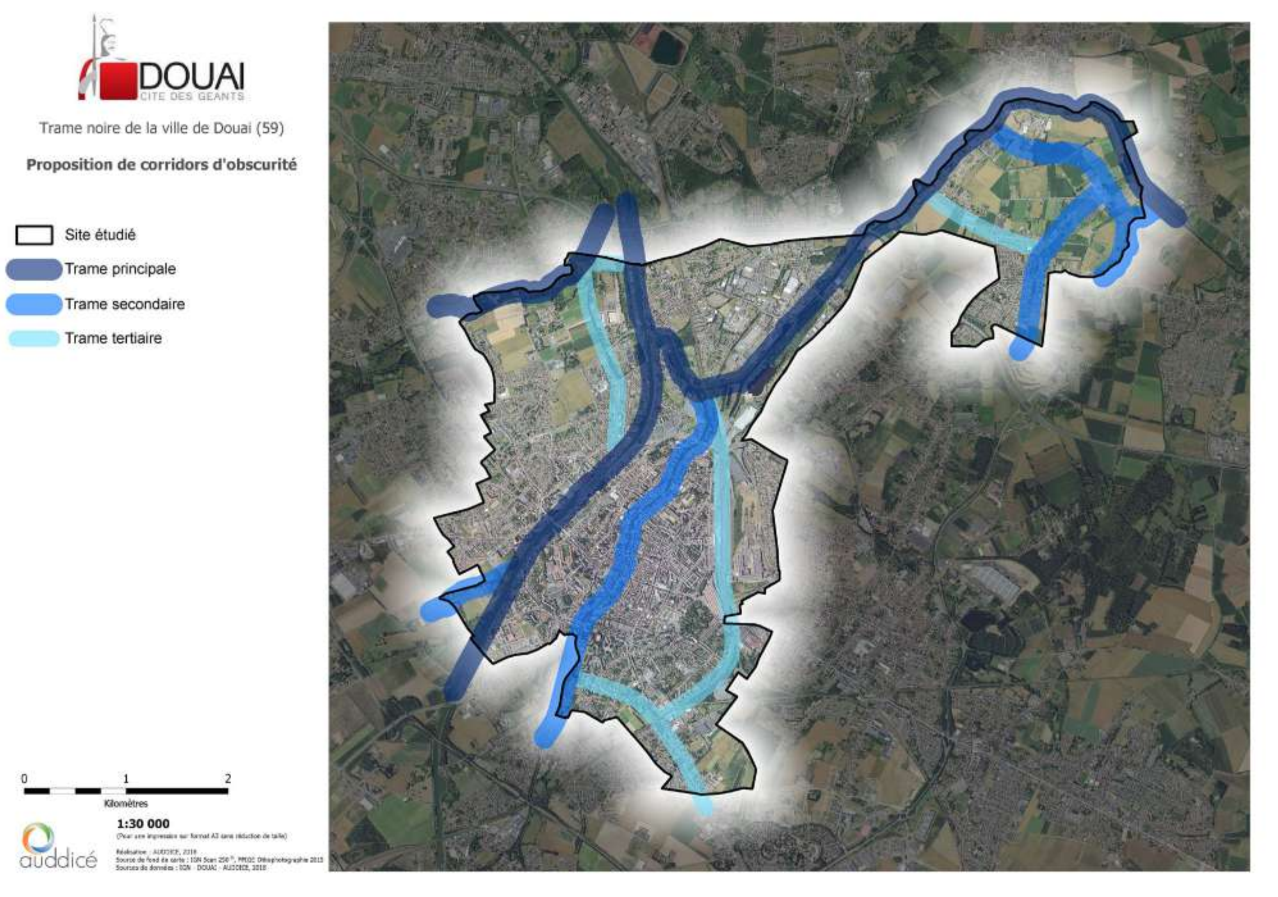


Figure 13: A bat activity map in Douai, France. The three shades of blue are related to intensity of bat activity where least dark blue is low intensity and darkest blue is high intensity. Source: Sordello *et al.*, 2022.

2.4.5. Sustainable development / Multifunctionality of dark infrastructure

To support environmental protection and for ALAN measurement to be accepted long-term, sustainability needs to be integrated into the design, creation and maintenance of outdoor lighting. In general, when mitigating light pollution, a reduction in energy use and ecological impacts will also follow, and often initiatives to improve energy efficiency and user experience can lessen light pollution (Jägerbrand and Bouroussis, 2021a; Stockhammer, Zulka and Schindler, 2022). However, this isn't always the case and there is a need to consider all aspects of sustainability in any lighting decisions. Awareness of light pollution as an environmental problem is relatively new compared to climate change and other forms of pollution, and there may be a need to increase recognition of its impact, and if necessary prioritise its management (Sordello *et al.*, 2022).

The example of traditional LEDs demonstrates how actions to improve energy efficiency and reduce carbon can have negative ALAN consequences. There are already technical developments to overcome the light pollution effects of traditional LEDs (see section 2.2.5), but management also plays an important role, especially in the decisions made around light installations. These must be assessed from a sustainable perspective on social, economic and environmental dimensions and all relevant aspects must be fully considered and assessed through indicators, preferably based on a range of metric units.

For example, a tool based on sustainability indicators, or individually chosen indicators, can be used in mandatory requirements in the procurement process for lighting installations, both for new projects and for the upgrading of old installations – at an EU level (Donatello *et al.*, 2017) (see section 2.2.3 and Box 7).

A good example of sustainable lighting design being integrated into urban design, by local government planners, can be found in the city of Rotterdam in the Netherlands, where all 100,000 light posts are currently fitted with LED fixtures that can be remotely adjusted for light intensity at any time of the night (Jägerbrand and Spoelstra, 2023). This enables responsive lighting, which can be adjusted to lower light levels when needed, such as times of the year when migratory, night flying, light sensitive species might be present.

To enable efficient and sustainable exterior lighting, a researcher has undertaken an examination of the synergies and trade-offs in these two areas. Through applying indicators spanning social, ecological and economic areas, the researcher can then assess where there are interlinkages and therefore the potential for mutual gains. A literature review was conducted, revealing a total of 33 indicators (with 18 in the area of ecology and environment; 5 in the area of economy; and 10 in the area of social sustainability).

The study found most interactions between variables for sustainable development and energy performance (52%), and the majority of these, (71%), were in the ecological and environmental dimension showing that environmental and ecological sustainability can also equate to energy efficiency and savings. The study lays down the foundations of assessing interactions between sustainable development and energy performance, to establish more efficient policies for decision-making processes regarding exterior lighting.

More recently an analysis of lighting masterplans (see section 2.4.1) from 16 Swedish municipalities, identified 28 sustainability indicators, of which, ten were in the dimension of ecology and environment and, 18 were in the social and society dimension of sustainability. The findings showed that there is a need for guidelines and recommendations for working with outdoor lighting from a sustainability perspective, especially in the social dimension, where most of the new indicators were identified.

The multifunctionality of green and blue infrastructure – where these ecological approaches bring multiple environmental, social and economic benefits – has already been highlighted to demonstrate advantages of adopting these initiatives. However, at present there is limited research available to provide an evidence base regarding the multifunctionality and ecosystem services of dark infrastructure which include ecological impacts.

Cory's Shearwater *Calonectris borealis* fledgling picture was taken while researching factors of light pollution-induced mortality in Tenerife, Canary Islands. A critical phase in the life of a nesting-burrow petrel is fledging – young birds leave their nest to fly to sea for the first time, normally at night. Unfortunately, thousands of fledglings are disoriented by artificial lights around the world in archipelagos such as Hawaii, Azores or Canary Islands. Once birds are grounded they are unable to take off again, and susceptible to death by vehicle collisions, starvation, dehydration or predation. Source: Airam Rodríguez (Estación Biológica de Doñana CSIC), CC BY 4.0 <https://creativecommons.org/licenses/by/4.0>, via Wikimedia Commons

Box 11: Case study: Targeted solution to protect marine birds using management and technological changes (Atchoi *et al.*, 2021).

Light pollution on urban coastlines in the Macaronesian archipelagos of the Azores, Madeira and the Canary Islands, have known impacts on seabirds. Negative impacts on seabirds in this region are most notable when juveniles leave their natal colonies for the first time, and are disoriented and attracted by artificial light at night (Rodríguez *et al.*, 2017). Long-term rescue campaigns search for, collect and release fallen juveniles. Alongside there has been an increasing number of actions to prevent or reduce light pollution, mostly centred on the critical fledging periods. To connect these initiatives, the 'LuMinAves' project was designed, to unite efforts across regions, and provide a common platform for development of enhanced mitigation practices.

The project ran from 2016 to 2020. It covered ten petrel species, spanning across the three archipelagos. Mitigation actions pre-dating the project were progressively applied throughout the region. For example, on Madeira, a pilot project integrated sustainable smart lighting into a municipality urban plan. In the Azores the rescue campaign, SOS Cagarro, partnered with private and public entities to turn off public lights in specific areas each year known for higher fallout (e.g., airport, churches and industry buildings). LuMinAves enabled the sharing of actions, procedures and outcomes, allowing direct learning and connectivity between partners.

The project also successfully gathered data via monitoring schemes. Maps depicting the spatial distribution of fallout were created for each island. This knowledge was used to inform the design of light pollution management strategies, and enabled the incentivisation of illumination changes to improve energy efficiency and reduce light pollution. For example, regional electrical companies and local governance associated a certificate of good environmental practices to their urban lighting plans, facilitating the implementation of new measures.

The project ended in December 2020, however, its actions and goals extend beyond its time frame. Partners formed a working group which is working on regional regulatory legislation regarding lighting protocols. Likewise, a sequential INTERREG project will be building upon LuMinAves actions to continue the efforts towards light pollution reduction and research in Macaronesia.

Box 12: Impact of Earth Hour on Urban Light Pollution in Berlin (Jechow, 2019).

The WWF Earth Hour campaign has grown over the years, and in 2018 was celebrated in 188 countries. It calls for voluntarily reduction of electricity consumption for a single hour of one day each year.

In principle the switch-off allows for the study of light pollution and the linkage to electricity consumption, but quantitative analysis is sparse, with only a few studies showing no clear impact.

Researchers have used a novel light measurement method, using differential photometry, with calibrated digital cameras that enable tracking of the switching off and switching back on of the lights of Berlin's iconic Brandenburg Gate, and the buildings of Potsdamer Platz adjacent to the park. This showed measurable light pollution reduction, despite the presence of moonlight.

By using this approach, several places around the world will allow similar studies that can provide insight into strategies to both reduce energy consumption and light pollution.

Connected dark infrastructure projects at national level

Several Dark Infrastructure projects have already been conducted in France as exploratory initiatives by local stakeholders from natural sites (national parks, regional nature parks) and numerous local authorities. France is a pioneer with this nocturnal ecological network initiative and has over 60 locations where activities are taking place to reduce or mitigate ALAN[8] Five French national parks (Cervennes, Pyrenees, Portcros, Mercantour, Reunion) conducted a joint project to map their light pollution and their dark infrastructure and are now implementing their action plans to restore darkness where it is degraded (Sordello, Paquier and Daloz, 2021). Figures 7 and 8 illustrate the work conducted by the Parc national des Pyrénées (PNP – Pyrenees National Park) to model light pollution within the national park and to map its dark infrastructure.

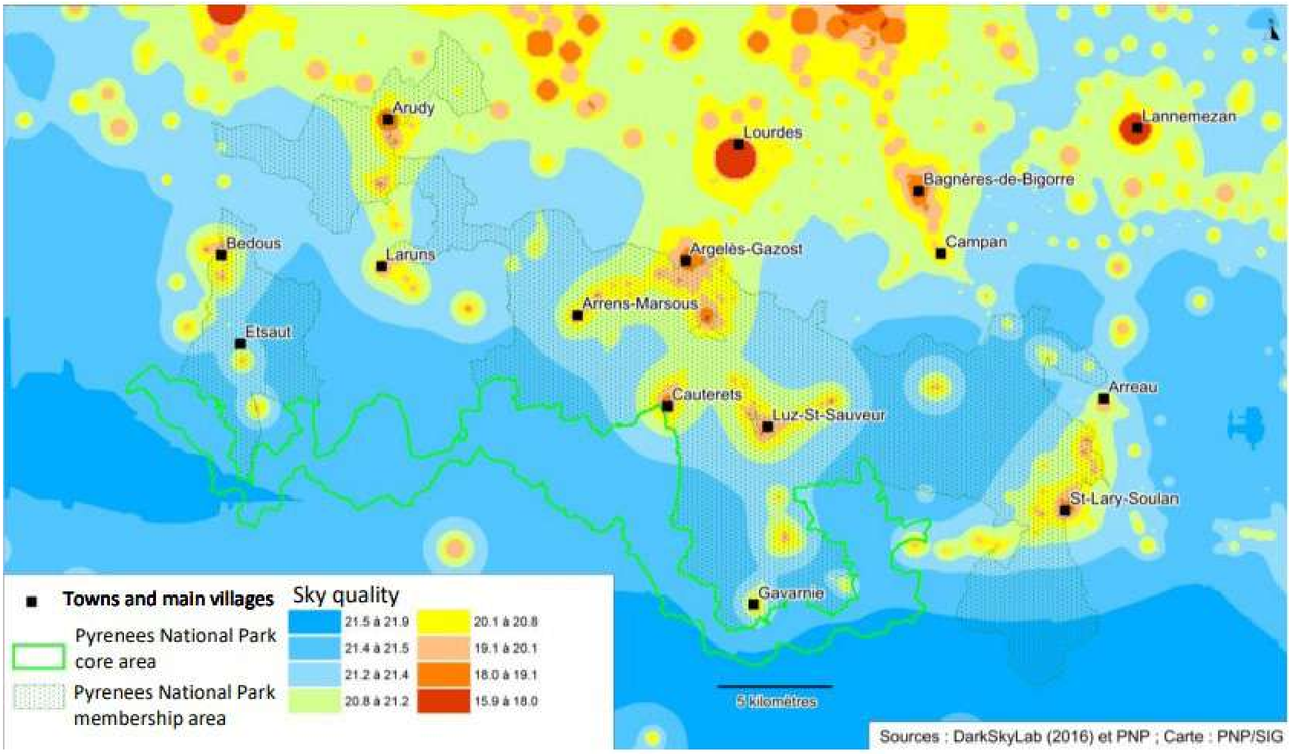


Figure 14: Map of light pollution modelled for the Pyrenees National Park. Source: © 2022, Romain Sordello, Fabien Paquier and Aurélien Daloz, Published with license by Office français de la biodiversité – available and downloaded via Creative Commons licence

8 http://www.trameverteetbleue.fr/tramenoire

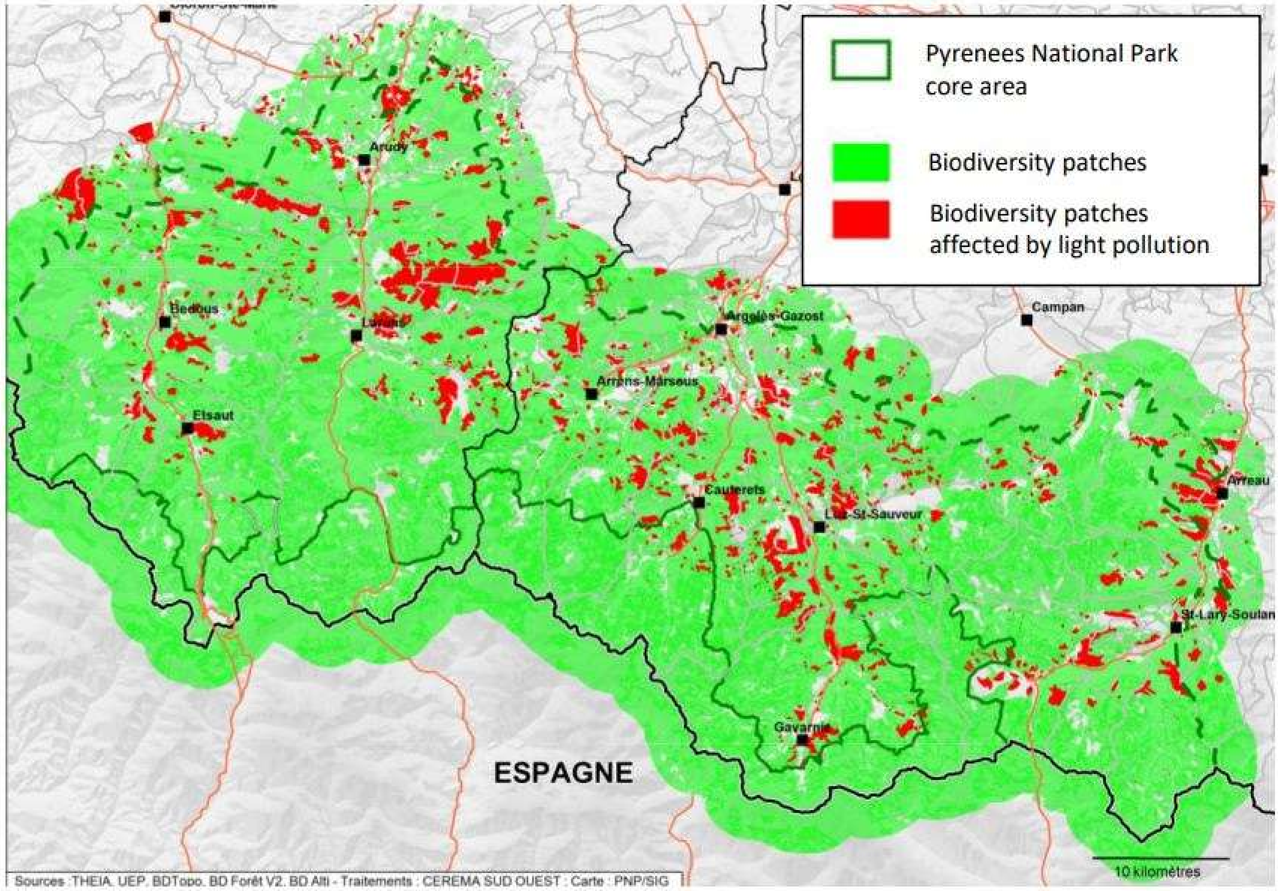


Figure 15: Biodiversity patches affected and unaffected by light pollution. Source: © 2022, Romain Sordello, Fabien Paquier and Aurélien Daloz, Published with license by Office français de la biodiversité - available and downloaded via Creative Commons licence

2.4.6. Cross-cutting approaches focussed on species and ecosystems

Few studies focus on the impact of artificial lighting on species composition, demography or ecosystem function, which are all directly relevant to conservation. Current research provides an estimate of impacts on species' conservation based on their expected sensitivity or vulnerability to light (Jägerbrand and Bouroussis, 2021). There is an agreement about the specific species and groups that are particularly affected by ALAN, but not necessarily about the different ways in which they are impacted, and what can be done to lessen the impact. Some of the generic groups that have been identified as potentially being most sensitive to light are listed in Table 4.

Table 4: Species and groups that may require higher prioritisation due to their increased sensitivity to light, or the risk of negative influence at sensitive periods in their life cycles. Source: Adapted from Jägerbrand and Bouroussis, 2021b.

Species and groups	Potential ecological impacts of artificial light at night (ALAN)
Nocturnal or crepuscular species	ALAN can result in decreased time and area for night-time activities important for survival, which can result in lower fitness and survival rates
Species living in vulnerable habitats	ALAN can have a particularly high impact
Species that migrate or move seasonally	ALAN can result in unwanted impact on migration or seasonal movements, which are vulnerable periods in lifecycles i.e. Monarch butterfly
Species with positive or negative phototaxis	ALAN may cause ecological traps by attracting species with positive phototaxis i.e. moths drawn to a light, resulting in high mortality
Endangered species	ALAN may decrease the species area of activities, for species with negative phototaxis, i.e. some bat species that are repelled by lighting, lowering fitness and survival rates
Species that depend on key ecosystem functions that are impacted by ALAN	ALAN may act as an additional disturbance, or cumulatively with other stressors, resulting in further degradation of habitats and a potential detrimental impact on species

Ecosystem functioning can be affected by artificial light, with serious consequences for habitat and ecosystem conservation. For example, light pollution can affect pollination by nocturnal insects (Macgregor *et al.*, 2017) resulting in disrupted pollen transport (see 2.4.6.2) and it may interrupt seed dispersion. Research has also indicated that ALAN can impact ecosystem functioning even outside of lit areas (Giavi *et al.*, 2020).

Indirect consequences of artificial light often arise from a competitive advantage or disadvantage that it bestows upon a specific species. For example, artificial light attracts certain fast-flying bat species that feed on a large number of insects around light sources (see 2.4.6.4). The competitive advantage that this gives to certain bat species may lead to an unwanted impact on other more light-averse bat species which is an issue for endangered species in light-polluted areas (Hooker, Lintott and Stone, 2022).

Various measures have been developed to address the impacts of light pollution at the species or ecosystem function level, which take specific conservation issues into consideration.

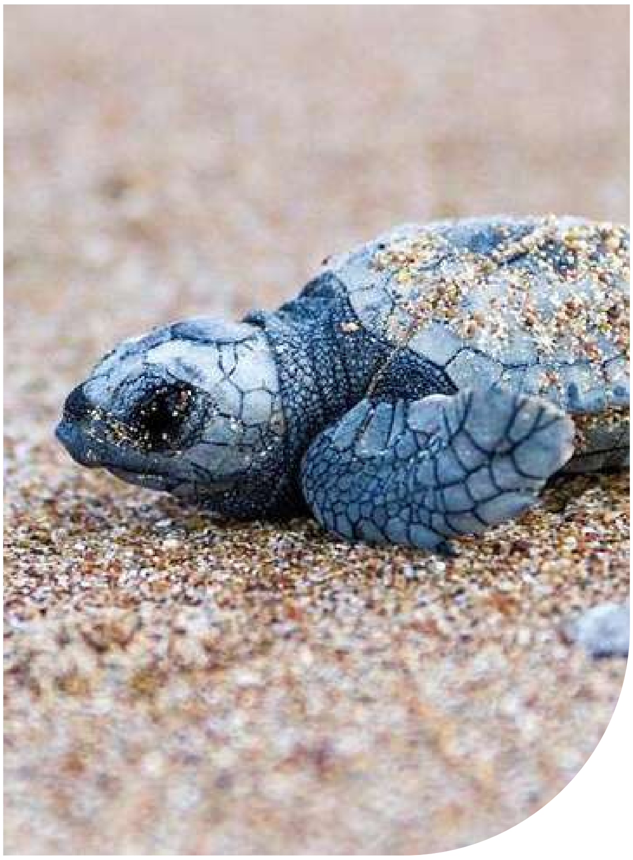
2.4.6.1. Measures to address light pollution at family, group and ecosystem level

Family focus: marine turtles

The Australian government has developed National Light Pollution Guidelines for Wildlife including Marine Turtles, Seabirds and Migratory Shorebirds (Commonwealth of Australia, 2020). The 'Light Pollution Guidelines' aim to raise awareness of the potential impacts of artificial light on marine turtles, and provide a framework for assessing and managing these impacts near important nesting beaches (Arthur, Whiting and Pendoley, 2020). This framework provides consistent, standardised and transparent processes and expectations for assessing, measuring, auditing and managing artificial light around wildlife.

Loggerhead sea turtle hatchlings, *Carreta carreta*, making their way to the ocean. Cape Hatteras National Seashore. Source: Public domain, via Wikimedia Commons

Around important marine turtle nesting beaches, the Light Pollution Guidelines recommend an Environmental Impact Assessment (EIA) approach. This should include consideration of the biological management objectives regarding artificial light, the proposed lighting design, mitigation and a risk assessment including the likelihood of negative consequence to nesting marine turtles or hatchlings. Light management must be considered on a case-by-case basis as lighting conditions are geographically dependent, so the guidelines do not prescribe specific light levels and mitigations. The success of light management is determined by whether wildlife can continue to engage in important behaviours, and effectiveness of mitigation should always be reviewed using biological monitoring and light auditing.



Loggerhead sea turtle hatchling, *Caretta caretta*, taken on a Natura 2000 site in Kyparissia, Greece. Source: Dionysisa303, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons

Research in the Mediterranean has suggested mitigation measures such as the elimination of unnecessary lights, the use of long wavelength lights, the shielding of light sources that are directly visible from a beach and the elimination of all upward-directed lighting (Dimitriadis *et al.*, 2018). Other complementary measures may also include the shading of nests from night lights and the preservation and enhancement of sand dunes and beach vegetation (Dimitriadis *et al.*, 2018). Some studies are evaluating specific mitigation approaches for specific cases, for example, research has shown that fully shielded, long-wavelength LED streetlight fixtures provide an appropriate option to minimize impacts to sea turtles along coastal roadways throughout the United States (Long *et al.*, 2022).

2.4.6.2. Group/ecosystem function focus: Insects, including pollinators

It is proposed that ALAN has been driving insect declines in combination with other factors such as habitat loss, pesticide use, invasive species and climate change (Stockhammer, Zulka and Schindler, 2022). The effects are varied, and range from disorientation in time and space, desensitisation to light (dazzled or blinded), and loss of ability to discriminate colours. There is concern that the increased usage of white LEDs will impact insects as they are more sensitive to short wavelengths. One group that is particularly prone to negative effects of ALAN are moths, and research has shown that light pollution affects their reproduction and development. In turn, it also affects the composition of moth assemblages and the ecosystem functions they perform.

The EU Pollinators Initiative is the first ever EU action framework to tackle the decline of wild pollinators. A workshop took place online in 2022, which aimed to strengthen actions to enhance pollinator-friendly artificial night lighting in Europe, through the existing Pollinators Initiative (Stockhammer, Zulka and Schindler, 2022). Organised by DG Environment and the German Environment Agency (Umweltbundesamt), the workshop was aimed at experts across stakeholder groups, including public authorities, practitioners engaged in spatial planning, innovation and social change experts, academia, land managers and non- governmental organisations

The resulting revised EU Pollinators Initiative was released in January 2023[9], recommending member states to mitigate the impact of light pollution through national and regional policies. The updated initiative also highlighted the Commission's new guidelines on light pollution mitigation for cities[10] and citizens for pollinator conservation[11]. The revised EU Pollinators Initiative states that the Commission has integrated recommendations on how to mitigate light pollution into its guidelines for citizens and cities, and will continue to promote them (European Commission, 2023). More specific details on the guidelines directed at mitigating the impacts of ALAN on pollinators can be seen in Box 11.

Butterflies near a light bulb. Source: https://www.shutterstock.com/image-photo/butterflies-old-lamp-58175626

2.4.6.3 Class focus: Birds – mitigating impact of ALAN inland

The City of Toronto in Canada received a Bird-friendly certification from Nature Canada for adopting best practice in effective lighting, to reduce negative impacts on birds. The City of Toronto, worked closely with Fatal Light Awareness Program (FLAP) Canada, to keep birds safe from deadly collisions with buildings, and developed a set of guidelines on best practices to protect birds with regard to glass[12].

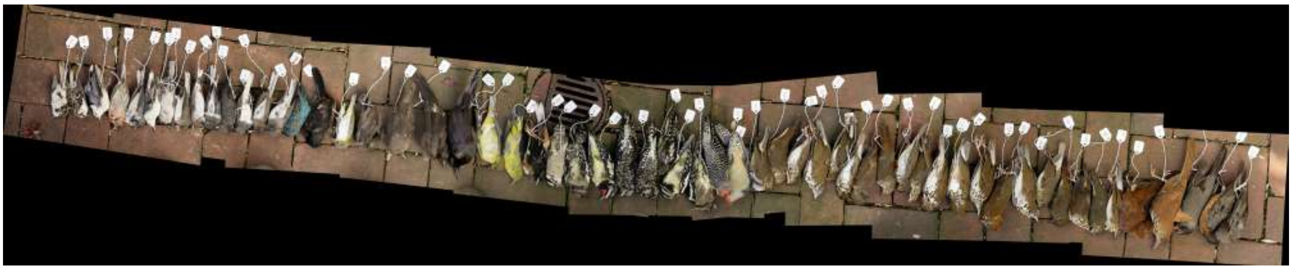
In the guide reflective glass, particularly surrounded by vegetation is a particular problem for bird collisions – as the reflective glass mirrors the surrounding vegetation, such as trees. Forest dwelling bird

9 EUR-Lex - 52023DC0035 - EN - EUR-Lex (europa.eu)
10 https://wikis.ec.europa.eu/display/EUPKH/Cities
11 https://wikis.ec.europa.eu/display/EUPKH/Citizens
12 https://www.toronto.ca/wp-content/uploads/2017/08/8d1c-Bird-Friendly-Best-Practices-Glass.pdf

species that feed near to canopies were the most likely to collide (City of Toronto, 2016).

The bird friendly building programme was developed by FLAP Canada and the World Wildlife Fund Canada, to address light pollution from buildings and reduce bird mortality. When bird friendly practices were adopted by building managers and tenants of some buildings in Toronto, they were shown to have a significant effect at reducing the number of birds killed. Light emission reduction was mostly from tenant awareness programmes, but computer-controlled lighting systems were also used in some buildings.

Architectural interventions suggested in the Toronto, glass guide, include, building-integrated structures that obscure glass from view, mute reflections during certain times of the day and provide visual cues for birds to avoid an area. These structures include: opaque awnings, sunshades, exterior screens, shutters, grilles and overhangs or balconies that provide shading below a projection. Other building guidelines include visual markers on the glass at regular intervals, coupled with opaque, matt materials on the glass to stop reflection. Guidance is tailored to the features of the building and surrounding vegetation.



Top: Migrating bird carcasses, killed by colliding with buildings. Bottom: Birds killed during the migration season in 2013 in Washington D.C. The birds were picked up by the group ‘Lights Out Washington D.C.’ and include species such as Worm-eating Warlblers, Scarlet Tanagers, American Woodcock, Saw whet Owl, Coopers Hawk, Black and White Warbler, Swamp Sparrow, Song Sparrow, Ruby-throated Hummingbird and other. Source: USGS, Native Bee and Inventory and monitoring programme, creative commons license, public domain. Flickr, CC BY 2.0- photos by Sam Droege

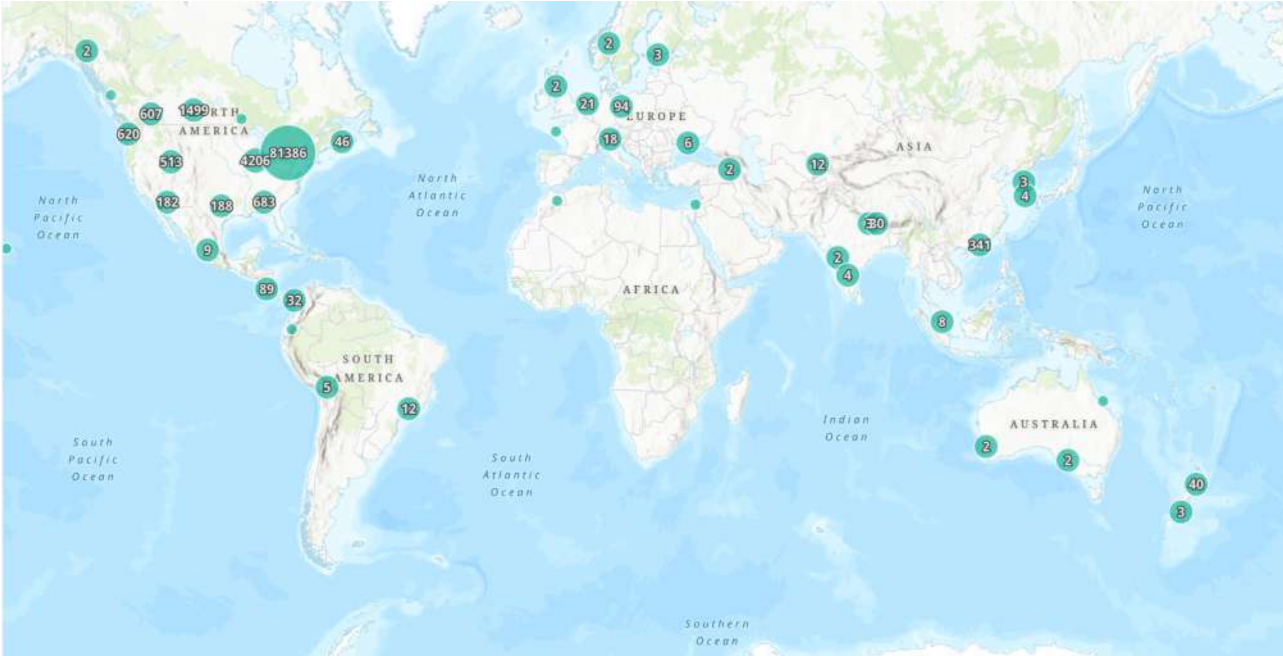


Figure 16: Global Bird Collision Mapper, by FLAP Canada, shows number of bird collisions reported via this portal form around the world. This Citizen Science resource offers insight into the breadth of these collisions. Source: https://www.birdmapper.org/pages/explore-the-map

2.4.6.4. Seeing the bigger picture – impact of ALAN and its management on bats (Hooker, Lintott and Stone, 2022)

Linear habitat features such as waterways are important for bats. Water surfaces and the vegetation provides foraging habitats and waterways also act as commuting corridors linking roosts and foraging/drinking areas (Smith and Racey, 2008; Lacoeuilhe *et al.*, 2016; Pinaud *et al.*, 2018). Waterways are particularly important for a number of slow-flying bat species (e.g. Myotis spp.) that have echolocation and wing morphology adapted for cluttered, low-light environments. These habitats are increasingly experiencing light pollution.

Part-night lighting (PNL) involves switching off street-lights during periods of low human activity and has been implemented widely in urban areas throughout Europe, mainly to reduce energy usage but also to limit light pollution. Studies of PNL have looked at the impacts of PNL on numbers of bats but have not drilled down into important details of conservation such as feeding behaviours or bat assemblages.

Recent research has provided a more detailed evaluation of PNL and shown that overall activity under full-night light treatments was significantly lower in comparison to both unlit nights and PNL treatments. This suggests that, to some extent, PNL limits the negative impacts of ALAN by allowing Myotis bats to have peaks of activity later in the night after lights are switched off. Superficially this may seem to highlight the efficacy of PNL as a mitigation method, however the results show that this is not true for all behaviours. For example, there was a 50% reduction in relative feeding activity in the PNL treatment suggesting that PNL reduces the feeding activity window for these species.

The results indicate that, despite being a valuable approach in terms of reducing carbon emissions and public sector costs, PNL schemes are unlikely to provide desired biodiversity benefits especially for bats due to species-specific impacts on activity and feeding. Therefore, if the aim it to limit the negative impacts of ALAN on biodiversity, it would be more beneficial to pursue alternative management strategies such as reducing light trespass, changing the intensity or spectrum of lighting and increasing dark corridor networks.

Building on this insight, it may be best to use different combinations of management strategies. There have been several initiatives at regional and national levels to address the negative impact of ALAN on bats that recommend a combination of technological and management strategies, depending on which species are present and which behaviours the light pollution could affect (roosting, feeding, reproduction etc.) The UNEP/ EUROBATS Guidelines for consideration of bats in lighting projects (Voigt, C.C et al, 2018) sets out a range of recommendations to avoid, mitigate for and compensate both direct and indirect effects of lighting schemes, which focus on the different behaviours that ALAN might disrupt.

Similarly, the Bats and Artificial Lighting in the UK Guidance Note outlines a simple process to consider the impact on bats as part of a proposed lighting scheme. It contains techniques which can be used on all sites in a stepwise process, starting with establishing the presence or absence of bats, and presence of roosting habitat, foraging habitat and their importance (Institution of Lighting Professionals and Bat Conservation Trust, 2018). Seeking the assistance of local ecologists is directed when bats are present, to conduct surveys. Avoidance of illumination of key habitat features is noted, with this being a requirement for roost entrances and flightpaths particularly, especially when rare or light averse bat species are present. When a development is proposed near to bat habitat, mitigation measures are advised under the guidance of an ecologist, with any lighting designed to be within lux limits and designed by a lighting professional.[13]

Lesser horseshoe bat (*Rhinolophus hipposideros*) roosting under the stairs in a church tower. Source: Lesser horseshoe bat (*Rhinolophus hipposideros*) bats roost... | Flickr © Flickr, CC BY 2.0- photo by Jessicajil

13 layout (bats.org.uk)

3. Monitoring ALAN remotely

There have been advances in a number of monitoring methods, especially in the use of remote sensing. Research opportunities are emerging with the development of new space borne, airborne and ground sensors for quantifying light at night (Levin *et al.*, 2020).

In particular satellite data has attracted growing interest where images of the Earth's surface are taken from space at night and can provide information on the distribution of light emissions (see box 13). However, there are a number of considerations that need to be considered in the use of this satellite data. The images are taken from above, and at distance, which means a key component to improving the utility of the insight they can provide is the translation of remotely sensed values to a ground level, where light pollution may be experienced differently.

Satellite data is also highly dependent on the weather conditions, such as cloud cover (Kyba *et al.*, 2011). For example, in areas with little or no artificial lighting, clouds darken the night sky, while in areas with artificial lighting they make it considerably brighter (Levin *et al.*, 2020). Snow cover also has the potential to significantly increase the luminance of the sky by reflecting any type of lighting (Jechow & Hölker, 2019b).

Field data can ground truth satellite observations (Levin *et al.*, 2020), and one solution is to compare ground-based night sky brightness measurements using, for example, sky quality meters (SQMs). These can either be directly compared to the light observed from space, or to the results from models of sky brightness that based on the satellite data (Wallner & Kocifaj, 2019). Low-cost night light radiometers such as SQMs, and the use of mobile phones to collect data, have expanded the number of surveyed sites on the ground, and enabled the active participation of citizen scientists in research (see section 3.1) to provide this comparison with ground data. However, SQM measurements can be influenced by numerous factors in the surrounding environment, for example reflection of light from vegetation can affect night sky brightness (Puschnig *et al.*, 2023). Also, the use of SQM meters for longer term measurements and monitoring of night sky brightness changes, requires corrections to data to account for aging effects such as the sensor degrading (Puschnig *et al.*, 2021).

Advances in remote sensing have enabled a wider coverage of data collection on night lighting, but there are various locations and environments that are notably less monitored than others. For example, citizen science cataloguing of the ISS night-time photos has highlighted that they do not represent all parts of the world, and are more common in the urban areas of North America, Europe, the Middle East, eastern China and Japan. Satellite data on ALAN for Europe comes largely from one satellite that covers Europe, with a spatial resolution of 1km, however nearer to the equator this lessens to around 2.7km (Bennie et.al., 2015). Additionally, the European satellite isn't always overhead at the correct time, with northern Europe having less coverage. With more recent technology, satellites can now achieve a spatial resolution of 5m (see box 13) the capabilities of monitoring ALAN may improve.

An increasingly important issue is that satellites have difficulties detecting LED-lighting systems, especially installations emitting lights with wavelengths below 500 nm. Blue light scatters more than red or yellow light, which makes it more difficult for the satellite to capture these light emissions and the measured values of light at lower wavelengths are less accurate (Pérez Díaz *et al.*, 2021). This may result in optimistic assessments of reductions in light pollution (Kyba *et al.*, 2017), however new approaches using mobile phones are enabling monitoring of light across the spectrum (see box 14).

Monitoring of ALAN remotely is associated with some limitations. For instance, the integration of satellite data with ecological data in both spatial and temporal dimensions presents challenges to mitigate discrepancies. This arises from the dynamic nature of night time light, whereas satellite imagery often relies on composites generated over extended periods of time, such as two weeks or summarized over a year, to construct images. Responses to light by living organisms is often direct and highly local, for instance for species with positive phototaxis and such responses may be difficult to match with large-scale monitoring.

Long-term light exposure is more likely to degrade habitat quality, making it challenging to attribute these effects directly to light pollution impacts.

Moreover, the issue of scale merits attention. There is a lack of comprehensive studies evaluating the applicability of satellite-derived data at local scales compared to larger scales. Local-scale considerations are particularly pertinent to numerous terrestrial organisms, however when considering aerial and migratory species it may be more important to have data at a larger scale (Simons *et al.*, 2020).

Box 13: Advances in satellite data (Pérez Díaz *et al.*, 2021)

The Visible Infrared Imaging Radiometer Suite (VIIRS) sensor onboard the Suomi NPP[14] was launched in October 2011, and has been fitted with a specific pan- chromatic sensor designed for measuring night time lights – the Day and Night Band (DNB). The VIIRS/DNB presents a significant improvement over the previous sensor, in data availability, in its higher spatial resolution (740 m, instead of about 3 km), in providing calibrated data which is sensitive to lower light levels and does not saturate in urban areas.

The first commercial satellite with high spatial resolution night-time capabilities (at 0.7 m), was the Israeli EROS-B satellite, which was launched in 2006, but only started offering night- time acquisition publicly in 2013 (Levin, *et al.*, 2014).

The first commercial satellite to offer multispectral (red, green and blue) night-time lights images (at 0.92 m) was launched in 2017: the Chinese JL1-3B (Jilin-1) satellite.

Cubesats, a class of miniaturised satellites, are a relatively new development, consisting of 10 cm cubes. Another satellite which offers the public global images of many regions on Earth at night is LJ1-01 (Luojia-1). Luojia-1, was built by Wuhan University and launched in June 2018, providing night- time images at 130m spatial resolution. Most recently, the Luojia-3 has been launched, which has a faster transmission speed, and greater accuracy of target detection, enabling real-time streaming of images. Importantly, it can also handle most of the data processing and analysis itself.

3.1. Making sense of data with citizen science

For data on ALAN to be valuable in informing mitigation and prevention strategies, it needs to be at scale, and in a form that can be analysed. There have been huge advances in the level, and speed of data processing, however, remote sensing data from sources such as satellites and space stations, usually requires some form or parsing, categorising or connecting of data to make it relevant for light pollution analysis. Citizen science has been playing a key role in enabling this to happen, and in collection of other ground-based data (Kyba *et al.*, 2013).

Currently, the astronaut photographs from the International Space Station (ISS) provide the largest online archive of night-time images of the Earth[15]. However, these images lack precise location and georeferencing. A citizen science program called "Cities at Night" has provided an improved catalogue of night-time images from the ISS (https://citiesatnight.org). With the collaboration of more than 20,000 volunteers, the project has tagged more than 190,000 nocturnal images of mid and high spatial resolution (resolution from 5 to 200 m) and the data has been used on several papers concerning light pollution monitoring (de Miguel *et al.*, 2014).

14 The Suomi National Polar-orbiting Partnership (Suomi NPP) is a weather satellite operated by the United States National Oceanic and Atmospheric Administration (NOAA). It was launched in 2011 and is currently in operation. The Visible Infrared Imaging Radiometer Suite (VIIRS) is the largest instrument aboard of Suomi-NPP and collects radiometric imagery in visible and infrared wavelengths of the land, atmosphere, ice, and ocean.

15 Photographs of the Earth at night taken from the International Space station, available from: https://eol.jsc.nasa.gov

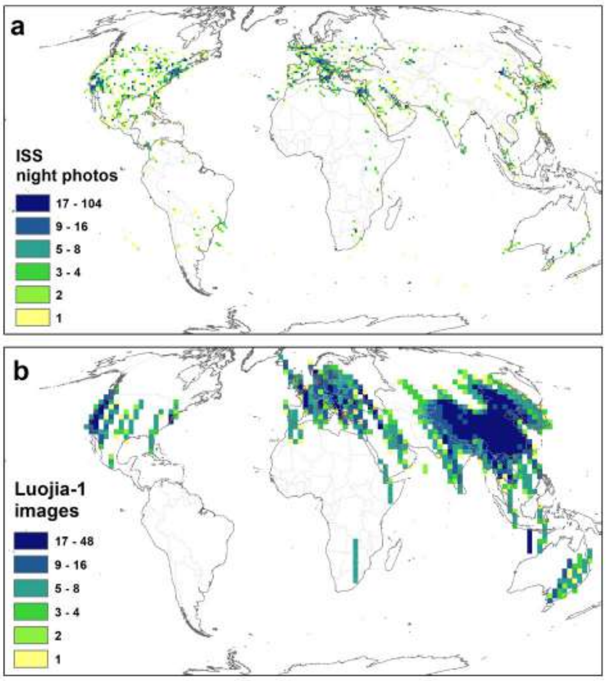


Figure 17. (a)The number of night time ISS photos identified by the 'Cities at Night' crowdsourcing, citizen science project within 100x100 grid cells. (b) The number of night time Luojia-1 images acquired so far (8675, in May 2019) with 250x250km grid cells. Source: Levin, *et al.*, 2020. ©2023, Noam Levin

The recent introduction of low-cost night light radiometers, starting with the Sky Quality Meter (SQM), has enabled rapid monitoring of night-time brightness while walking, cycling or driving to allow monitoring of temporal changes in night sky brightness. The most widespread citizen science projects using SQMs is "Globe at Night" (Walker *et al.*, 2007) which has been running since 2006.

In addition to instrumental observations, citizen scientists are able to make visual observations of night sky brightness by examining stellar visibility. While visual observations have lower precision than instrumental observations (Kyba *et al.*, 2013), they have the advantage of correctly accounting for spectral changes in night sky brightness due to changing lighting technology (Sánchez de Miguel *et al.*, 2015). Projects using mobile phone data collected by citizens are also enabling spectral analysis of night light (see box 14).

Box 14: NightUp citizen science project – extracting colour data (Muñoz-Gil *et al.*, 2022)

The NightUp citizen science experiment is collecting information about the spatial distribution of colour of artificial lights at night. Using a cross-platform mobile application, users take photos of streetlights and an algorithm detects the lamps in the photos and extracts their colour. In order to compare results, the devices would ideally be calibrated, but it is unrealistic to assume each user could calibrate their own device or that researchers could do it for each model available on the market. As such, the study assumed the calibration that smartphone cameras undergo to meet the ISO standards would be sufficient to obtain satisfactory results. With the geolocation of the NightUp data, it can be used to create maps that display the colour of lamps in different regions. The first pilot of NightUp was conducted near Barcelona where researchers had an updated streetlight database containing information on the geolocation and the lamp technology (e.g., high-pressure sodium or LED) for each streetlight in the city. This enabled researchers to test the accuracy and data acquisition of NightUp in various conditions, as well as the colour extraction algorithm and the pilot showed that an estimation of the colour of artificial light at night that was sufficiently precise to distinguish warmer light sources from colder ones. In the future this information could be used by local governments to optimize outdoor lighting and address light pollution problems as well as by scientists to study the effect of the colour of light. The NightUp data could also be used to efficiently calibrate satellite images to improve the precision of ecological and economical parameters extracted from them. Furthermore, because of its minimal technical requirements, the researchers believe that NightUp can potentially expand to a global scale with the support of successful engagement strategies, allowing scientists to access and characterise vast regions. However, it still needs to assessed if the NightUp approach will work for new and spectral tunable light sources.

Figure 18. Top row: Three examples of light source location by means of the NightUp algorithm. Bottom row: The area in the rectangle of the image is cropped, and the circle in the bottom right hand corner showed the colour assigned to each lamp. Source: © Gorka Muñoz-Gil, Alexandre Dauphin, Federica A. Beduini, and Alejandro Sánchez de Miguel, Published with license by MDPI - via Creative Commons licence

4. Emerging issues in improving research approaches to ALAN, and knowledge gaps on impacts and mitigation

As discussed in previous chapters, a number of context specific mitigation measures are already in place worldwide, which seem to be ameliorating the negative impact of light pollution on certain species, or groups of species. In addition, more general mitigation approaches are emerging, such as shielding light fixtures, or only using them at certain times. In the short term these measures appear to have had some positive impacts on target species. For example, in New York, the Twin Towers memorial lights were attracting migratory bird species, but these are now turned off intermittently to allow trapped birds to escape (Jägerbrand and Spoelstra, 2023).

Yet Jägerbrand and Brutemark, 2022, urge caution in assuming that some of the more generalist mitigation approaches are always the best way to lower ALAN's harmful ecological impacts on biodiversity. Instead, they suggest these measures should only be used with long-term monitoring and assessment alongside, to note the impacts on all species – not just the most photosensitive groups in aquatic and terrestrial habitats. Monitoring of these mitigation measures should include a consideration of ecology, demography, migration, the various stages in species lifecycles and interactions with prey and predator and how these are affected by light at night (Jägerbrand and Brutemark, 2022). By incorporating well-planned monitoring studies, alongside the introduction of these mitigation measures, it is possible to determine the baseline measurements for species prior to the introduction of mitigation measures, to demonstrate evidenced-based success or failure of the mitigation strategies.

Jägerbrand and Brutemark, 2022, suggest research on the effectiveness of some of the more popular mitigation strategies that are being adopted on a large scale should address the following questions:

1. Which species, ecosystems and ecological processes will benefit the most, and the least, from popular general strategies to mitigate light pollution?

2. How much will responses to ALAN differ between species (with various photo sensitivities), as well as between ecosystems?

3. Do established applications (or adaptations) in light installations or conservation measures have the intended mitigating effects on species, biodiversity and ecosystems?

4. How can we measure ecological light pollution?

4.1. Establishing standardised thresholds, measurement protocols and mitigation guidelines

The interdisciplinary nature of ALAN research has resulted in different measurement approaches, procedures and use of various light units. The research community continue to call for standardised light measurements to enable comparison across the disciplines (Hölker *et al.*, 2021). In addition, the researchers should also provide accurate records of how measurements of ALAN were taken, with which equipment and from which position – for example holding a light meter upright at shoulder height or horizontally from a position at tree height. This will vary depending on the area being investigated, sources of light pollution and behaviour of concerned species or taxa. These would undoubtedly help in the establishment of recommended technical measures but, in reality, it is unlikely that one single approach and unit will emerge that will suit everyone's needs.

Ecological studies on ALAN should use SI (international standardised system) units to quantify light, however, there are advantages and disadvantages to the different ways of measuring light, and the prioritisation of these pros and cons will depend on the context of application (Widmer *et al.*, 2022). As such, flexible measurement options are helpful as they enable bespoke mitigation and prevention strategies for different aspects of light pollution, such as location, spatial scale, existing policy, target species and functions of light.

To develop effective mitigation measures, measuring light in a standardised manner and addressing research gaps are needed. In addition, further research measuring light for local conditions on the ground is required – rather than relying only on satellite data, which shows light emitted into space rather than light emitted below a forest canopy, or towards the ground (Jägerbrand and Brutemark 2022). Although some species are impacted by light directed upwards – such as nocturnally migrating bird species and avian orientation – most species are exposed to light emitted below the horizontal plane, into light-sensitive habitats such as aquatic habitats or nature reserves (Jägerbrand and Brutemark 2022).

For example, to investigate ALAN impacts on a small terrestrial mammal, such as a vole, one would need to measure light in the relevant exposure area – for example, on the ground in the directions in which the animal may be looking. One would also need to quantify the light in units of relevance for the target organism, probably combining radiance with the spectra distribution, and then analyse the data depending on which spectra the organisms perceive the most. In addition, one should measure the ambient light at the study area in different parts of the study area and at different times, recording factors that might influence the measurements, such as the phase of the moon, presence of clouds and other abiotic factors.

Measuring local light environments that are known to impact species, in a standardised manner, would aid in establishing the impact of intensity, timing, spectra and other aspects of ALAN on species and habitats. This would also be the start of establishing useful thresholds to improve mitigation measures based on accurate field data.

Standardisation to restrict spill light, is urgently needed to prevent the negative effects of unintentional lighting in vulnerable habitats such as open aquatic environments (Jägerbrand and Spoelstra, 2023). Overall improved guidelines on standards of lighting in different areas, which consider the harmful ecological impacts of ALAN are required – to stop the excessive use of light – as is often the case at present.

Although research into the impacts of ALAN on ecosystems has grown considerably over the last 10 years, there are still a number of knowledge gaps which require further research. These research gaps were summarised in a 2021 review for Frontiers in Ecology and Evolution, by Spoelstra and 10 colleagues, who distilled them into 11 research questions covering ALAN-sensitive species traits through to interactions with other stressors, such as climate change. However, most of these questions are building research knowledge over the longer term, which supports the identification of effective mitigation measures for ALAN, but is less pertinent to current solutions. However, some of the questions listed by Spoelstra et al, 2021, are more directly related to current mitigation measures, for example, harmonising light measurement across disciplines – as discussed above – as well as identifying the opportunities and challenges for effective management of ALAN (Spoelstra *et al.*, 2021).

Establishing the ALAN intensity thresholds of many species, is highlighted by Jägerbrand and Spoelstra as an area needing more research data. The ALAN intensity thresholds of species can vary between species, but also according to exposure duration, life-history stage and habitat structure. To translate research more directly into ecological protection, research should aim to establish a numerical threshold value on the bases of illuminance or luminance of current light sources and technologies. If researchers adopt this approach, it will allow research to be directly translated into guidelines for future lighting design, and retrofitting/upgrading existing lighting systems (Jägerbrand and Spoelstra, 2023).

Further research on environmental lighting zones would be of benefit, with Zilienska, *et al.*, 2023, suggesting there is currently no evidenced-based consensus on the maximum light levels allowed in outdoor urban residential areas to limit light spill.

It is clear that there is not a one size fits all approach to mitigating the effects of anthropogenic (artificial) light on all species. Monitoring the effectiveness of different types of mitigation measures, and combinations of these, for different taxa and environments, is an area which will require further research. Technological solutions, in the form of tuneable spectra LED, dimmable lighting and sensor timing systems, alongside better lighting design incorporating shielding and shutters, have all helped to mitigate the impacts of ALAN in areas that require lighting. However, we do not have technical solutions to all environmental challenges posed by ALAN, and need engineers and lighting designers to help to create luminaire systems that further reduce reflection, glare and light spill.

4.2. Interdisciplinary research on the effectiveness of measures for mitigating the impacts of ALAN

Mitigating measures should always be considered as a last resort, with the first position being that natural darkness is preferential in most circumstances. For a mitigation measure to be required, there needs to have been careful consideration and justification given as to why artificial light is required at all in a given location. The default position should always be that no artificial light is present at night, and planners should be seeking a justification as to why artificial light is needed when installing any new luminaires. The justification will usually be around human safety with regard to road, car park, or street lighting. However, in these circumstances the minimal amount of light required should be installed with shielding and on a timer to enable periods when they can be switched off – for example when important migratory species are present. A consideration of light-vulnerable protected species should also be made, if they are present in the surrounding habitat (see boxes 2 and 7 for more detail).

In order to improve technical and management approaches to reducing the environmental harm of ALAN, there needs to be continuing evaluation to feed back into further development and improvement. As outlined in the framework for dark infrastructure (Sordello *et al.*, 2022), this will involve comparison before and after implementation of a given mitigation measure, with indicators related to light pollution and those related to biodiversity. Biodiversity indicators need to combine different aspects, including species richness, abundance and community functioning (life traits, relationships between species).

To develop effective indicators, research is needed to explore questions, such as: how does ALAN alter biodiversity by redistributing species; how does ALAN affect biodiversity through indirectly altering species interactions; and lastly, what are the effects of ALAN on biodiversity at the ecosystem and the landscape level? (Hölker *et al.*, 2021).

It is necessary to identify indicator species – often rare or protected species that are among the most vulnerable nocturnal animal groups to ALAN – such as bats, amphibians, nocturnal Lepidoptera i.e. moths such as noctuid or sphingid moth and Lampyrid beetles – for different types of habitats/ecosystems. However, the reactions of these species to light may be quick and direct, whereas other species may be impacted over the long term, with notable changes in species composition at the ecosystem level. Given the differences known so far in species responses to spectra and intensity of ALAN, a simple solution to mitigating the effects of light on all species is unlikely (Jägerbrand and Spoelstra, 2023). Thus, it is useful to investigate different types of mitigation measures and their impacts on taxa, as well as looking to successful examples of mitigation measures in differing habitats, as presented above.

There is a lot of research regarding ALAN mitigation and LED technology, with the general consensus being that future LED installations should ideally use light fixtures that are dimmable, tuneable and respond to a timer. Further research on a number of ALAN variables is needed, including a multitude of aspects of just two of these: colour and intensity of light emitted: responses of organisms to these over time (day, season), and impacts on biodiversity in different habitats. Monitoring data demonstrates that ALAN is present in many areas, such as underwater habitats at night – but more research is needed on the impacts of this across species in a dose-effect manner, i.e. increasing light intensity, or changing colour spectra of emitted light.

The use of blue/white light, however, has an impact on a wide variety of terrestrial and marine taxa, with insects particularly impacted. Amber lighting has been proposed as a solution to this by the Dark Skies Consortium and the IUCN, and even red lighting in some situations such as in installations in marine areas, or to prevent disturbance to most bat species. However, caution in this regard has been suggested by Jägerbrand and Spoelstra, in their 2023 review, who note that in using highly adapted spectra – such as red lighting – you may create an ecological trap for species that are unable to sense this light and therefore become more vulnerable to predatory species that can detect this light (Jägerbrand and Spoelstra, 2023). In addition, in protected areas and areas with rare protected red-light sensitive species, for example lesser horseshoe bats, even red light should be used with caution, and where possible no lighting should be the default.

Further interdisciplinary research is required in the future on lit areas, such as roadways, and pavements, where light is required to enable human access in these areas, whilst minimising ecological impacts. An EU workshop on light pollution in autumn 2022, suggested piloting projects in sensitive areas to identify least environmentally harmful lighting to achieve this goal amongst Member States (Council of the European Union, 2022). As part of this evaluation more information is needed on other environmental stressors that could affect light pollution, and particularly its interplay with other pollutants (Widmer *et al.*, 2022). The interaction of light pollution with other pollutants is still poorly understood, and therefore a growing concern of the science community. Researchers have developed a practical method to record the size, composition and distribution of aerosol particles through satellite imagery (Kocifaj & Barentine, 2021), enabling an assessment of how air pollution interplays with light pollution. This has shown that reducing air pollution, specifically aerosols, decreases night-sky brightness by tens of percent at relatively small distances from light sources.

Alongside pollution other global change drivers, such as climate change or land-use change, can interact with the effects of ALAN (Rillig *et al.*, 2019), which could be additive (the sum of the impacts is equal to each impact added together), antagonistic (cumulative effect that is less than additive) or synergistic, whereby cumulatively effects of sum of stressors is more than the additive effect (Birk *et al.*, 2020). One example is night-time warming that combines with light pollution and has non-additive impacts on predator–prey interactions (Miller *et al.*, 2017). Researchers are developing novel ways to disentangle these effects on biodiversity and provide insight into how approaches could be put into practice to potentially tackle more than one environmental issue (Widmer *et al.*, 2022). For example, Wilson *et al.* (2021) used a large data set generated by community and citizen scientists to analyse effects of ALAN and noise pollution on bird occurrences. This showed a number of informative insights, such as that species occupying closed habitat[16] were less tolerant of both sensory stressors compared to those occupying open habitat.

This complexity of interactions in light pollution and its impact, further emphasises the need for interdisciplinary research that can consider different aspects of light at night time, its interaction with other environmental stressors, and its multiple impact (Spoelstra *et al.*, 2021). Two largescale interdisciplinary research projects investigating the impact of light pollution and effectiveness of mitigation measures, are planned to be funded within the Horizon Europe Research and Innovation Programme (HORIZON-CL6-2023-BIODIV-01-2)[17]. Both projects will investigate light and noise pollution with respect to impacts on biodiversity and ecosystem services and innovative mitigation measures, with 'AquaPlan' (101135471), focussed on European seas lakes and rivers, whereas 'Plan B' (101135308) is focussed on terrestrial ecosystems.

Lampyris noctiluca, Female common glow worm of Europe, displaying to attract a male, Germany. Source: Photo by Wofl~commonswiki CC BY-SA 2.0 DE https://commons.wikimedia.org/wiki/File:Lampyris_noctiluca.jpg

16 Closed habitat species live in areas with vegetation cover such as forest. Open habitats have less canopy/vegetation cover, such as grassland.
17 Biodiversity and ecosystem services (HORIZON-CL6-2023-BIODIV-01)

4.3. Species for which the impact of ALAN is not known

Research is emerging on the impact of ALAN on the only migratory insect species listed by the Convention on Migratory Species (CMS), the Monarch butterfly, *Danaus plexippus*. This study indicates that ALAN is likely impacting the internal circadian clock of this daytime active butterfly species, causing them to fly at night if subjected to artificial light, potentially impacting their migratory behaviour (Parlin, Stratton and Guerra, 2022). The process when Monarch butterflies emerge from their chrysalises is also controlled by a light-triggered circadian clock, therefore, constant light from ALAN could also disrupt this. Further research on the impact of exposure of artificial light at night on this well-known American butterfly species is required.

The European glow worm, *Lampyris noctiluca*, and the rarer *Phosphaenus hemipterus*, is a non-migratory European species impacted by ALAN. Despite ALAN impacting the behaviour of these charismatic bioluminescent species in Europe, there are few studies on how this is affecting their abundance, and distribution (Owens *et al.*, 2022). However, some recent studies demonstrate that some of these bioluminescent animals can discern between different colours of light, even at low light intensities, and respond to changes in intensity of LED lights (Booth *et al.*, 2004; Van den Broeck, *et al.*, 2021). Clearly further research is required to elucidate the impact ALAN might have given these emerging findings in this group.

There is a lack of information regarding how ALAN impacts the majority of migratory species. No studies were found for any CMS-listed mammals (apart from bats), crocodiles or Chondrichthyes (sharks, and rays) with the latter being notably at risk in the Mediterranean Sea, where more than 50% of species are listed as at risk of extinction (Serena *et al.*, 2020). There is a limited amount of information available about some migratory fish, including the CMS-listed European eel, which raise concerns – but further research may be necessary before action can be taken. Whereas the impact of artificial light on marine turtles has been studied extensively, there is a knowledge gap when it comes to non-marine turtles (Perry *et al.*, 2008).

The sensitivity of different taxonomic groups to different spectra of light is an area which requires more attention. Hölker *et al.* (2021) note that many species of aquatic turtles, and fish are more sensitive to longer wavelength in freshwaters (i.e. red light) and to shorter wavelengths in marine environments (i.e. blue light). It cannot then be assumed that all turtle species are most sensitive to shorter wavelengths – the case with marine turtles – as freshwater species of fish and turtles may be more sensitive to red light, due to how light is filtered by salty water (where red light does not penetrate far due to the salt content) compared with freshwater (Hölker *et al.*, 2021).

There is little research on the impact of ALAN on two groups of marine turtle populations – Kemp's Ridley turtle (*Lepidochelys kempii*) and the upper Amazonian population of the Arrau turtle (*Podocnemis expansa*). The Kemp's Ridley turtle is listed as critically endangered by the IUCN and found in European waters, with a French study from 2021 investigating stranding events, bycatch and cold stunned turtles in the Bay of Biscay area – noting that further research was needed into the environmental drivers leading to these occurrences (Chambault *et al.*, 2021).

Many bird species have been shown to be vulnerable to light pollution, but there are also calls in the literature for more research. Many of the bird species listed on the CMS do not belong to the orders or families which are covered by the current guidelines. How the prey of migratory species is affected by ALAN also needs to be studied further, for example future research into the impacts of ALAN on moths (which are prey for many other species) needs to consider for all life stages, rather than only focusing on adult moths, as well as looking at more moth species (Boyes *et al.*, 2021).

4.4. Marine and Freshwater habitats lacking ALAN data

More than 50% of the world's population live within a distance of 3 km (Kummu, *et al.*, 2011) from water, and there are many current and future shifts that may increase ALAN in marine areas, such as night-time fishing and floating cities (Herbert-Read *et al.*, 2022). However, whilst information on the extent and the amount of ALAN potentially affecting water bodies is in its infancy, ecological studies assessing the impact of artificial light that penetrates into the ocean on marine organisms is even scarcer (Smyth *et al.*, 2021; Jechow and Hölker, 2019a).

Aquatic habitats need protection from ALAN and they are vulnerable, as aquatic organisms are adapted to low light conditions and these environments are largely open spaces, with few barriers to prevent light penetration. With the extreme light sensitivity of aquatic habitats, the precautionary principle should be applied in most cases, perhaps following the lead from France, where light on water surfaces is forbidden by law. As with all situations discussed previously, the default should always be no artificial lighting in or near an aquatic habitat. Where lighting is unavoidable for human safety, for example, on an oil rig or boat, the light should be restricted to the lowest intensity required, shielded, be used on a timer and in an appropriate colour spectrum to minimise impact on aquatic organisms.

There is little guidance on addressing the impacts of ALAN and management of lighting in the marine environment, although there is research and suggestions around the use of artificial lighting in commercial fishing (Nguyen and Winger, 2019). Sport fishing, also known as recreational fishing, sometimes uses artificial light at night to attract fish to the boats (see figure 20). However, this practice has an impact on non-target species in the aquatic environments, and potentially on migratory seabirds. The approach to regulating this multi-billion-dollar hobby differs between different worldwide jurisdictions – with some banning recreational night fishing entirely (Greece), while others restrict the use of artificial light in night fishing (Spain) (Pawson *et al.*, 2008; Cooke *et al.*, 2017). The Convention on Migratory Species suggests a case-by-case approach to assessing, managing and mitigating ALAN (see 2.4.6) (Marangoni *et al.*, 2022; Nunny, 2021). Monitoring of night light in marine and coastal areas is improving, and studies are able to use modelling techniques to estimate the level of night light on the seafloor (Davies *et al.*, 2020). Further research to establish the thresholds for ecological and environmental impacts in marine and freshwater habitats is warranted, focusing on indicator species that are most likely impacted.

At present there are very few studies on the impact of using tuneable LEDs to mitigate ALAN in marine ecosystems. Tim Smyth, *et al.* (2020), however, suggest that their research in the Tamar estuary offers a compelling case for using artificial red light in costal installations to reduce exposure in marine habitats, as it attenuates faster and is less visible to marine animals. The application of red light in marine environments to mitigate the impacts of ALAN is likely to be favourable (ibid.), however, a number of marine organisms are also negatively affected by amber and red light. As such, retrofitting red light filters to existing luminaires, or switching to long length lights is likely to improve potential ALAN impacts on most marine organisms, but will not completely eradicate the impacts altogether.

Despite a lack of data in marine areas, Marangoni et.al. (2022) offer ten golden rules for mitigating the impact of ALAN in marine habitats – citing existing data on the impacts of ALAN in the ocean, and applying the precautionary principle (see figure 19 below).

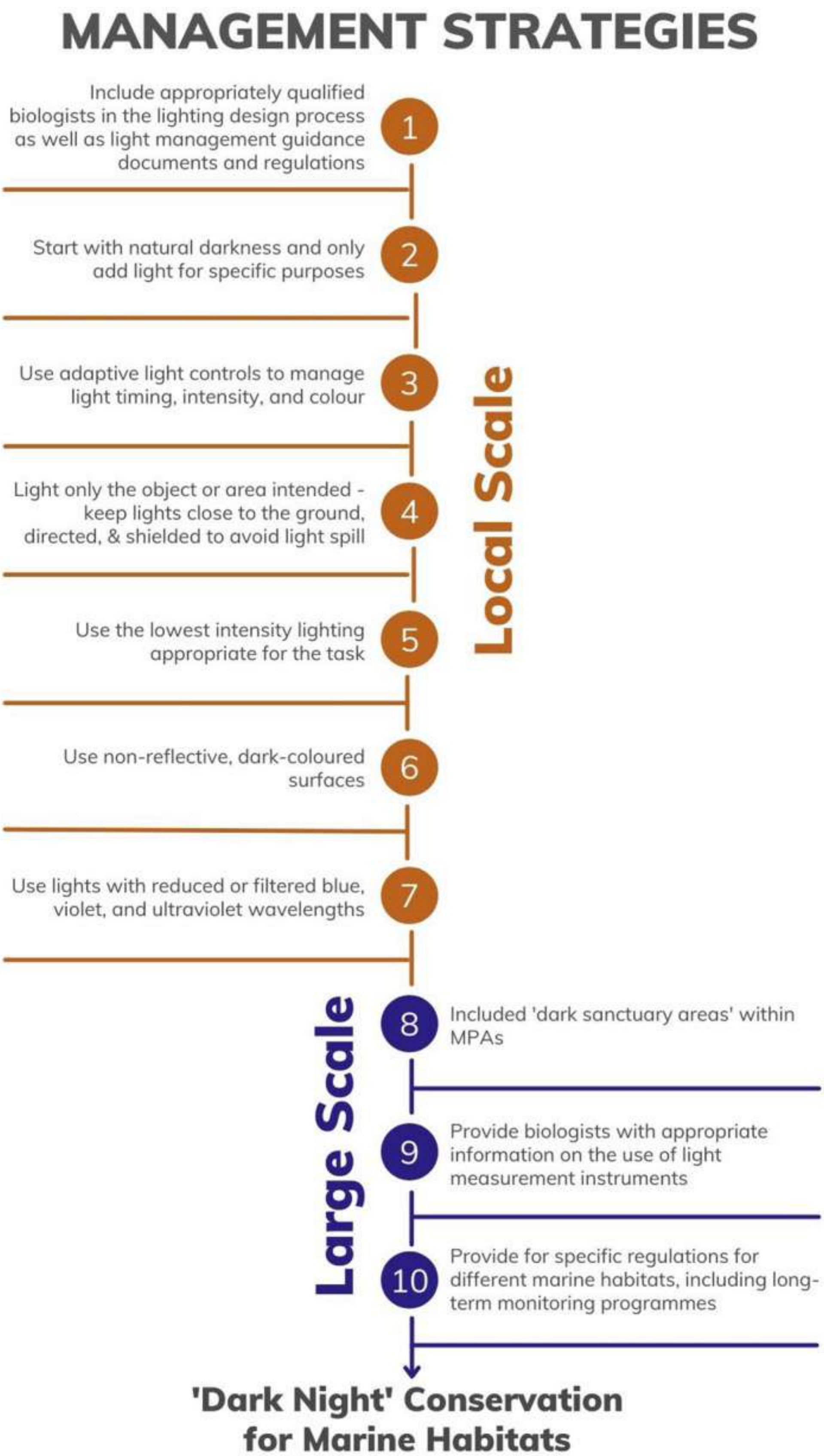


Figure 19. Ten golden rules for dark night conservation for marine habitats. Source: © 2022 The Authors. *Global Change Biology* published by John Wiley & Sons Ltd – available and downloaded via Creative Commons licence

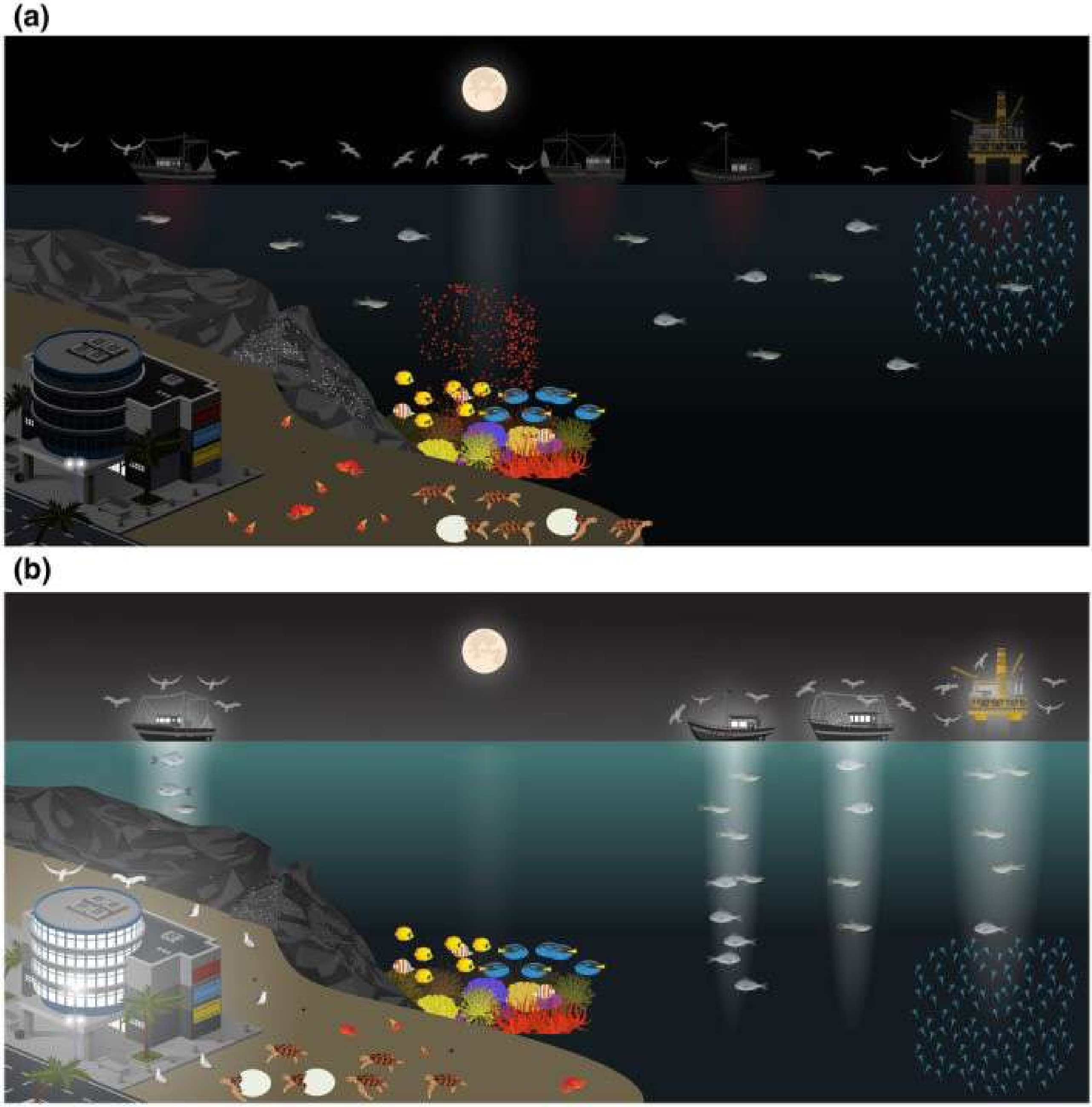


Figure 20: (a) Different marine environments not affected by Artificial Light Pollution at Night (ALAN), and (b) marine environments under the potential impacts of ALAN: (i) Sandy beaches effects on invertebrate species day-night activity rhythms and biodiversity, effects in the on-beach orientation of adults and hatchling turtles, and seabirds fledgling grounded by ALAN; (ii) Rocky intertidal shores – influence in metabolic activity/behavior of primary producers, sessile and mobile animals; (iii) Shallow water coral reefs – effects on gametogenesis and the synchronization of gamete release in prominent coral species, and negative impacts over fish reproduction, (iv) Pelagic environment – inhibition of vertically migrating zooplankton, and disorientation and mortality of seabirds. Source: © 2022 The Authors. *Global Change Biology* published by John Wiley & Sons Ltd – available and downloaded via Creative Commons licence.

However, there is a paucity of data on freshwater systems: they have not been studied with satellite data due to their relatively small area (Jechow and Hölker, 2019a), and the most widespread method to measure ALAN in freshwater uses simple handheld luxmeters above the water surface. Few citizen science studies have been developed to describe nocturnal artificial light conditions of aquatic systems.

> **As well as being an issue on land, light pollution impacts the marine environment particularly those areas with intensive offshore development and coastal urbanization. An area of 1.9 million km2 of the world's coastal seas are exposed to ALAN at a depth of 1m (equivalent to 3.1% of the global exclusive economic zones).**

Source: Smyth *et al.*, 2021.

> **Very low light levels that artificial light generates are critically important to biological organisms, ... But how much of an impact it has in the marine environment has been pretty understudied.**

Source: Tim Smyth, lead author and oceanographer, 'global atlas of artificial light in the sea'.

In addition to overcoming these challenges there is a need to consider the different forms of light pollution for different types of water. Blue wavelengths are transmitted to greater depths in the ocean, as water molecules absorb the longer wavelengths. In contrast, coastal waters and freshwater systems typically absorb longer wavelengths and are more variable in their inherent optical properties (Kühne *et al.*, 2021).

4.5 Geographical disparities in impacts of ALAN

There are many regions and countries that will be more affected by light pollution in the future, but which currently have a low level of awareness of the problem. For example, residential lighting is becoming more possible in developing countries as technology is accelerating accessible and affordable lighting, particularly from renewable sources.

Although accessibility to lighting has been hindered by the pandemic it seems it is likely to increase again (International Energy Agency (IEA), 2022). This is a welcome development, but also one that will increase light pollution in these countries. For example, researchers have recently highlighted light pollution as an emerging issue in India with a survey on awareness showing that 57% of Indian people surveyed were unaware of the term 'light pollution' (Kaushik *et al.*, 2022).

Within Europe, the northern European Member States have longer nights and are more densely populated, so it may be that ALAN has more of an impact in these areas. However, some of the southern Member States may have more night-time migratory bird species. Further elucidation on the geographical disparity of ALAN's impacts on the environment could aid creation of appropriate local guidelines.

> **Expressing concern over satellite data showing that global light pollution has increased by at least 49% over the 25 years to 2017, and that there are hardly any areas with complete night darkness left in Europe**

International Workshop - 'Light Pollution 2022;' note from Czech Presidency.

5. Summary and conclusions

Artificial light at night is an emerging environmental threat, with a growing research field which has produced hundreds of articles in the last five years. Some progress has been made in understanding aspects of the harm that exposure of artificial light at night can cause the environment, including sensitive habitats, vulnerable night-time active taxa and, of course, humans. However, understanding how to mitigate the environmental impacts of ALAN is complex, and there is no single solution for all scenarios, because organisms have different visual systems, and a diversity of ways to responding to light.

Yet solutions are emerging, and case studies now abound on different types of mitigation measure which limit the negative impact of ALAN in different situations. These include technical aspects of lights, such as shielding, dimming and timers, as well as the impacts of different colour spectra. The ideal solution of course is not to use artificial light at night at all, and keep naturally dark areas dark, to protect species present in these habitats. However, when lighting is needed for human activity in an outdoor space, then the least amount of light required should be used – lighting only the area needed, with the minimal amount of light required to ensure visibility for the user. In identifying where these areas of lighting are justified, depends on the context; however, for road traffic lighting the Swedish Transport Association case study, detailed in Box 7, offers a best practice approach.

It is important also to dispel a common misconception, by clarifying that an area with brighter artificial light at night is not always safer. If lighting is poorly designed, unshielded and glaring, it can cause temporary blindness in a person, making it more difficult to identify objects and potential threats, and for human eyes to adjust to see clearly the low contrast surroundings. Accepting that dimmer well-placed lighting can be safer and, therefore, preferable to poorly designed brighter lighting would enable lower ALAN in human-inhabited areas, benefitting biodiversity and human health (Zielinska-Dabkowska, *et al.*, 2023).

Where and when ALAN is unavoidable, using low light intensity, warmer light spectra, such as amber and red, although not a perfect solution, is less harmful overall than higher intensity, or blue spectra LED lighting. However, it is worth noting that reducing artificial light – both its extent and its duration – is more beneficial overall. So, it may be useful, in some situations, to retrofit dimmable, warmer spectra LEDs that are shielded and on a timer.

There are a myriad of other management and technological measures to mitigate the impacts of ALAN, with some examples discussed in this brief already, which can be combined and tailored according to the needs of a particular area. Some of these measures include adaptive street lighting, buffer zones around dark reserves, dark corridors – connecting dark infrastructure – buildings designed to reduce light spill and reflection on glass, and dense vegetation to hinder light spill. It is clear that more research is needed to monitor the effectiveness of these mitigation measures, singly and in combination, at protecting the vast array of wonderful night-time active species we have in Europe, such as the lesser horseshoe bat, European glow worm and loggerhead turtles, from the negative effects of ALAN.

There are a number of policy barriers that have prevented widespread uptake of the mitigation measures discussed in this brief. Most lack of uptake is due to this being an emerging field, where many mitigation strategies may only have one or two case studies relevant to a particular species or context. The establishment of standardised thresholds and guidelines is emerging, and so uniformity across the European Member States (MS) is presently lacking, however, some examples of local authorities and MSs good practice from within this brief could be useful in this regard.

Reassuringly, it is within our power to reduce the environmental harm caused by artificial light at night, often simply by switching off the lights. This is exactly what some cities have begun to do due to the energy crisis, by instigating lighting curfews. These money-saving steps by local governments also benefit biodiversity, for example reducing the impacts of skyglow on migratory birds or turtle hatchlings.

Light pollution has historically been perceived as less of a priority issue than some other environmental stressors, and so there is less awareness amongst the media, and the public of this issue, and the wide-ranging environmental and human health impacts this may have. However, a growing field of research demonstrating ALAN's negative impacts, alongside knowledge of some quite simple measures that can mitigate these, are leading to this issue gaining more widespread political attention. With many light-pollution reduction strategies also lowering energy use, and potential costs to local authorities – this could be an area where gains could be made on all fronts by some carefully selected measures.

Outdoor lighting is not currently included in the 2030 Agenda for Sustainable Development, adopted by all members to the United Nations, although most of the 17 sustainable development goals are impacted by light pollution. To ensure a more ecological sustainable future in Europe, and globally, individuals, cities, governments and international conservation organisations need to include the effects of anthropogenic lighting in planning and decision-making.

Box 15: Actions to mitigate ALAN in homes, businesses and through Green Public Procurement

Wildlife species are more sensitive to light than humans, with artificial light at night disrupting the nocturnal behaviour of many species, including pollinators such as nocturnal moths, thus impacting the successful pollination of plants. As this topic is gaining increasing attention with regards to Green Public Procurement,[18] recommendations were developed for road lighting and traffic signals (Wilk, Rebollo and Hanania, 2019):

- Use of lighting products compatible with dimming controls that limit upward light, blue light emissions and switch off lighting in closed parks;
- limit illumination to desired areas such as sidewalks or roads;
- dim light sources to the lowest acceptable light intensity;
- reduce the number of light fixtures installed in and around ecologically vulnerable areas;
- shield path lights in green spaces from the top and the bottom to minimise their impact on nearby biodiversity;
- install temporal limits – motion activation and/or automatic timers that extinguish lights when not needed, or when vulnerable species are likely to be most affected, i.e. during the two-month long courtship season of the common glow-worm (firefly);
- use red wavelength LED lights, adjust wavelength to red and exclude blue and ultraviolet spectrum.

What we can all do in our homes:

To lower skyglow in your city, town or village you can minimise light pollution outside your house, in your garden, terrace or front door. Do you need lights in these spaces all the time? If not, can they be used only at certain times of night? Motion activation or temporal lighting with automatic timers can help. Extinguish lights when not needed, or dim to the lowest acceptable light intensity. Use lights which are shielded – so light doesn't travel upwards or downwards unnecessarily, and use warm lights with a red wavelength rather than a blue one. Lastly, simply close your curtains or shutters in the evening when you turn on lights inside your home (IEEP, 2020).

Businesses:

Dark sky standard for domestic and non-domestic lighting was developed by the United Kingdom Dark Skies Partnership (UKDSP), a collaborative forum of the Commission for Dark Skies, the Countryside Charity (CPRE), the Institute of Lighting Professionals and the Society of Light and Lighting. The aim of UKDSP is to improve sky quality by reducing ALAN via education, effective behavioural change and promotion of environmentally-sensitive lighting (UKDSP, 2021):

- Using automated blackout blinds and shutters at night – a relatively low-cost and effective option for eliminating internal light spill without impacting on internal spaces;
- timers on blinds should be set for within one hour after sunset;
- they can be used either in the design phase, or post installation;
- break up continuous glazing by removal or use of external shutters and shields to keep the overall glazed area to less than 50% of the total elevation area;
- glazing should not exceed 25% of the floor area to meet energy efficiency building regulations (which does depend on thermal properties of the glass);
- turn off internal lights when not needed or at close of business;
- any commercial greenhouse should have zero light spill.

18 Technical report "Revision of the EU Green Public Procurement Criteria for Road Lighting and traffic signals" which proposes concrete G-index values (directly related to blue light content) for parks, gardens and ecologically sensitive areas.

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