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National Light Pollution Guidelines for Wildlife

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Acknowledgement of Country

We acknowledge the Traditional Custodians of Australia and their continuing connection to land and sea, waters, environment and community. We pay our respects to the Traditional Custodians of the lands we live and work on, their culture, and their Elders past and present.

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Introduction

Natural darkness has a conservation value in the same way that clean water, air and soil have intrinsic value. Artificial light at night is increasing globally by about 2% per year (Kyba et al. 2017), though this number is likely an underestimate (Sánchez de Miguel et al. 2021). Animals perceive light differently from humans, and artificial light can disrupt critical behaviour and cause physiological changes in wildlife (Russart & Nelson 2018a). For example, hatchling marine turtles may not be able to find the ocean when beaches are lit (Witherington & Martin 2003), and fledgling seabirds may not take their first flight if their nesting habitat never becomes dark (Rodríguez et al. 2017a). Tammar Wallabies exposed to artificial light have been shown to delay reproduction (Robert et al. 2015), and clownfish eggs incubated under constant light do not hatch (Fobert, Burke da Silva & Swearer 2019).

Consequently, artificial light has the potential to stall the recovery of a threatened species. For migratory species, the impact of artificial light may compromise an animal's ability to undertake long-distance migrations integral to its life cycle.

Artificial light at night provides for human safety, amenity and increased productivity. Australian legislation and standards regulate artificial light for the purpose of human safety. These guidelines do not infringe on human safety obligations. Where there are competing objectives for lighting, there may be a need for creative solutions that meet both human safety requirements for artificial light and threatened and migratory species conservation.

The guidelines outline the process to be followed where there is the potential for artificial lighting to affect wildlife. They apply to new projects, to lighting upgrades (retrofitting) and where there is evidence of wildlife being affected by existing artificial light.

The technology around lighting hardware, design and control is changing rapidly and biological responses to artificial light vary by species, location and environmental conditions. It is not possible to set prescriptive limits on lighting. Instead, these guidelines take an outcomes approach to assessing and mitigating the effect of artificial light on wildlife.

Figure 1 Pink Anemone fish and marine turtle laying eggs

Photos: Nigel Marsh and Robert Thorn.

How to use these guidelines

These guidelines provide users with the theoretical, technical and practical information required to assess whether artificial lighting is likely to affect wildlife, and the management tools to minimise and mitigate that effect. These techniques can be applied regardless of scale, from small, domestic projects to large-scale industrial developments.

The aim of the guidelines is that artificial light will be managed so wildlife is:

1) not disrupted within, or displaced from, important habitat

2) able to undertake critical behaviours such as foraging, reproduction and dispersal.

The guidelines recommend:

1) always using Best practice lighting design to reduce light pollution and minimise the effect on wildlife.
2) undertaking an environmental impact assessment of effects of artificial light on listed species for which artificial light has been demonstrated to affect behaviour, survivorship or reproduction.

Technical appendices

The guidelines are supported by a series of technical appendices that provide additional information: Appendix A – Best practice lighting design, Appendix B – What is light and how does wildlife perceive it?, Appendix C – Measuring biologically relevant light, and Appendix D – Artificial light auditing. There is also an Appendix E – Artificial light management checklist and protected matters information on the management of artificial light for taxa including Appendix F – Marine turtles, Appendix G – Seabirds, Appendix H – Migratory shorebirds, Appendix I – Bats, Appendix J – Terrestrial Mammals and Appendix K – Ecological Communities.

Regulatory considerations for the management of artificial light around wildlife

These guidelines provide technical information to guide the management of artificial light for *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) listed threatened and migratory species, species that are part of a listed ecological community, and species protected under state or territory legislation for which artificial light has been demonstrated to affect behaviour, survivorship or reproduction.

Environment Protection and Biodiversity Conservation Act 1999

The EPBC Act regulates any action that will have, or is likely to have, a significant impact on Matters of National Environmental Significance (MNES), including listed threatened and migratory species. Any action likely to have a significant impact on MNES must be referred to the Australian Government for assessment. Further, it is an offence under the EPBC Act to kill, injure, take or trade a listed threatened, migratory or marine species in a Commonwealth area. Anyone unsure of whether the EPBC Act applies is strongly encouraged to seek further information.

State and territory legislation and policy

State and territory environmental legislation and policy frameworks may also have provisions for managing threats, such as light, to listed species. For example, artificial light is a form of pollution regulated for impacts on humans and the environment under the *Australian Capital Territory Environment Protection Act 1997*. Consideration should be given to the function of relevant state and territory environment and planning legislation and policy concerning the protection of wildlife from artificial light.

Local and regional government requirements

Advice should also be sought from local government as to whether specific requirements apply in the area of interest concerning artificial light and wildlife. For example, the Queensland Government's Sea Turtle Sensitive Area Code provides for local governments to identify sea turtle sensitive areas within local government planning schemes. Development in these areas will need to avoid adverse effects to sea turtles from artificial lighting.

Australian standards

Australian standards provide agreed limits for various lighting scenarios, generally for the purposes of human safety and for the provision of amenity. For example, Australian Standard DR AS/NZS 1158.3.1:2018 *Lighting for roads and public spaces pedestrian area (Category P) lighting* provides minimum light performance and design standards for pedestrian areas.

Australian standards also provide for consideration of environmental concerns. Australian Standard AS/NZS 4282:2019 *Control of the obtrusive effects of outdoor lighting* recognises the impact of artificial light on biota.

These Light Pollution Guidelines for Wildlife should be followed to ensure all lighting objectives are adequately addressed. This may require solutions to be developed, applied and tested to ensure lighting management meets the needs of human safety and wildlife conservation. The Case studies illustrate examples of how a liquefied natural gas (LNG) processing plant, a transport authority and a marine research vessel have addressed this challenge.

Associated guidance

These guidelines should be read in conjunction with:

- EPBC Act Significant impact guidelines 1.1: Matters of National Environmental Significance: Significant impact guidelines 1.1
- EPBC Act Significant impact guidelines 1.2: Actions on, or impacting upon, Commonwealth land, and actions by Commonwealth agencies
- recovery plans and approved conservation advices for listed threatened species
- approved wildlife conservation plans for listed migratory species
- state and territory environmental legislation, regulations, and policy and guidance documents
- up-to-date scientific literature
- local and Indigenous knowledge.

Wildlife and artificial light

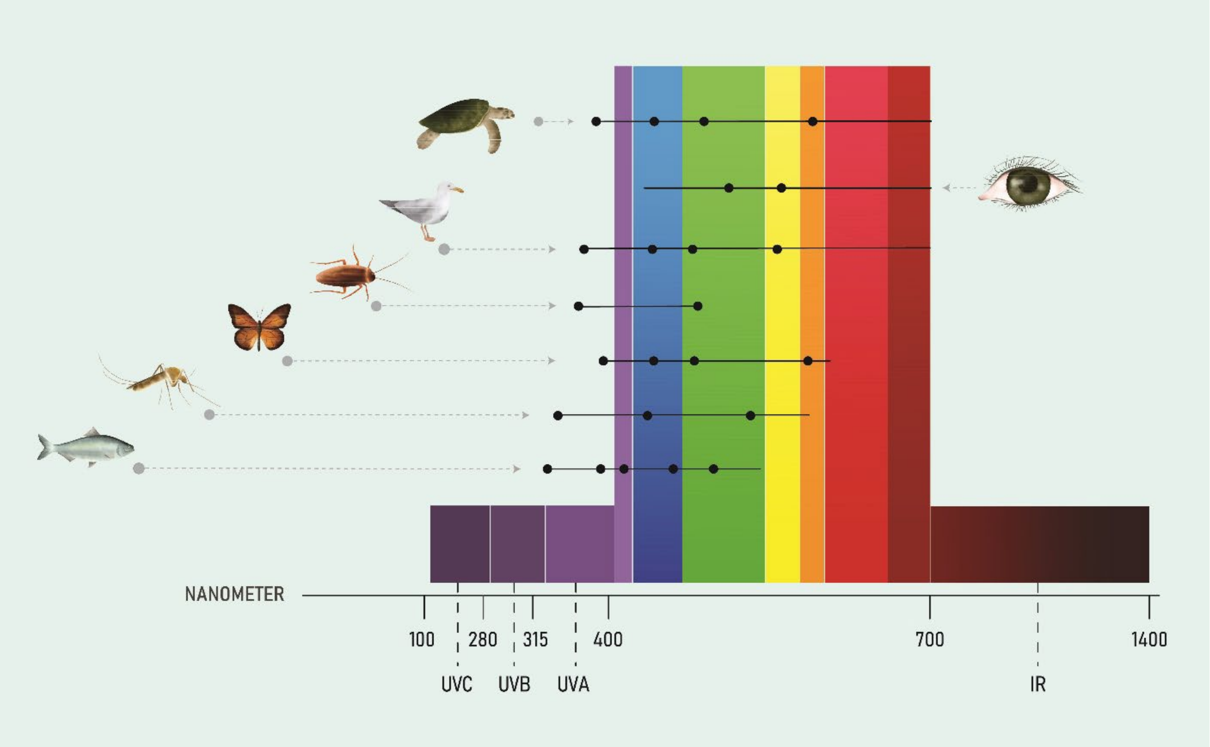
Vision is a critical cue used by wildlife to orient themselves in their environment, find food, avoid predation and communicate (Rich & Longcore 2006). An important consideration in the management of artificial light for wildlife is an understanding of how light is perceived by animals, both in terms of what the eye sees and the animal's viewing perspective.

Animals perceive light differently from humans. Most animals are sensitive to ultraviolet (UV)/violet/blue light (Campos 2017), while some birds are sensitive to longer wavelength yellow/orange light (Reed 1986), and some snakes can detect infrared wavelengths (Newman & Hartline 1981) (Figure 2). Understanding the sensitivity of wildlife to different light wavelengths is critical to assessing the potential effects of artificial light on wildlife.

The way light is described and measured has traditionally focused on human vision. To manage light appropriately for wildlife, it is critical to understand how light is defined, described and measured and to consider light from the wildlife's perspective.

For a detailed explanation of these issues see Appendix B – What is light and how does wildlife perceive it?. The Glossary provides a summary of terms used to describe light and light measurements and notes the appropriate terms for discussing the effects of light on wildlife.

Figure 2 Comparative light perception among different species groups



Ability to perceive different wavelengths of light in humans and wildlife is shown by horizontal lines. Black dots represent reported peak sensitivities. Figure adapted from Campos (2017).

How light affects wildlife

Artificial light is known to adversely affect many species (Russart & Nelson 2018a; Gaston, Visser & Holker 2018) and ecological communities (Sanders & Gaston 2018; Bennie et al. 2016). It can change behaviour and/or physiology, reducing survivorship or reproductive output. It can also have the indirect effect of changing the availability of habitat or food resources. It can attract predators and invasive pests, both of which may pose a threat to listed species.

Behavioural changes in wildlife have been well described for some species. Adult marine turtles may avoid nesting on beaches that are brightly lit (Price et al. 2018; Witherington 1992), and adult and hatchling turtles can be disoriented and unable to find the ocean in the presence of direct light or skyglow (Witherington & Martin 2003; Witherington 1992; Thums et al. 2016). Similarly, lights can disorient flying birds, particularly during migration, and cause them to divert from efficient migratory routes or collide with infrastructure (Cabrera-Cruz, Smolinsky & Buler 2018). Birds may starve when artificial lighting disrupts foraging, and fledgling seabirds may not be able to take their first flight if their nesting habitat never becomes dark (Rodríguez et al. 2017a). Migratory shorebirds may use less preferable roosting sites to avoid lights and may be exposed to increased predation where lighting makes them visible at night (Rodríguez et al. 2017a).

Physiological changes have been described in the Tammar Wallaby when it is exposed to artificial light, resulting in delayed reproduction (Robert et al. 2015); and clownfish eggs incubated under constant light do not hatch (Fobert, Burke da Silva & Swearer 2019). The stress hormone corticosterone in free-living songbirds has been shown to increase when they are exposed to white light compared with green or red light, and those with high stress hormone levels have fewer offspring (Ouyang et al. 2015). Plant physiology can also be affected by artificial light, with changes to growth, timing of flowering and resource allocation. This can then have flow-on affects for pollinators and herbivores (Bennie et al. 2016).

The indirect effects of artificial light can also be detrimental to threatened species. The Mountain Pygmy Possum, for example, feeds primarily on the Bogong Moth, a long-distance nocturnal migrator that is attracted to light (Warrant et al. 2016) (see Box 1 in Appendix J – Terrestrial Mammals Appendix). Recent declines in moth populations, in part due to artificial light, have reduced the food supply for the possum (Commonwealth of Australia 2016b). Changes in food availability due to artificial light affect other animals, such as bats (Haddock et al. 2019a), and cause changes in fish assemblages (Bolton et al. 2017). Lighting may also attract invasive pests such as cane toads (González-Bernal, Brown & Shine 2014), and predators, increasing pressure on listed species (Wilson et al. 2019).

The way in which light affects a listed species must be considered when developing management strategies, as this will vary on a case-by-case basis.

These guidelines provide additional information on the management of artificial light at Appendix F – Marine turtles, Appendix G – Seabirds, Appendix H – Migratory shorebirds, Appendix I – Bats, Appendix J – Terrestrial Mammals and Appendix K – Ecological Communities.

Consideration should be given to the direct and indirect effect of artificial light on all listed species for which artificial light has been demonstrated to negatively affect behaviour, survivorship or reproduction.

Light-emitting diodes (LEDs)

During the life of these guidelines, light technology may change dramatically. At the time of writing, LEDs were rapidly becoming the most common light type used globally. This is primarily because they are more energy efficient than earlier light sources. LEDs and smart control technologies (such as motion sensors and timers) provide the ability to control and manage the physical parameters of lighting, making them integral tools in managing the effects of artificial light on wildlife.

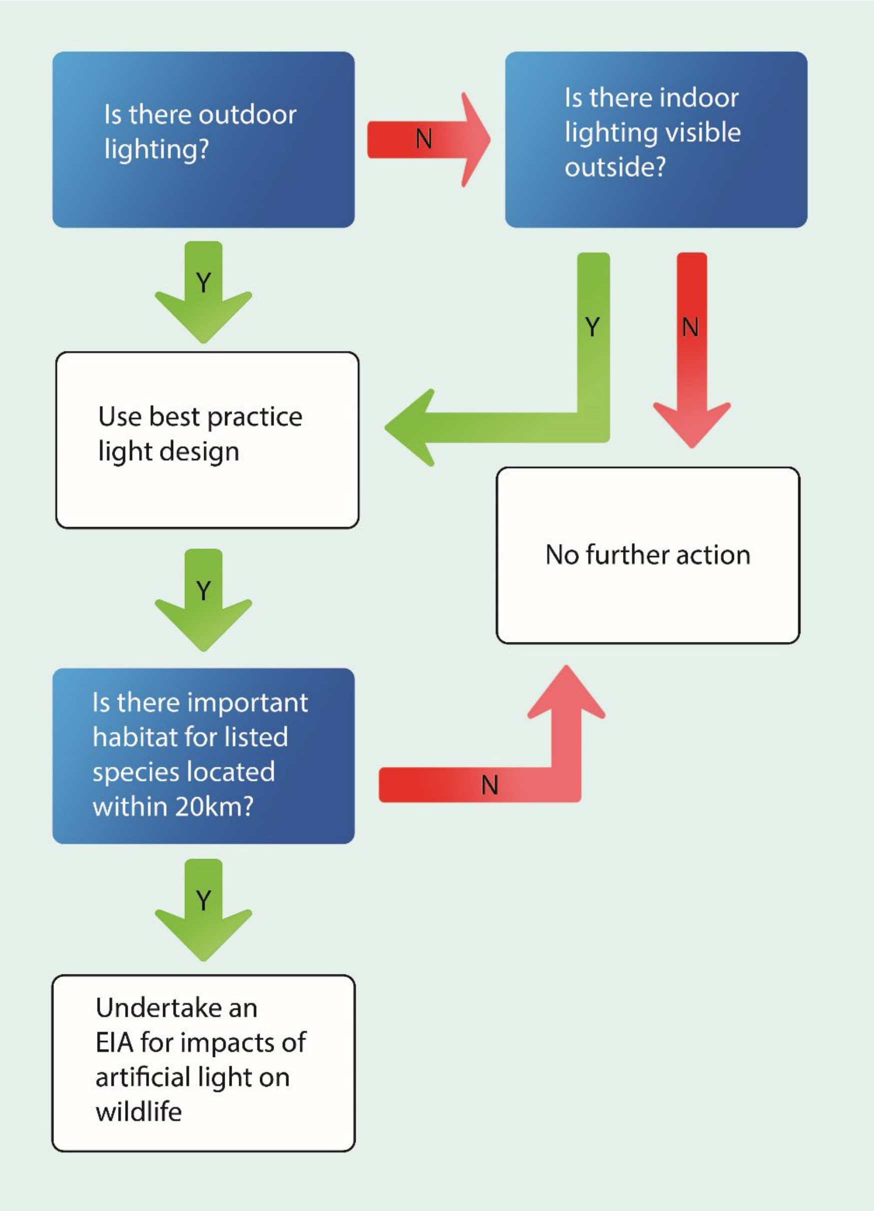
While LEDs are part of the solution, consideration should be given to some of the characteristics of LEDs that may influence the effect of artificial light on wildlife. White LEDs generally contain short-wavelength blue light. Short-wavelength light scatters more readily than long-wavelength light, contributing more to skyglow. Also, most wildlife is sensitive to blue light (Figure 2). More detailed consideration of LEDs, their benefits, and challenges for their use around wildlife are provided in Appendix B – What is light and how does wildlife perceive it?.

When to consider the impact of artificial light on wildlife

Is artificial light visible outside?

Any action or activity that involves externally visible artificial lighting should consider the potential effects on wildlife (see Figure 3). These guidelines should be applied at all stages of management, from the development of planning schemes to the design, approval and execution of individual developments or activities, through to retrofitting of light fixtures and management of existing light pollution. Best practice lighting design is recommended as a minimum whenever artificial lighting is externally visible.

Figure 3 Decision tree to determine whether to undertake an environmental impact assessment of the effects of artificial light on wildlife



Best practice lighting design

Natural darkness has conservation value and should be protected through good-quality lighting design and management for the benefit of all living things. To that end, all infrastructure that has outdoor artificial lighting or internal lighting that is externally visible should incorporate best practice lighting design.

Incorporating best practice lighting design into all infrastructure will not only have benefits for wildlife but also save energy and provide an economic benefit for light owners and managers.

Best practice lighting design incorporates the following design principles:

1) Start with natural darkness and only add light for specific purposes.

2) Use adaptive light controls to manage light timing, intensity and colour.

3) Light only the object or area intended – keep lights close to the ground, directed, and shielded to avoid light spill.

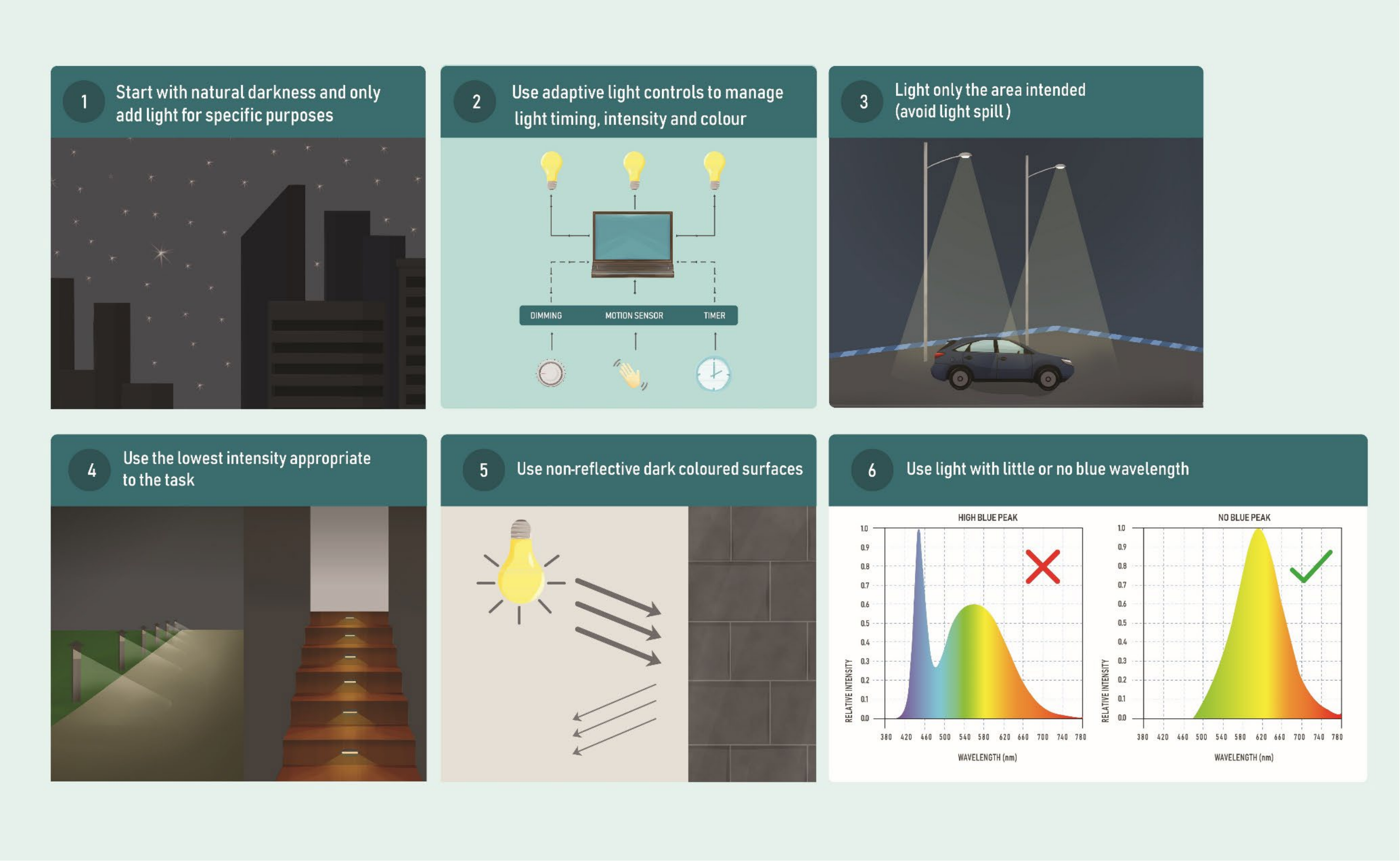
4) Use the lowest intensity lighting appropriate for the task.

5) Use non-reflective, dark-coloured surfaces.

6) Use lights with reduced or filtered blue, violet and ultraviolet wavelengths.

Figure 4 illustrates best practice lighting design principles. For a detailed explanation see Appendix A – Best practice lighting design.

Figure 4 Principles of best practice lighting design



Is there important habitat for listed species located within 20 km?

Important habitats are areas that are necessary for an ecologically significant proportion of a listed species to undertake important activities such as foraging, breeding, roosting or dispersal. This might include areas that are of critical importance for a particular life stage, areas at the limit of a species range or habitat, and areas where the species is declining. They may also be habitats where the presence of light pollution may cause a significant decline in a listed threatened or migratory species.

Important habitat will vary depending on the species. For some species, areas of importance have been designated through recovery plans and conservation advice, and under planning regulations (for example, the Queensland Sea Turtle Sensitive Area Code). Important habitat includes areas that are consistent with ‘habitat critical to the survival’ of a threatened species and ‘important habitat’ for listed migratory species as described in EPBC Act Significant impact guidelines 1.1 (Commonwealth of Australia 2013). Important habitat may include areas designated as biologically important areas (BIAs) or, in the case of migratory shorebirds, internationally important or nationally important habitat. Consideration should be given to the ecological characteristics of Ramsar sites and the biological and ecological values of national and world heritage areas.

Taxa-specific descriptions of important habitat can be found in Appendix F – Marine turtles, Appendix G – Seabirds, Appendix H – Migratory shorebirds, Appendix I – Bats, Appendix J – Terrestrial Mammals and Appendix K – Ecological Communities. For sources of relevant information on other listed species, see Associated guidance and Desktop study of wildlife.

Where there is important habitat for listed species that are known to be affected by artificial light within 20 km of a project, species-specific impacts should be considered through an environmental impact assessment (EIA) process.

The 20 km threshold provides a precautionary limit based on observed effects of skyglow on marine turtle hatchlings demonstrated to occur at 15 km to 18 km (Kamrowski et al. 2014; Hodge, Limpus & Smissen 2007), and on fledgling seabirds grounded in response to artificial light 15 km away (Rodríguez et al. 2014). The effect of light glow may occur at distances greater than 20 km for some species and under certain environmental conditions. The 20 km threshold provides a nominal distance at which artificial light impacts should be considered, not necessarily the distance at which mitigation will be necessary. For example, if a mountain range lies between the light source and an important turtle nesting beach, further light mitigation is unlikely to be needed. However, where island infrastructure is directly visible on an important turtle nesting beach across 25 km of ocean in a remote location, additional light mitigation may be necessary.

Managing existing light pollution

The impact of artificial light on wildlife will often be the cumulative effect of all light sources in the region. As the number and intensity of artificial lights in an area increases there will be a visible, cumulative increase in skyglow. Skyglow is the brightness of the night sky caused by the reflected light scattered from particles in the atmosphere. Skyglow comprises both natural and artificial skyglow. As skyglow increases, so does the potential for adverse impacts on wildlife.

Generally, there is no one source of skyglow, and management should be undertaken on a regional, collaborative basis. Artificial light mitigation and minimisation will need to be addressed by the community, regulators, councils and industry to prevent the escalation of, and where necessary reduce, the effects of artificial light on wildlife.

The effect of existing artificial light on wildlife is likely to be identified by protected species managers or researchers that observe changes in behaviour or population demographic parameters that can be attributed to increased artificial skyglow. Where this occurs, the population/behavioural change should be monitored and documented and, where possible, the source(s) of light identified. An Artificial light management plan should be developed in collaboration with all light owners and managers to mitigate impacts.

Environmental impact assessment of effects of artificial light on wildlife

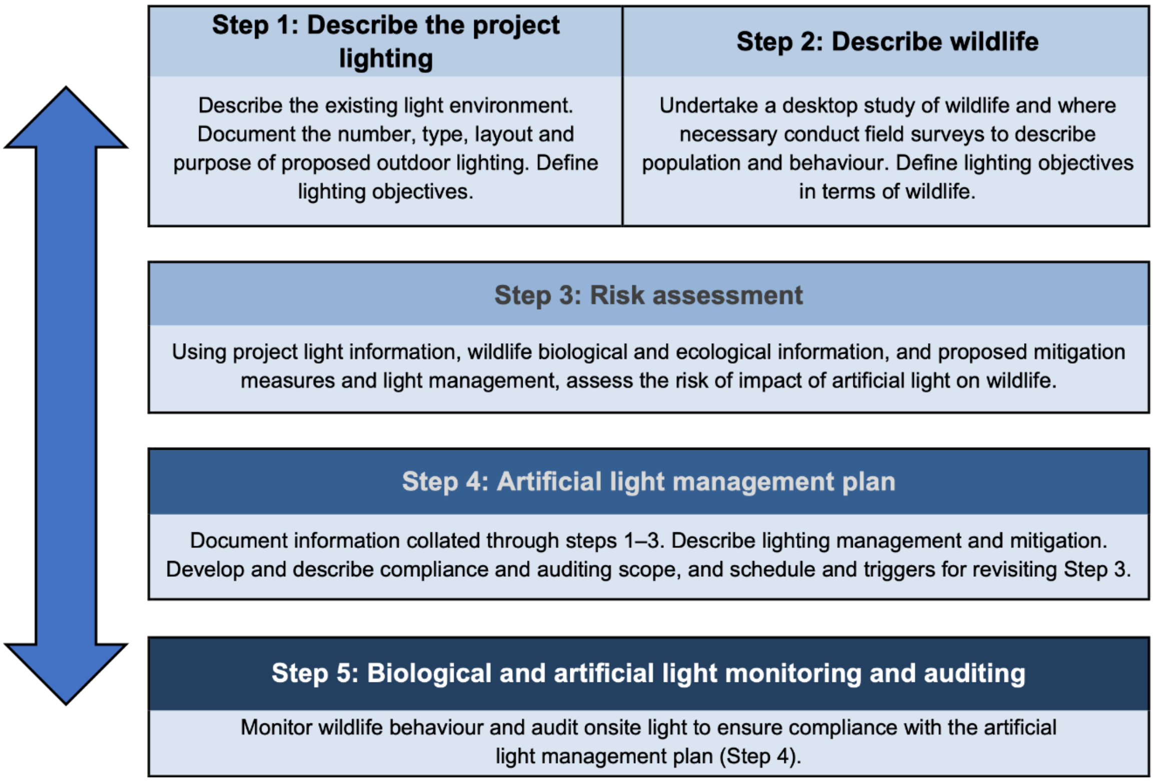
There are 5 steps involved in assessing the potential effects of artificial light on wildlife, and the adaptive management of artificial light requires a continuing improvement process (Figure 5). The amount of detail included in each step depends on the scale of the proposed activity and the susceptibility of wildlife to artificial light. The first 3 steps of the EIA process should be undertaken as early as possible in the project's life cycle, and the resulting information should be used to inform the project design phase.

Appendix F – Marine turtles, Appendix G – Seabirds, Appendix H – Migratory shorebirds, Appendix I – Bats, Appendix J – Terrestrial Mammals and Appendix K – Ecological Communities give specific consideration to each of these taxa. However, the process should be adopted for other protected species affected by artificial light.

Qualified personnel

Lighting design/management and the EIA process should be undertaken by appropriately qualified personnel. Management plans should be developed and reviewed by appropriately qualified lighting practitioners in consultation with appropriately qualified wildlife biologists or ecologists.

Figure 5 Flow chart describing the environmental impact assessment process



Step 1: Describe the project lighting

Describe the existing light environment. Document the number, type, layout and purpose of proposed outdoor lighting. Define lighting objectives.

Step 2: Describe wildlife

Undertake a desktop study of wildlife and where necessary conduct field surveys to describe population and behaviour. Define lighting objectives in terms of wildlife.

Step 3: Risk assessment

Using project light information, wildlife biological and ecological information, and proposed mitigation measures and light management, assess the risk of impact of artificial light on wildlife.

Step 4: Artificial light management plan

Document information collated through steps 1–3. Describe lighting management and mitigation. Develop and describe compliance and auditing scope, and schedule and triggers for revisiting Step 3.

Step 5: Biological and artificial light monitoring and auditing

Monitor wildlife behaviour and audit onsite light to ensure compliance with the artificial light management plan (Step 4).

Step 1: Describe the project lighting

Describe the existing light environment and characterise the light likely to be emitted from the site. Information should be collated, including the location and size of the project footprint; the number and type of lights; their height, orientation and hours of operation; site topography; and proximity to wildlife and/or wildlife habitat. This information should include whether lighting will be directly visible to wildlife or contribute to skyglow; the distance over which this artificial light is likely to be perceptible; shielding or light controls used to minimise lighting; and spectral characteristics (wavelength) and intensity of lights.

Project-specific lighting should be considered in the context of the existing light environment and the potential for cumulative effects of multiple light sources. The information collected should be sufficient to assess the likely effects of artificial light on wildlife given the biology and ecology of species present (Step 2: Describe wildlife).

Where there will be a need to monitor the effectiveness of artificial light mitigation and management strategies (Step 5: Biological and light monitoring and auditing), baseline monitoring will be necessary. Measurements of the existing light environment should recognise and account for the biologically relevant short (violet/blue) and long (orange/red) wavelengths of artificial lighting (see Appendix C – Measuring biologically relevant light).

Lighting objectives

During the planning phase of a project, the purpose of artificial lighting should be clearly articulated, and consideration should be given as to whether artificial light is required at all. Lighting objectives should be specific in terms of location and times at which artificial light is necessary, whether colour differentiation is required and whether some areas should remain dark. The objectives should include the wildlife requirements identified in Step 2: Describe wildlife and be consistent with How to use these guidelines.

For more information about developing lighting objectives, see Appendix A – Best practice lighting design.

Step 2: Describe wildlife

Describe the biology and ecology of wildlife in the area that may be affected by artificial light (species identified during the screening process – see Figure 3). The abundance, conservation status and regional significance of wildlife will be described, as will the location of important habitat. Recognise biological and ecological parameters relevant to the assessment, particularly how artificial light will be viewed by an animal. This includes an animal's physiological sensitivity to wavelength and intensity, and its visual field.

Depending on the availability of information, the scale of the activity and the susceptibility of wildlife to artificial light, this step may only require a desktop analysis. Where there is a paucity of information or the potential for effects is high, field surveys may be necessary. Where there will be a need to monitor the effectiveness of lighting mitigation and management strategies (Step 5: Biological and light monitoring and auditing), baseline monitoring will be necessary.

Desktop study of wildlife

A review of the available government databases, scientific literature and unpublished reports should be conducted to determine whether listed or protected wildlife that are susceptible to the effects of artificial light could be present. Tools to identify species or important habitat that may occur within 20 km of the area of interest include:

- the department's Protected Matters Search Tool
- the department's National Conservation Values Atlas
- state and territory protected species information
- scientific literature
- local and Indigenous knowledge.

To assess the risks to a species, an understanding of the animal's susceptibility to the effects of light should be evaluated, as well as the potential for artificial light to affect the local population.

The species conservation status should be identified. Relevant population demographic and behavioural characteristics that should be considered include population size, life stages present, and normal behaviour in the absence of artificial light. This step should also identify biological and ecological characteristics of the species that will be relevant to the assessment. This may include understanding the seasonality of wildlife using the area; the behaviour (that is, reproduction, foraging, resting) of wildlife; migratory pathways; and life stages most susceptible to artificial light. Consideration should also be given to how artificial light may affect food sources, availability of habitat, competitors or predators.

Field surveys for wildlife

Where there are insufficient data to understand the actual or potential importance of a population or habitat, it may be necessary to conduct field surveys. The zone of influence for artificial lighting will be case and species-specific. Surveys should describe habitat, species abundance and density on a local and a regional scale at a biologically relevant time of year.

Baseline monitoring
Where it is considered likely that artificial lighting will impact wildlife, it may be necessary to undertake baseline monitoring to inform mitigation and light management (Step 5: Biological and light monitoring and auditing).

Field survey techniques and baseline monitoring needs will be species-specific. Detailed parameters and approaches are described Appendix F – Marine turtles, Appendix G – Seabirds, Appendix H – Migratory shorebirds, Appendix I – Bats, Appendix J – Terrestrial Mammals and Appendix K – Ecological Communities. Guidance from species experts should be sought for other species.

Step 3: Risk assessment

Using information collated in steps Step 1: Describe the project lighting and Step 2: Describe wildlife, the level of risk to wildlife should be assessed. Risk assessments should be undertaken on a case-by-case basis, as they will be specific to the wildlife involved, the lighting objectives and design, and the prevailing environmental conditions. Assessments should be undertaken in accordance with Australian Standard AS ISO 31000:2018 *Risk Management – Guidelines* (or superseding equivalent), which provides principles for adaptive management and continuous improvement. The scale of the assessment is expected to be commensurate with the scale of the activity and the vulnerability of the wildlife present.

In general, the assessment should consider how important the habitat is to the species (for example, whether it is the only place where the species is found), the biology and ecology of wildlife, the amount and type of artificial light at each phase of development (for example, construction or operation) and whether the lighting scenario is likely to cause an adverse response. The assessment should consider the artificial light impact mitigation and management that will be implemented. It should also consider factors likely to affect an animal's perception of light; the distance to the lighting source; and whether light will be directly visible or viewed as skyglow. The process should assess whether wildlife will be disrupted or displaced from important habitat, and whether wildlife will be able to undertake critical behaviours such as foraging, reproduction and dispersal.

Where a likely risk is identified, either the project design should be modified, or further mitigation should be put in place to reduce the risk.

If the residual risk is likely to be significant, consideration should be given to whether the project should be referred for assessment under the EPBC Act and/or relevant state or territory legislation.

Step 4: Artificial light management plan

The management plan will document the EIA process. The plan should include all relevant information obtained in steps Step 1: Describe the project lighting to Step 3: Risk assessment. It should describe the lighting objectives; the existing light environment; susceptible wildlife present, including relevant biological characteristics and behaviour; and proposed mitigation. The plan should clearly document the risk assessment process, including the consequences that were considered, the likelihood of occurrence, and any assumptions that underpin the assessment. Where the risk assessment deems it unlikely that the proposed artificial light will affect wildlife and an artificial light management plan is not required, the information and assumptions underpinning these decisions should be documented.

Where an artificial light management plan is deemed necessary, it should document the scope of monitoring and auditing to test the efficacy of proposed mitigation and triggers to revisit the risk assessment. This should include a clear adaptive management framework to support continuous improvement in light management, including a hierarchy of contingency management options if biological and light monitoring or compliance audits indicate that mitigation is not meeting the objectives of the plan.

The detail and extent of the plan should be proportional to the scale of the development and potential impacts to wildlife.

Toolboxes of options are provided in Appendix F – Marine turtles, Appendix G – Seabirds, Appendix H – Migratory shorebirds, Appendix I – Bats, Appendix J – Terrestrial Mammals and Appendix K – Ecological Communities. Guidance from species experts should be sought for other species.

Step 5: Biological and light monitoring and auditing

The success of the impact mitigation and artificial light management should be confirmed through monitoring and compliance auditing. Light audits should be regularly undertaken, and biological and behavioural monitoring should be undertaken on a timescale relevant to the species present. Observations of wildlife interactions should be documented, accompanied by relevant information such as weather conditions and moon phase. Consideration should be given to monitoring control sites. Monitoring should be undertaken both before and after changes to artificial lighting are made at both the affected site and the control sites. The results of monitoring and auditing are critical to an adaptive management approach, with the results used to identify where improvements in lighting management may be necessary. Audits should be undertaken by appropriately qualified personnel.

Baseline, construction and post-construction artificial light monitoring, wildlife biological monitoring and auditing are detailed in Appendix C – Measuring biologically relevant light, Appendix D – Artificial light auditing and the technical appendices: Appendix F – Marine turtles, Appendix G – Seabirds, Appendix H – Migratory shorebirds, Appendix I – Bats, Appendix J – Terrestrial Mammals and Appendix K – Ecological Communities.

Step 6: Review

Once light audits and biological monitoring have been completed, a review of whether the lighting objectives have been met should be conducted. The review should incorporate any changing circumstances and make recommendations for continual improvement. The recommendations should be incorporated through upgraded mitigations, changes to procedures, and renewal of the light management plan.

Case studies

Unlike many forms of pollution, artificial light can be removed from the environment. The following case studies show it is possible to balance the requirements of both human safety and wildlife conservation.

Gorgon LNG plant on Barrow Island, Western Australia

The Chevron Australia Gorgon Project is one of the world's largest natural gas projects. The LNG processing facility is on Barrow Island, a Western Australian Class A nature reserve off the Pilbara Coast known for its diversity of fauna, including important nesting habitat for Flatback Turtles (Moro et al. 2018).

The LNG plant was built adjacent to important turtle nesting beaches. The effect of light on the turtles and emerging hatchlings was considered from early in the design phase of the project, and species-specific mitigation was incorporated into project planning (Moro et al. 2018). Light management is implemented, monitored and audited through a light management plan, and turtle population demographics and behaviour through the Gorgon Gas Development and Jansz Feed Gas Pipeline *Long-term Marine Turtle Management Plan* (Chevron Australia 2018).

Lighting is required to reduce safety risks to personnel and to maintain a safe place of work under workplace health and safety requirements. The lighting objectives considered these requirements while also aiming to minimise light glow and eliminate direct light spill on nesting beaches. This includes directional or shielded lighting, the mounting of light fittings as low as practicable, louvered lighting on low-level bollards, automatic timers or photovoltaic switches, and black-out blinds on windows. Accommodation buildings were oriented so that a minimal number of windows faced the beaches, and parking areas were located to reduce vehicle headlight spill onto the dunes.

Lighting management along the LNG jetty and causeway adopted many of the design features used for the plant and accommodation areas. LNG loading activity is supported by a fleet of tugs that were custom built to minimise external light spill. LNG vessels are requested to minimise non-essential lighting while moored at the loading jetty.

Figure 6 LNG plant on Barrow Island

Photo: Chevron Australia.

To reduce skyglow, the flare for the LNG plant was designed as a ground box flare, rather than the more conventional stack flare. A louvered shielding wall further reduced the effects of the flare.

Lighting reviews are conducted prior to the nesting season to allow time to implement corrective actions if needed. Workforce awareness is conducted at the start of each turtle breeding season to further engage the workforce in the effort to reduce light wherever possible.

The Long-term Marine Turtle Management Plan (Chevron Australia 2018) provides for ongoing risk assessment of the impact of artificial light on the Flatback turtles nesting on beaches adjacent to the LNG plant, including mitigation measures to minimise the risk from light to turtles. The plan also provides for an ongoing turtle research and monitoring program.

Phillip Island

Victoria's Phillip Island is home to one of the world's largest colonies of listed migratory Short-tailed Shearwaters (*Ardenna tenuirostris*). It supports more than 6% of the global population of this species (Rodríguez et al. 2014). Shearwaters nest in burrows and are nocturnally active at their breeding colonies. Fledglings leave their nests at night. When exposed to artificial light, fledglings can be disoriented and grounded. Some fledglings may reach the ocean but then be attracted back toward coastal lighting. Fledglings are also vulnerable to collision with infrastructure when disoriented, and once grounded they become vulnerable to predation or roadkill (Rodríguez et al. 2017a) (Figure 7).

Phillip Island also attracts over a million visitors a year during peak holiday seasons to visit the Little Penguin (*Eudyptula minor*) ecotourism centre, the Penguin Parade®. Most visitors drive from Melbourne across a bridge to access the island. The increase in road traffic at sunset during the Easter break coincides with the maiden flight of fledgling shearwaters from their burrows (Rodríguez et al. 2014).

In response to the deaths of fledglings, Phillip Island Nature Parks has an annual shearwater rescue program to remove and safely release grounded birds (Rodríguez et al. 2014). In collaboration with SP Ausnet and Regional Roads Victoria, road lights on the bridge to the island are turned off during the fledgling period (Rodríguez et al. 2017b). To address human safety concerns, speed limits are reduced and warning signals put in place during fledgling season (Rodríguez et al. 2017b; Rodríguez, Dann & Chiaradia 2017). The reduced road lighting and associated traffic controls and warning signals, combined with a strong rescue program, have reduced the mortality rate of shearwaters (Rodríguez et al. 2014).

Figure 7 Short-tailed Shearwater (*Ardenna tenuirostris*) fledgling grounded by artificial light, Phillip Island

Photo: Airam Rodriguez.

Raine Island research vessel light controls

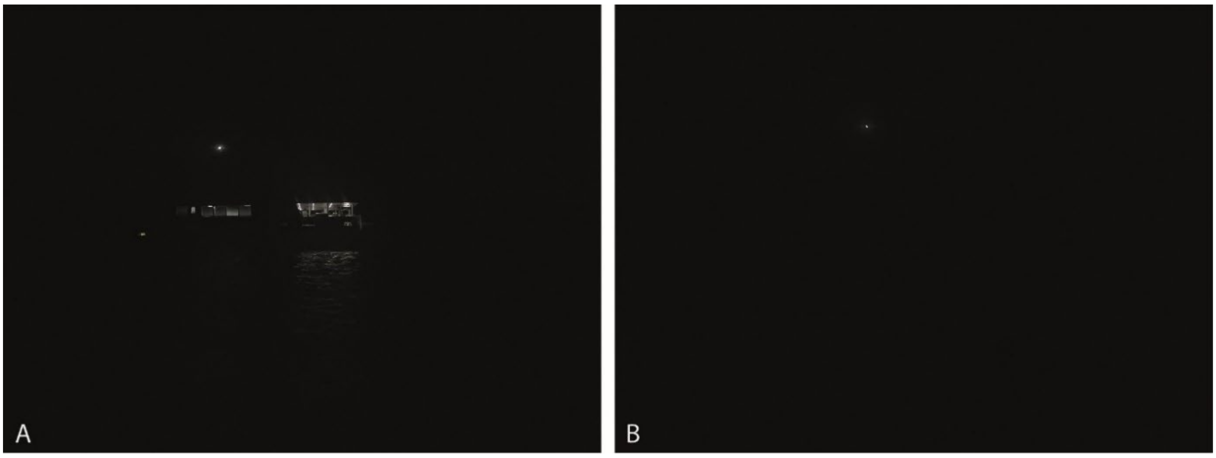
The Queensland Marine Parks primary vessel *Reef Ranger* is a 24 m catamaran jointly funded by the Great Barrier Reef Marine Park Authority and the Queensland Parks and Wildlife Service under the Field Management Program (FMP). The *Reef Ranger* is often anchored at offshore islands that are known marine turtle nesting sites and is regularly at Raine Island, one of the world's largest Green Turtle nesting sites (Limpus et al. 2003) and a significant seabird rookery.

Vessels often emit a lot of artificial light when at anchor. The FMP took measures to minimise direct lighting spillage from the *Reef Ranger*. It implemented a lights-off policy around turtle nesting beaches, where the use of outdoor vessel lights was limited except for safety reasons.

The original fit-out of the vessel did not include internal block-out blinds (Figure 8). These were installed before the 2018–19 Queensland turtle nesting season. The blinds stop light being emitted from inside the vessel, thereby limiting light spill around the vessel (Figure 8). This can make an important difference at remote (naturally dark) sites such as Raine Island.

Anecdotal evidence suggests that hatchlings previously attracted to, and captured in, light pools around the vessel are no longer drawn to the *Reef Ranger*.

Figure 8 Vessel lighting management at Raine Island



A: Vessel with decking lights, venetian blinds down and anchor light on. B: Vessel with outside lights off and block-out blinds installed (note that the white anchor light is a maritime safety requirement).
Photo: Queensland Parks and Wildlife Service.

Appendix A – Best practice lighting design

Natural darkness has conservation value in the same way as clean water, air and soil and should be protected through good-quality lighting design.

The following simple management principles can be used to reduce light pollution:

1) Start with natural darkness and only add light for specific purposes.

2) Use adaptive light controls to manage light timing, intensity and colour.

3) Light only the object or area intended – keep lights close to the ground, directed, and shielded to avoid light spill.

4) Use the lowest intensity lighting appropriate for the task.

5) Use non-reflective, dark-coloured surfaces.

6) Use lights with reduced or filtered blue, violet and ultraviolet wavelengths.

The application of best practice lighting design for all outdoor lighting is intended to reduce skyglow and minimise the effects of artificial light on wildlife.

Lighting objectives

At the outset of a lighting design process, the purpose of artificial lighting should be clearly stated, and consideration should be given as to whether it is required at all.

Exterior lighting for public, commercial or industrial applications is typically designed to provide a safe working environment. It may also be required to provide for human amenity or commerce. Conversely, areas of darkness, seasonal management of artificial light, or minimised skyglow may be necessary for wildlife protection, astronomy or dark-sky tourism.

Lighting objectives will need to consider the regulatory requirements and Australian standards relevant to the activity, location and wildlife present.

Objectives should be described in terms of specific locations and times at which artificial light is necessary. Consideration should be given to whether colour differentiation is required and whether some areas should remain dark – either to contrast with lit areas or to avoid light spill. Where relevant, wildlife requirements should form part of the lighting objectives.

A lighting installation will be deemed a success if it meets the lighting objectives (including wildlife needs) and areas of interest can be seen by humans clearly, easily, safely and without discomfort.

The following are general principles for lighting that will benefit the environment and local wildlife and reduce energy costs.

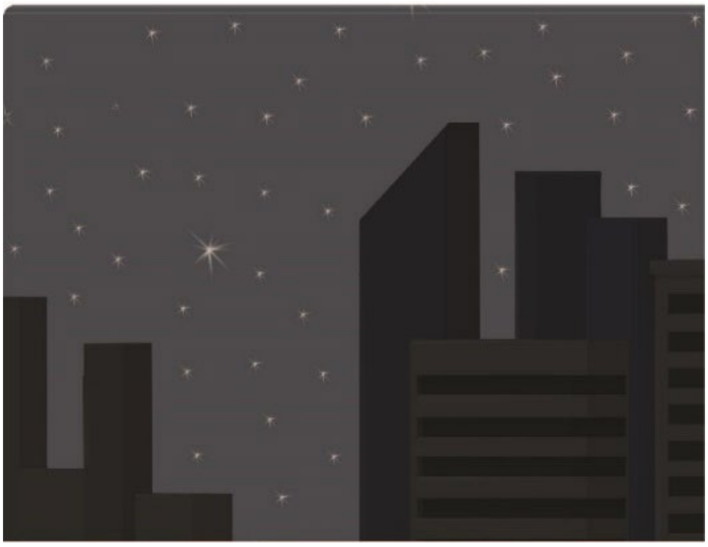
Principles of best practice lighting design

Good lighting design incorporates the following design principles. They are applicable everywhere, especially in the vicinity of wildlife.

1. Start with natural darkness

The starting point for all lighting designs should be natural darkness (Figure 9). 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. Designers should consider an upper limit on the amount of artificial light and only install the amount needed to meet the lighting objectives.

Figure 9 Start with natural darkness

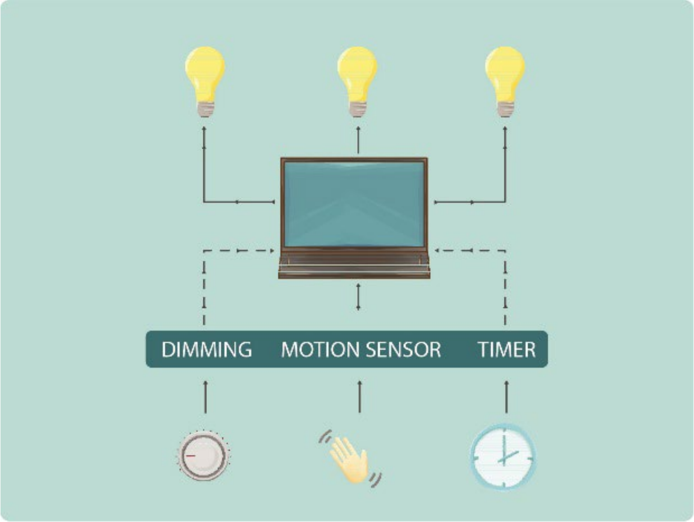


In a regional planning context, consideration should be given to designating ‘dark places’ where activities that involve outdoor artificial light are prohibited under local planning schemes.

2. Use adaptive controls

Recent advances in smart control technology provide a range of options for better controlled and targeted artificial light management (Figure 10). For example, traditional industrial lighting should remain illuminated all night because high-pressure sodium, metal halide and fluorescent lights have long warm-up and cool-down periods. This could jeopardise operator safety in the event of an emergency. With smart-controlled LED lights, plant lighting can be switched on and off instantly and activated only when needed – for example, when an operator is physically present at the site.

Figure 10 Use adaptive controls to manage light timing, intensity and colour



Smart controls and LED technology allow for:

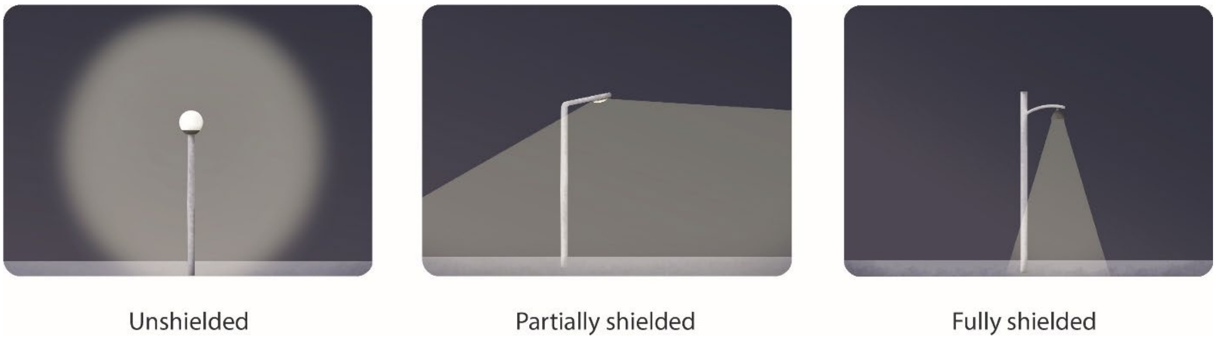
- remotely managing lights (computer controls)
- instantly switching lights on and off
- controlling light colour (emerging technology)
- dimming, timers, flashing rate, motion sensors and well-defined directivity of light.

Adaptive controls should maximise the use of the latest lighting technology to minimise unnecessary light output and energy consumption.

3. Light only the intended object or area – keep lights close to the ground, directed and shielded

Light spill is light that falls outside the area intended to be lit. Light that spills above the horizontal plane contributes directly to artificial skyglow, while light that spills into adjacent areas on the ground (also known as light trespass) can be disruptive to wildlife in adjacent areas. All light fittings should be located, directed and shielded to avoid lighting anything but the target object or area (Figure 11). Existing lights can be modified by installing a shield.

Figure 11 Lights should be shielded to avoid lighting beyond the target area or object


Unshielded

Partially shielded

Fully shielded

Figure adapted from Witherington and Martin (2003).

Lower height lighting that is directional and shielded can be extremely effective. Light fixtures should be located as close to the ground as possible and shielded to reduce skyglow (Figure 12).

Figure 12 Walkway lighting should be mounted as low as possible and shielded

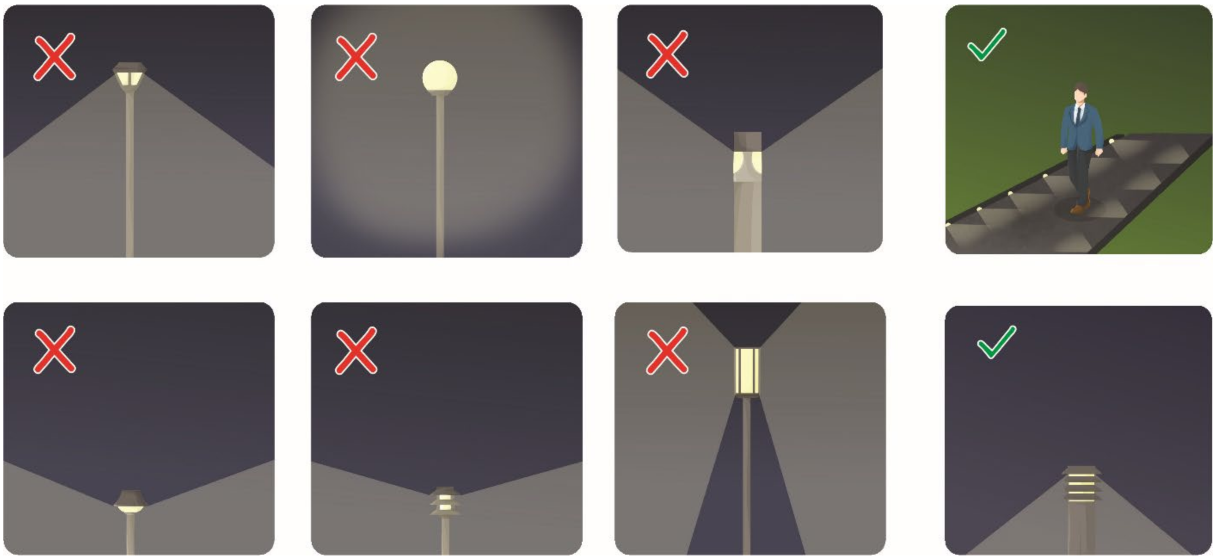


Figure adapted from Witherington and Martin (2003).

Artificial light can be prevented from shining above the horizontal plane by ensuring the luminaire is mounted horizontally relative to the ground and not at an angle, or mounted on a building so that the structure prevents the light shining above the horizontal plane – for example, recessing a light into an overhanging roof eave. When determining the angle of mounting, consideration should be given to the reflective properties of the receiving environment.

If an unshielded fitting is to be used, consideration should be given to the direction of the light and the need for some form of permanent physical opaque barrier that will provide the shielding requirement. This can be a cover or part of a building (Figure 13). Care should be taken to also shield light-coloured adjacent surfaces, to prevent excessive reflected light from adding to skyglow.

Figure 13 Lighting should be directed to ensure only the intended area is lit

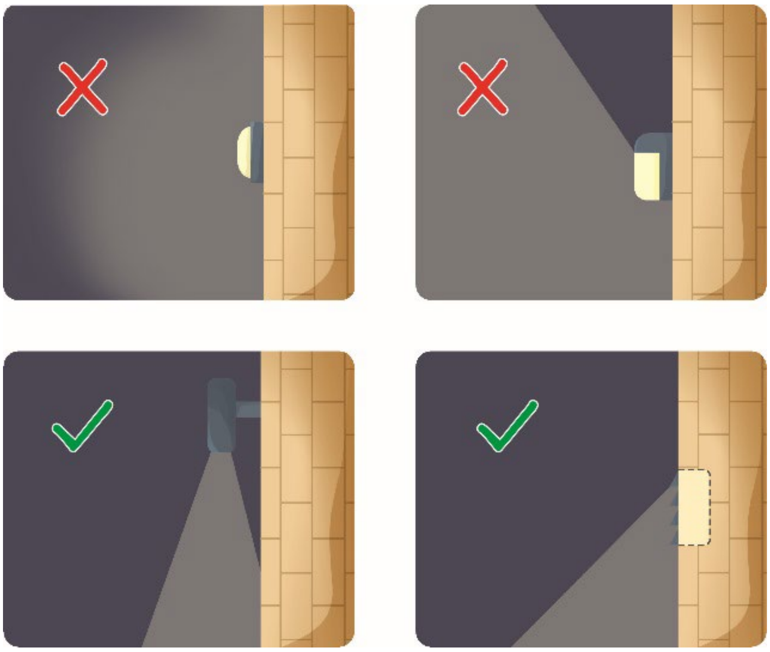


Figure adapted from Witherington and Martin (2003).

Consideration should also be given to blocking light spill from internal light sources. This should include block-out blinds or shutters for transparent portions of a building, including skylights, and use of glass in windows and balconies with reduced visible light transmittance values.

4. Use appropriate lighting

Lighting intensity should be appropriate for the activity. Starting from a base of no lights, use only the minimum number and intensity of lights needed to provide safe and secure illumination for the area at the time required to meet the lighting objectives. The minimum amount of light needed to illuminate an object or area should be assessed during the early design stages and only that amount of light installed. For example, Figure 14 provides options from best to worst for lighting a parking area.

Figure 14 Lighting options for a parking area

Unacceptable

Poor

Acceptable

Best

Figure adapted from Witherington and Martin (2003).

Off-the-shelf lighting design models

Computer design engineering packages that do not include wildlife needs and only recommend a standard lighting design for general application should be avoided or, if used, modified to suit the specific project objectives, location and risk factors.

Consider the intensity of light produced rather than the energy required to make it

Improvements in technology mean that new bulb types produce significantly greater amounts of light per unit of energy. For example, LED lights produce between 2 and 5 times the amount of light produced by incandescent bulbs. The amount of light produced (lumen), rather than the amount of energy used (watt) is the most important consideration in ensuring that an area is not over lit.

Consider re-evaluating security systems and using motion sensor lighting

Technological advances mean that techniques such as computer-managed infrared tracking of intruders in security zones is likely to result in better detection rates than a human observer monitoring an illuminated zone.

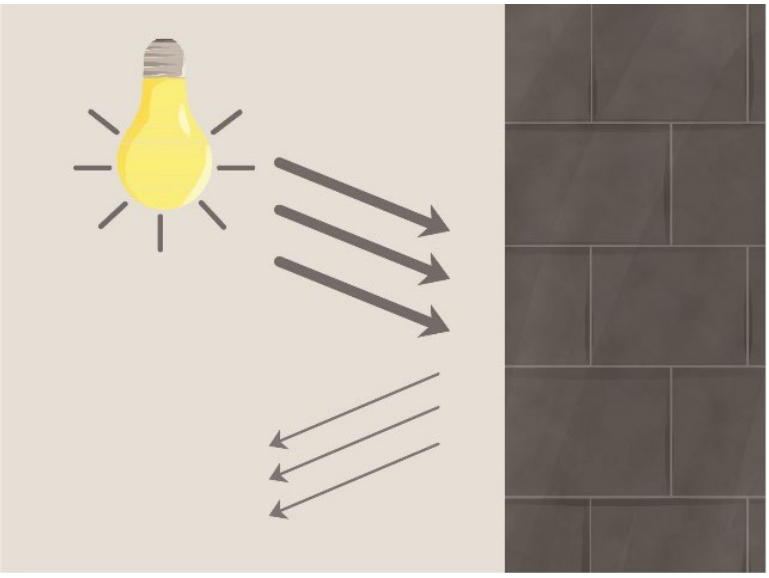
Use low-glare lighting

High-quality, low-glare lighting should always be a strong consideration regardless of how the project is to be designed. Low-glare lighting enhances visibility for the user at night, reduces eye fatigue, improves night vision and delivers light where it is needed.

5. Use non-reflective, dark-coloured surfaces

Light reflected from highly polished, shiny or light-coloured surfaces such as white painted infrastructure, polished marble or white sand can contribute to skyglow. For example, alternatives to painting storage tanks with white paint to reduce internal heating should be explored during front-end engineering design. In considering surface reflectance, the need to view the surface should be taken into consideration, as darker surfaces will require more light to be visible. The colour of paint or material selected should be included in the artificial light management plan.

Figure 15 Use non-reflective dark-coloured surfaces



6. Use lights with reduced or filtered-out blue, violet and ultraviolet wavelengths

Short-wavelength light (blue) scatters more readily in the atmosphere and therefore contributes more to skyglow than longer wavelength light. Further, most wildlife are sensitive to short-wavelength (blue/violet) light (for detailed discussion see Appendix B – What is light and how does wildlife perceive it?). Generally, only lights with little or no short wavelength (400 nm to 500 nm) violet or blue light should be used, to avoid unintended effects. Where wildlife are sensitive to longer wavelength light (for example, some bird species), consideration should be given to wavelength selection on a case-by-case basis.

When determining the appropriate wavelength of light to be used, all lighting objectives should be considered. If good colour rendition is required for human use, then other mitigation measures such as tight control of light spill, use of head torches, or timers or motion sensors to control lights should be implemented.

It is not possible to tell how much blue light is emitted from an artificial light source by the colour of light it produces (see Light-emitting diodes in Appendix B). LEDs of all colours, particularly white, can emit a large amount of blue light, and the correlated colour temperature (CCT) only provides a proxy for the blue light content of a light source. Consideration should be given to the spectral characteristics (spectral power distribution curve) of the lighting to ensure short-wavelength (400 nm to 500 nm) light is minimised.

Appendix B – What is light and how does wildlife perceive it?

A basic understanding of how light is defined, described and measured is critical to designing the best artificial light management for the protection of wildlife.

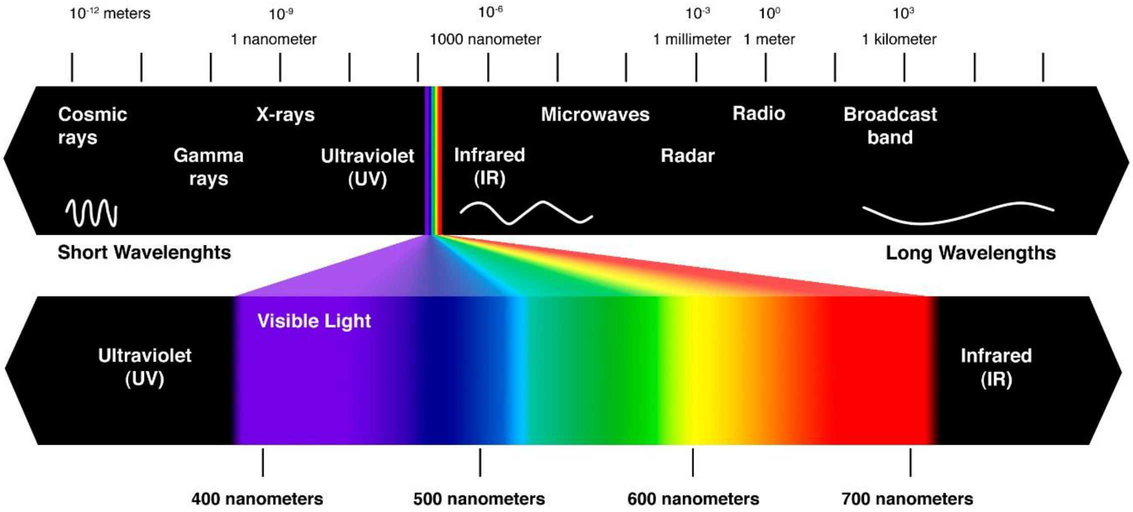
Humans and animals perceive light differently. However, defining and measuring light has traditionally focused exclusively on human vision. Commercial light monitoring equipment is calibrated to the sensitivity of the human eye and has poor sensitivity to the short-wavelength light that is most visible to wildlife. Impacts of artificial light on wildlife vary by species and should be considered on a case-by-case basis. These issues should be considered when describing, monitoring and designing lighting near important wildlife habitat.

What is light?

Light is a form of energy and is a subset of the electromagnetic spectrum that includes visible light, microwaves, radio waves and gamma rays (Figure 16). For humans, visible light ranges from 380 nm to 780 nm – between the violet and red regions of the electromagnetic spectrum. For animals, visible light ranges from 300 nm to greater than 700 nm, depending on the species. White light is a mixture of all wavelengths of light, ranging from short-wavelength blue to long-wavelength red light.

The perception of different wavelengths as 'colour' is subjective and is described and characterised by how the human eye perceives light: red (700 nm), orange (630 nm), yellow (600 nm), green (550 nm), blue (470 nm), indigo (425 nm) and violet (400 nm) (Figure 16). Generally, this is not how animals see light (Figure 2).

Figure 16 The electromagnetic spectrum



The 'visible light spectrum' occurs between 380 nm and 780 nm and is the part of the spectrum that the human eye can see. Credit: Mihail Pernichev (Iristech 2018).

Artificial light

Artificial light at night has many positive attributes. It can enhance human safety and provide for longer periods of work or recreation. However, it can also have a negative effect. For example, it can cause:

- physiological damage to retinal cells in human and animal eyes (Algvere, Marshall & Seregard 2006)
- disruption of the circadian cycles in vegetation, animals and humans (Russart & Nelson 2018a; Bennie et al. 2016; West et al. 2010)
- changes in animal orientation, feeding or migratory behaviour (Warrant et al. 2016; Pendoley & Kamrowski 2015a; Bird, Branch & Miller 2004; Salmon 2006).
- The biological mechanisms that cause these effects vary. It is necessary to understand some basic light theory and language to assess and manage the effect of light on wildlife. Some basic principles are briefly described in this section.

Vision in animals

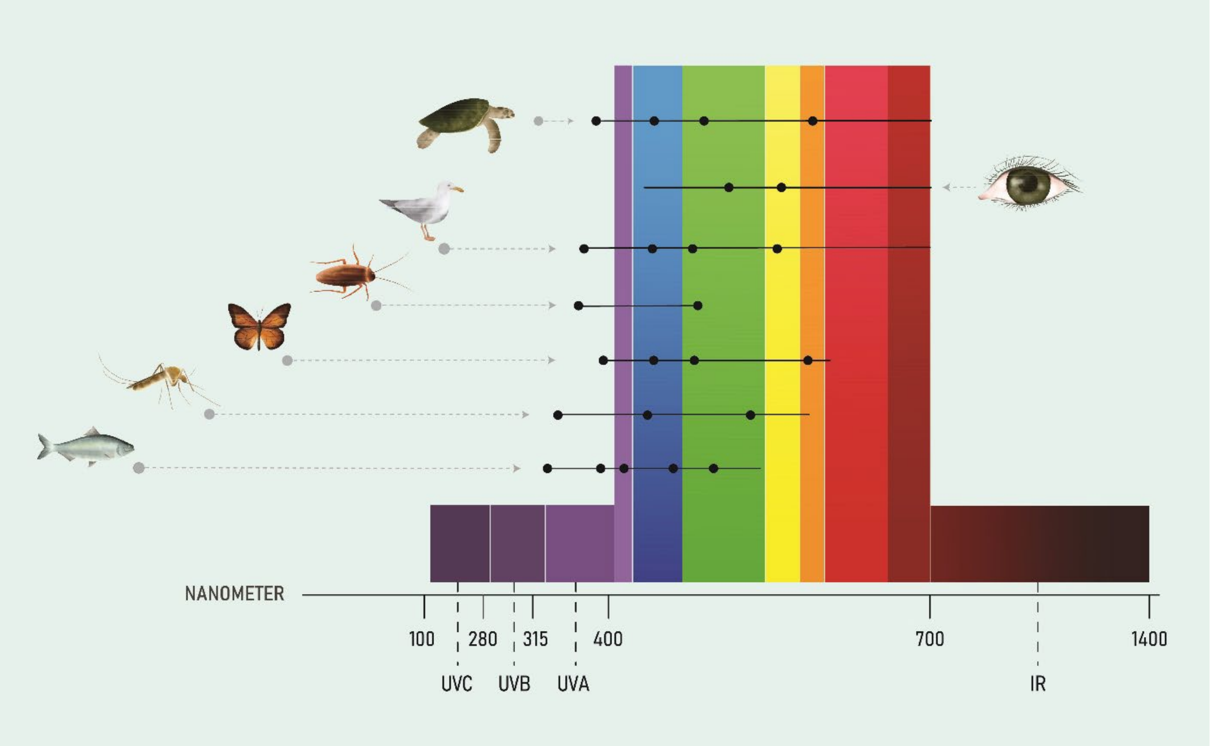
Vision is a critical cue for animals to orient themselves in their environment, find food, avoid predation and communicate (Rich & Longcore 2006). Humans and wildlife perceive light differently. Some animals do not see long-wavelength red light at all, while others see light beyond the blue-violet end of the spectrum and into the ultraviolet (Figure 17).

Both humans and animals detect light using photoreceptor cells in the eye called cones and rods. Colour differentiation occurs under bright light conditions (daylight). This is because bright light activates the cones, and it is the cones that allow the eye to see colour. This is known as photopic vision.

Under low-light conditions (dark-adapted vision), light is detected by cells in the eye called rods. Rods only perceive light in shades of grey (no colour). This is known as scotopic vision. It is more sensitive to shorter wavelengths of light (blue/violet) than photopic vision.

Variations in the number and types of cells in the retina means animals and humans do not perceive the same range of colours. In animals, being ‘sensitive’ to light within a specific range of wavelengths means they can perceive light at that wavelength, and it is likely they will respond to that light source.

Figure 17 Comparative light perception among different species groups



Ability to perceive different wavelengths of light in humans and wildlife is shown by horizontal lines. Black dots represent reported peak sensitivity. Note the common sensitivity to short-wavelength light across all wildlife. Figure adapted from Campos (2017).

Sensitivity to blue light

Sensitivity to high-energy, short-wavelength UV/violet/blue light is common in wildlife (Figure 17). This light is strongly detected under scotopic (dark-adapted) vision, particularly in nocturnal species. Short-wavelength light at the blue end of the spectrum has higher energy than longer wavelength light at the red end of the spectrum. This is important to understanding the damaging physical impact that the short-wavelength, high-energy UV/blue light has on photoreceptor cells in the human eye (Tosini, Ferguson & Tsubota 2016). Although the effect on wildlife has not been well described, it is not unreasonable to expect that at high intensities blue light has the potential to damage photoreceptors in wildlife.

In addition to the potential for physical damage to the eye from exposure to blue light (400 nm to 490 nm), there is mounting evidence that exposure to these wavelengths at night may affect human and wildlife physiological functions. This is because of a third type of photoreceptor cell that has recently been identified in the retina of the mammalian eye – the photosensitive retinal ganglion cells (pRGCs). The pRGCs are not involved in image-forming vision (this occurs in the rods and cones), but instead are involved in the regulation of melatonin and in synchronising circadian rhythms to the 24-hour light/dark cycle in animals (Ecker et al. 2010). These cells are particularly sensitive to blue light (Berson 2007). Melatonin is a hormone found in plants, animals and microbes. Changes in melatonin production can affect daily behaviours such as waking time (de Jong et al. 2015), foraging behaviour and food intake (Angers et al. 2003); and seasonal cues such as the timing of reproduction in animals, causing offspring to be born during non-optimal environmental conditions (Robert et al. 2015).

Factors affecting perception of light

Factors affecting how wildlife perceive light include the type of cells being employed to detect light (photopic versus scotopic vision), whether the light is viewed directly from the source or as reflected light, how the light interacts with the environment, and the distance from the light source. These influences are discussed below.

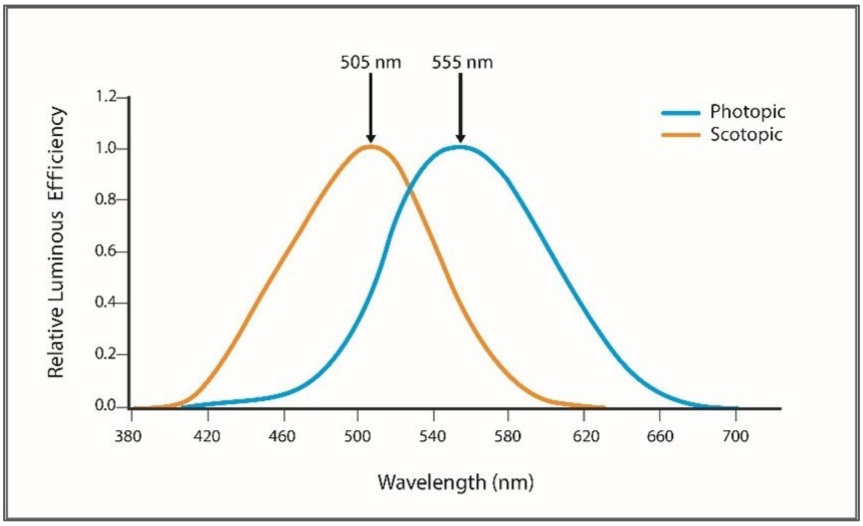
Perspective

Understanding an animal's perception of light will include consideration of the animal's visual field. For instance, when flying, birds will generally be looking down on artificial light sources, whereas turtles on a nesting beach will be looking up. Further, some birds' field of view will stretch around to almost behind their head.

Bright versus dim light

Understanding photopic and scotopic vision is important when selecting the colour (wavelength) and intensity of a light. In animals scotopic (dark adapted) vision allows for the detection of light at very low intensities (Figure 18). This dark adaptation may explain why nocturnal wildlife are extremely sensitive to white and blue light even at low intensities.

Figure 18 Scotopic and photopic luminosity functions in humans



Data source: Colour & Vision Research Laboratory (CVRL) database, Luminosity functions.

Direct versus reflected

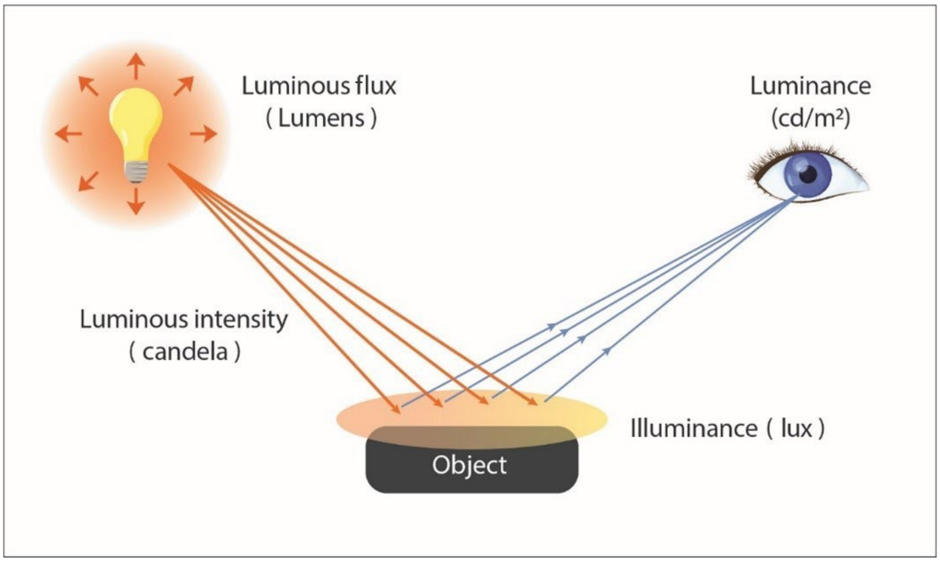
Understanding the difference between light direct from the source (luminance) and how much incident light illuminates a surface (illuminance) is important when selecting methods for measuring and monitoring light. Equipment used to measure illuminance and luminance is not interchangeable and will lead to erroneous conclusions if used incorrectly.

Luminance describes the light that is emitted, passing through or reflected from a surface that is detected by the human eye. The total amount of light emitted from a light is called luminous flux and represents the light emitted in all directions (Figure 19). Luminance is quantified using a spectroradiometer or luminance meter.

Illuminance measures how much of the incident light (or luminous intensity) illuminates a surface. Illuminance is quantified using an illuminance spectrophotometer or lux meter.

The total amount of light emitted by a bulb is measured in lumens and is different to watts, which are a measure of the amount of power consumed by the bulb. Lumens, not watts, provide information about the brightness of a bulb.

Figure 19 Luminous flux, luminance and illuminance



Visibility of light in the environment

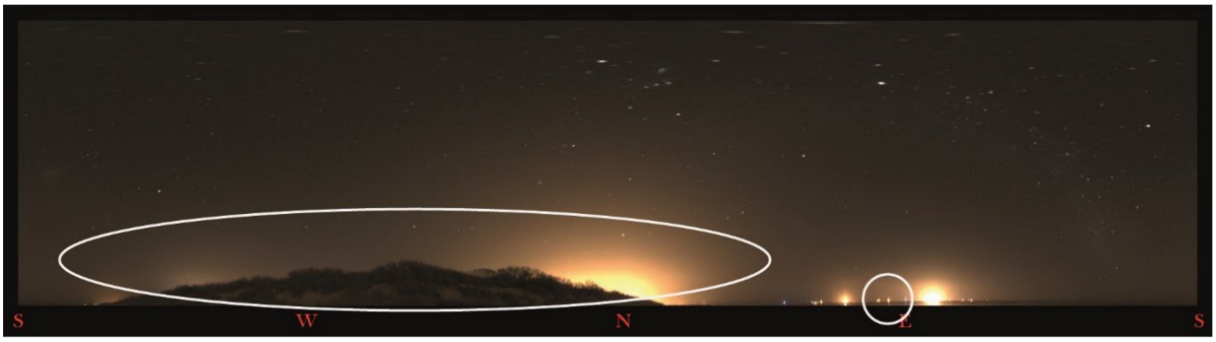
The physical properties of light include reflection, refraction, dispersion, diffraction and scattering. These properties are affected by the atmosphere through which light travels. Short-wavelength violet and blue light scatters in the atmosphere more than longer wavelength light such as green and red, due to an effect known as Rayleigh scattering (Benenson et al. 2006).

Scattering of light by dust, salt and other atmospheric aerosols increases the visibility of light as skyglow, while the presence of clouds reflecting light back to earth can substantially illuminate the landscape (Kyba et al. 2011). Hence the degree of overhead skyglow is a function of aerosol concentration and cloud height and thickness.

Direct light versus skyglow

Light may appear as either a direct light source from an unshielded lamp with direct line of sight to the observer, or as skyglow (Figure 20). Skyglow is the diffuse glow caused by source light that is screened from view but creates a glow in the atmosphere through reflection and refraction. Skyglow is affected by cloud cover and other particles in the air. Blue light scatters more in the atmosphere compared with yellow-orange light. Clouds reflect light well, adding to skyglow.

Figure 20 Skyglow created by lights shielded by a vegetation screen, and point sources of light directly visible

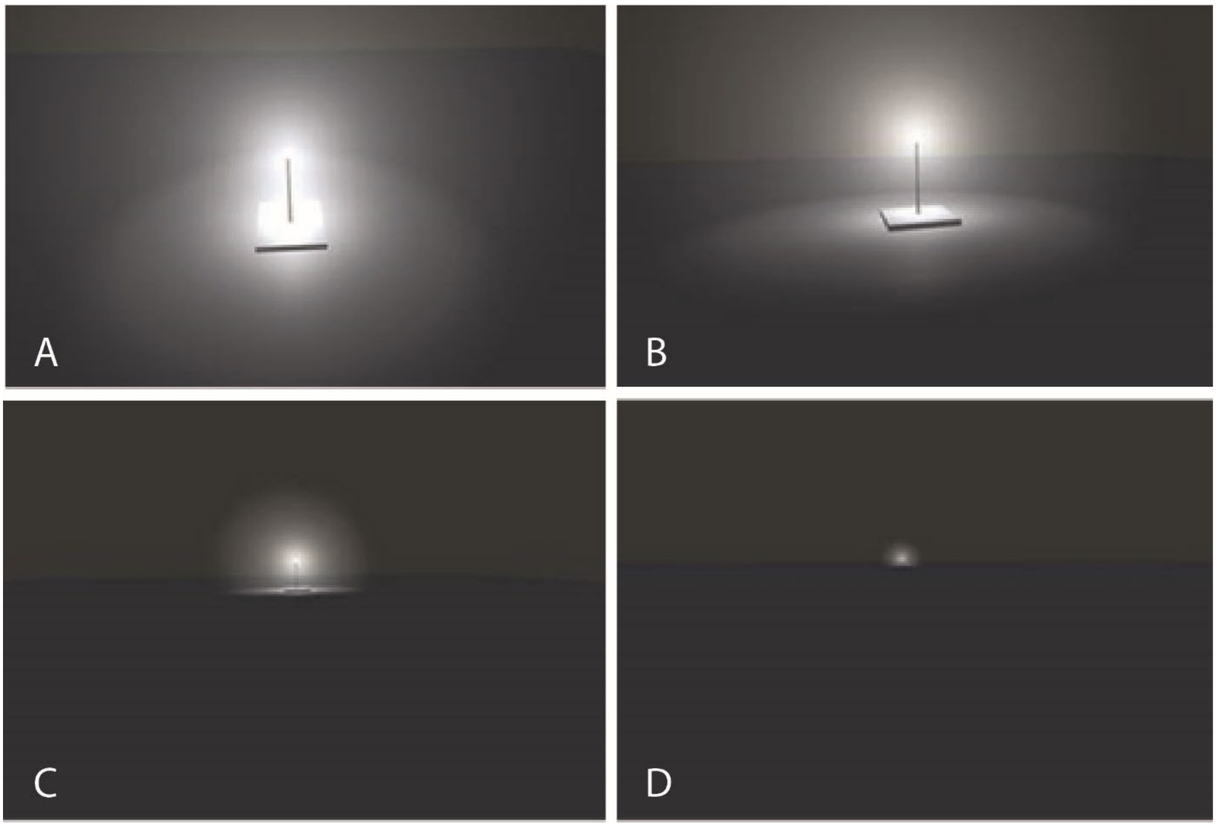


Circled left: lights shielded by vegetation screen. Circled right: point sources of light directly visible

Distance from light source

The physical properties of light follow the inverse square law, which means that the visibility of the light, as a function of its intensity and spatial extent, decreases with distance from the source (Figure 21). This is an important factor to consider when modelling light or assessing the impact of light across different spatial scales, for example across landscape scales compared to within development footprints.

Figure 21 Modelled changes in the visibility of an unshielded 1,000 W white LED viewed from 10 m, 100 m, 1 km and 3 km

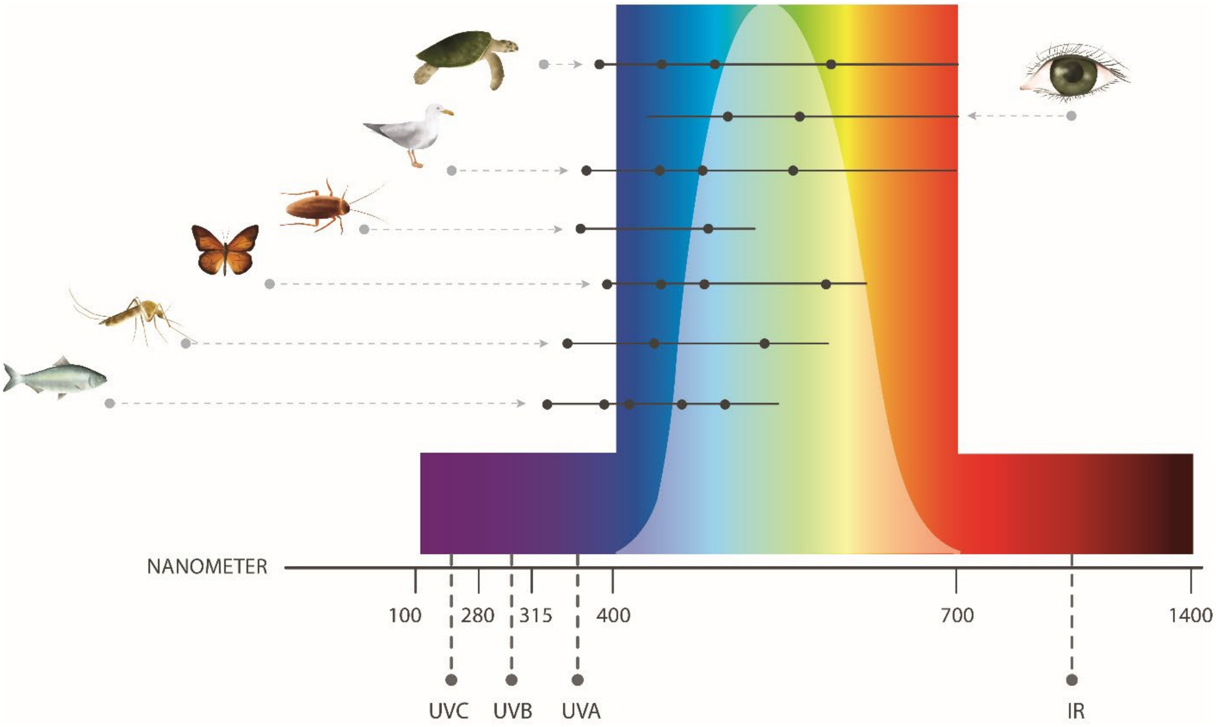


A. 10 m; B. 100 m; C. 1 km; D. 3 km.

Measurement of light

Light has traditionally been measured photometrically or using measurements that are weighted to the sensitivity of the human eye (peak 555 nm). Photometric light is represented by the area under the Commission Internationale de l'Éclairage (CIE) curve, but this does not capture all light visible to wildlife (Figure 22).

Figure 22 Comparative light perception among different species groups



Photometric light is represented by the area under the CIE curve (white area) compared with ability to perceive different wavelengths (black lines) and reported peak sensitivity (black dots) in humans and wildlife. Note that the area under the CIE curve does not include much of the violet and ultraviolet light visible to many animals. Figure adapted from Campos (2017).

Light can also be measured radiometrically. Radiometric measurements detect and quantify all wavelengths from ultraviolet (UV) to infrared (IR). The total energy at every wavelength is measured. This is a biologically relevant measure for understanding wildlife perception of light. Terms such as radiant flux, radiant intensity, irradiance and radiance all refer to the measurement of light across all wavelengths of the electromagnetic spectrum.

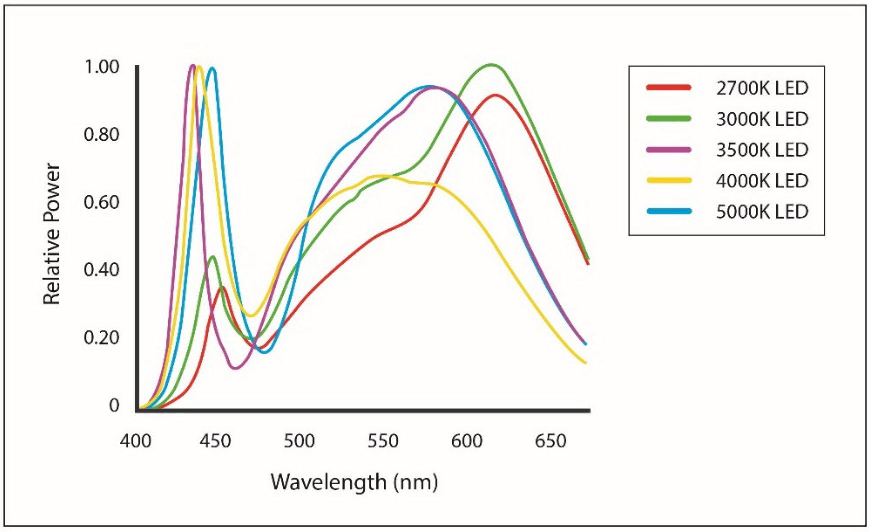
Understanding the difference between photometry (weighted to the sensitivity of the human eye) and radiometry (measures all wavelengths) is important when measuring light, since many animals are highly sensitive to light in the blue and the red regions of the spectrum and, unlike photometry, the study of radiometry includes these wavelengths.

Photometric measures (such as illuminance and luminance) can be used to discuss the potential impact of artificial light on wildlife, but their limitations should be acknowledged and considered, as these measures may not correctly weight the blue and red wavelengths to which animals can be sensitive.

Spectral curve

White light is made up of wavelengths of light from across the visible spectrum. A spectral power curve (Figure 23) provides a representation of the relative presence of each wavelength emitted from a light source. A lighting design should include spectral power distribution curves for all planned lighting types, as this will provide information about the relative amount of light emitted at the wavelengths to which wildlife are most susceptible.

Figure 23 Spectral curves showing the blue content of white 2,700 K and 5,000 K LED lights



Note the difference in relative power output in the blue (400 nm to 500 nm) wavelength range. Figure courtesy of Ian Ashdown.

Light-emitting diodes (LEDs)

Light-emitting diodes are rapidly becoming the most common light type globally, as they are more energy efficient than previous lighting technology. They can be smart controlled, are highly adaptable in terms of wavelength and intensity, and can be instantly turned on and off.

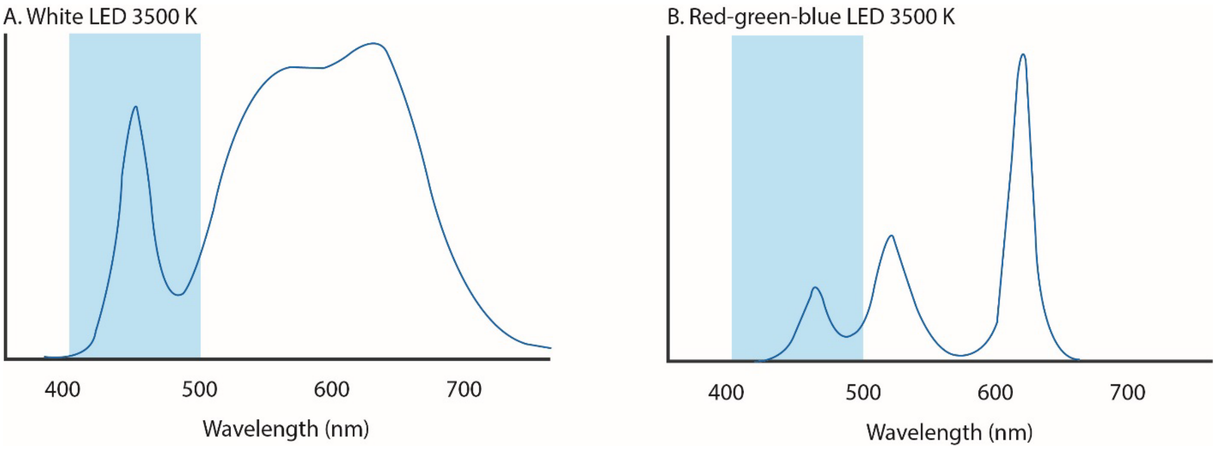
Characteristics of LED lights that are not found in older types of lamps but should be considered when assessing the impacts of LEDs on wildlife include:

- With few exceptions, all LED lights contain blue wavelengths (Figure 23 and Figure 24).
- The wattage of an LED is a measure of the electrical energy needed to produce light and is not a measure of the amount or intensity of light that will be produced by the lamp.
- The output of light produced by all lamps, including LEDs, is measured in lumens (lm).
- LED lamps require less energy to produce the equivalent amount of light output. For example, 600 lm output of light requires 40 watts (W) of energy for an incandescent light bulb and only 10 W of energy for an LED lamp. Another way to look at this is that a 100 W incandescent bulb will produce the same amount of light as a 20 W LED. Consequently, it is important to not replace an old-style lamp with the equivalent wattage LED.
- Different LED lights with the same correlated colour temperature (CCT) can have very different blue content (Figure 24) yet can appear to the human eye to be a similar colour. As the colour temperature of a white LED increases, so can the blue content (Figure 23). Little

or none of this increase in blue-wavelength light is measured by photometric equipment (that is, lux meter, luminance, illuminance meter, sky quality meter – see Appendix C – Measuring biologically relevant light).

- LED technology allows for tuneable red-green-blue (RGB) colour management. This has the potential to enable species-specific management of problematic wavelengths (for example, blue for most wildlife, but also yellow/orange).

Figure 24 Comparison of the blue-wavelength spectral content of 2 LED lights with the same CCT (3,500k)



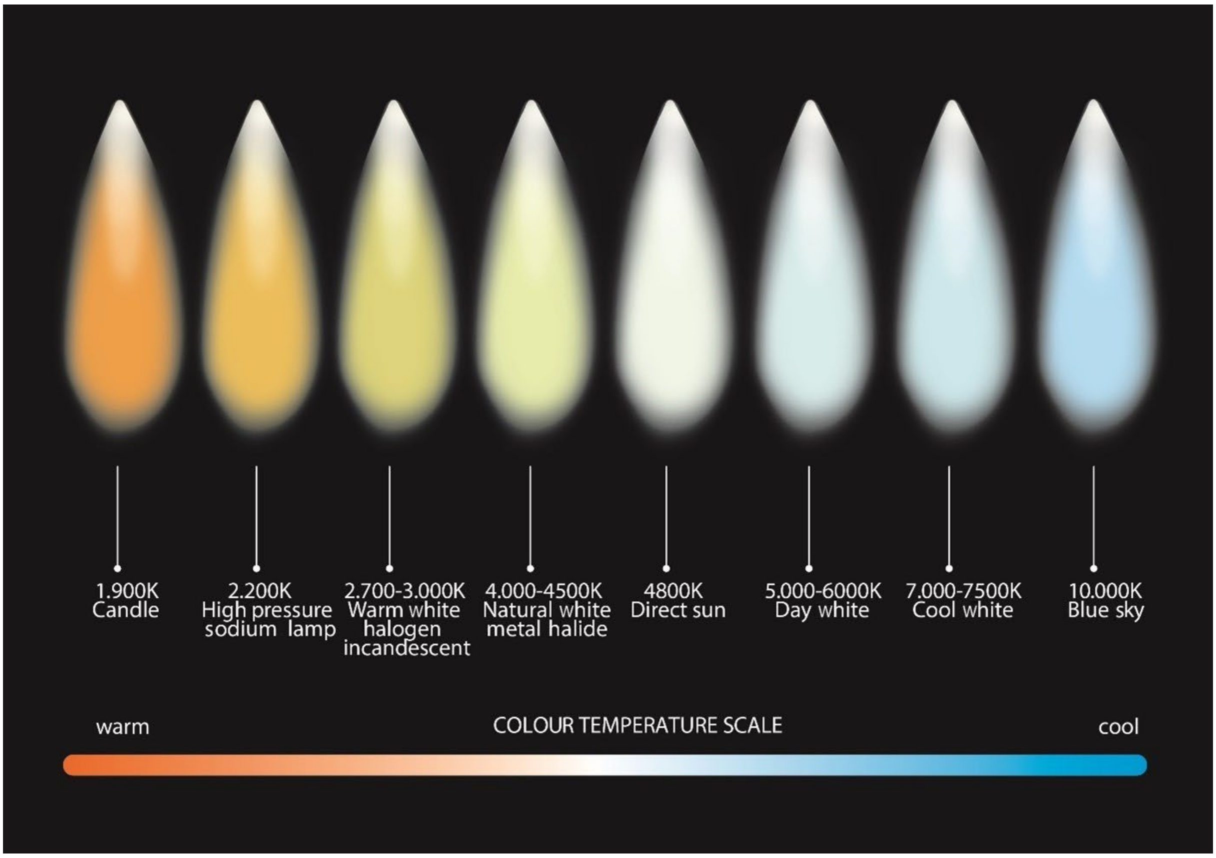
The blue band shows the blue region of the visible spectrum (400 nm to 500 nm). The light in A has much more blue light content than the light in B, yet the 2 appear to the human eye as the same colour. For animals with different sensitivities to light wavelength than those of humans, they may appear very different. Figure courtesy of Ian Ashdown.

Correlated colour temperature

CCT describes the colour appearance of a white LED. It is expressed in degrees Kelvin, using the symbol K, which is a unit of measure of absolute temperature. Practically, colour temperature is used to describe light colour and perceived 'warmth'; lamps that have a warm yellowish colour have a low CCT, between 1,000 K and 3,000 K, while lamps with a cool bluish colour have a CCT over 5,000 K (Figure 25).

CCT does not provide information about the blue content of a lamp. All LEDs contain blue light (Figure 23), and the blue content generally increases with increased CCT. The only way to determine whether the spectral content of a light source is appropriate for use near sensitive wildlife is to consider the spectral curve. For wildlife that are sensitive to blue light, an LED with low amounts of short-wavelength light should be chosen, whereas for animals sensitive to yellow light (Reed 1986), LEDs with little or no light at peak sensitivity should be used (Longcore et al. 2018).

Figure 25 Correlated colour temperature (CCT) range from warm (1,000 K) to cool (10,000 K)



Appendix C – Measuring biologically relevant light

Animals and humans perceive light differently. Commercial light monitoring instruments currently focus on measuring the region of the spectrum most visible to humans. It is important to recognise and account for this fact when monitoring light for wildlife impact assessment purposes.

Commercial light modelling programs also focus on light most visible to humans, and this should also be recognised and accounted for in the impact assessment of artificial light on wildlife.

Information critical to monitoring the effects of artificial light on wildlife includes:

- spatial extent of skyglow
- bearings and intensity of light sources along the horizon
- visibility of light (direct and skyglow) from wildlife habitats
- spectral distribution of light sources.

Describing the light environment

When describing the light environment, consideration should be given to how wildlife is likely to perceive artificial light. Light measurements should be obtained from within important habitat and taken from a biologically relevant perspective (for example, close to the ground, from the sky or under water). Consideration should also be given to elevation from the horizon, the spatial extent of skyglow and the wavelength distribution (spectrum) of light present.

It is important that light measurements are taken at appropriate times. This may include biologically relevant times (for example, when wildlife is using the area). Baseline measurements should be taken when the moon is not in the sky, when the sky is clear of clouds and in the absence of temporary lighting (such as road works). Conditions should be replicated as closely as possible for before and after measurements.

Measuring light for wildlife

Measuring light to assess its effect on wildlife is challenging and an emerging area of research and development. Most instruments used to measure skyglow are still in the research phase, with only a few commercial instruments available. Further, the wide range of measurement systems and units in use globally makes it difficult to choose an appropriate measurement metric, and often results cannot be compared between techniques due to variations in how the light is measured. There is currently no globally recognised standard method for monitoring light for wildlife.

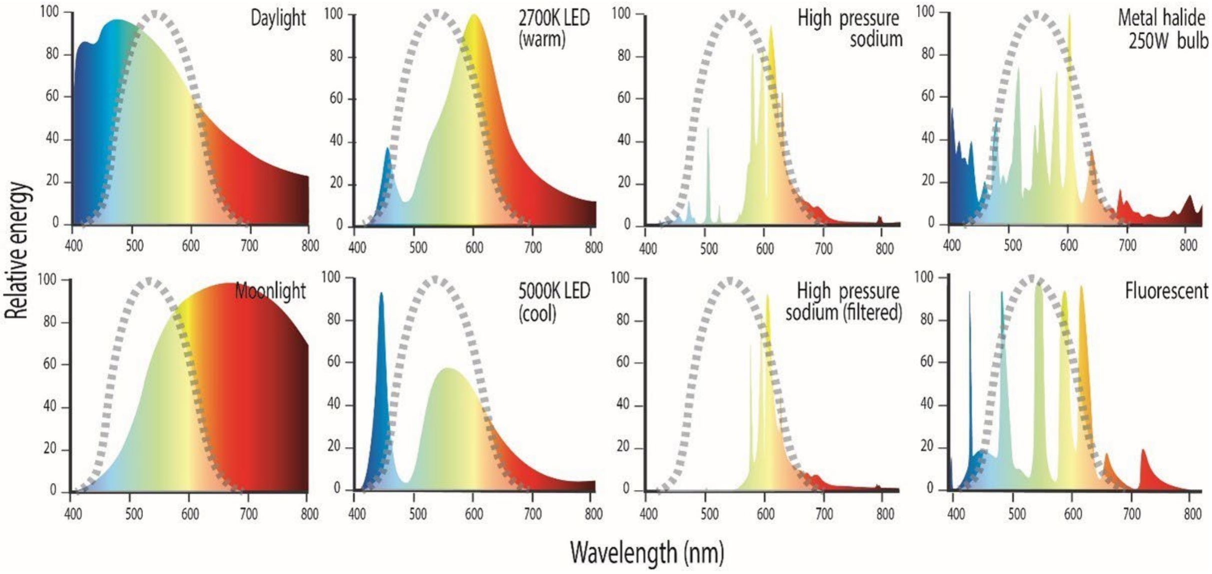
Radiometric versus photometric measurement techniques

Radiometric instruments detect and quantify light equally across the spectrum (see Measurement of light in Appendix B) and are the most appropriate instruments for monitoring and measuring light for wildlife management. However, while the techniques to measure radiometric light are well developed in physics, astronomy and medicine, they are less well developed in measurement of light in the environment. The instruments currently being developed are largely the result of academic and/or commercial research and development, are expensive, and require specialised technical skills for operation, data analysis, interpretation and equipment maintenance.

The majority of both commercial and research instruments quantify photometric light, which is weighted to the sensitivity of the human eye, as per the CIE luminosity function curve described in Measurement of light in Appendix B. Due to many photometers being modified with filters to mimic human vision, they do not accurately represent what an animal with high sensitivity to the blue (400 nm to 500 nm) or the red (650 nm to 700 nm) regions of the spectrum will see (Figure 22). In these cases, the sensitivity to this additional light must be accounted for when reporting results.

When using photometric instruments for monitoring light, this insensitivity to the short and long wavelength regions of the spectrum should be recognised and accounted for in the assessment of impact. Information on the spectral power distribution of commercial lights is readily available from manufacturers and suppliers and should be used to inform any artificial light impact assessment or monitoring program. An example of the spectral power distribution curves for various light sources is shown in Figure 26, along with an overlay of the CIE curve, which represents the light that is measured by all commercial photometric instruments.

Figure 26 Spectral power distribution curves for different types of light sources



Photometric instruments only quantify light that is within the CIE curve (area under the grey dashed line). This is shown in comparison with the spectral curves of a range of different light sources.

Recognising that light-monitoring instruments suitable for wildlife are in the developmental stage and that there is a lack of agreed methods and measurement units, monitoring programs should aim to measure relevant short and long wavelengths if possible. The measurement methods should be clearly described, including the region of the spectrum measured, and where measurement is not possible, how the short and long wavelength regions are being accounted for. Methods to do this might include a visual assessment of the colour of light in the sky from direct observation or imagery. Orange glow is typically associated with long-wavelength-rich lights (high-pressure sodium (HPS), low-pressure sodium (LPS), phosphor converted (PC) amber LED or amber LED), and white glow is associated with white light sources rich in short-wavelength blue light (white LED, halogens, fluorescents, metal halide et cetera).

Alternatively photometric instruments can be used under conditions where most light sources are the same – for example, street lighting or industrial facilities. Monitoring results can be compared for measurements of the same light types (for example, comparing 2 HPS sources, spatially or temporally) but, in the context of wildlife monitoring, this approach cannot be used to compare light from an HPS and an LED, since they have different wavelength distributions. This limitation must be considered when using photometric instruments to measure cumulative skyglow, which may include light from multiple sources and light types. Detailed qualitative spectral information on light types can also be collected to ground truth and confirm light types contributing to skyglow.

A light monitoring program might therefore include the collection of a range of different characteristics of light (such as colour, light type, areal extent, spectral power distribution, and intensity) using various instruments and techniques. These methods and techniques, including all their limitations and assumptions, should be clearly stated and considered when interpreting results. See Measurement techniques below for a review of various instrumental techniques for monitoring light.

When selecting the most appropriate measuring equipment to monitor the biological impacts of light on wildlife, it is important to decide what part of the sky is being measured: horizon, zenith (overhead) or whole sky. For example, marine turtles view light on the horizon between 0° and 30° vertically and integrate across 180° horizontally (Lohmann et al. 1997), so it is important to include measurement of light in this part of the sky when monitoring for the effects on hatchling orientation during sea-finding. In contrast, juvenile shearwaters on their first flight view light in 3 dimensions (vertically, from below and from above) as they ascend into the sky. Overhead skyglow (zenith) measurements are important when the observer is trying to avoid glare contamination by point sources of light low on the horizon. Quantifying the whole of skyglow is important when measuring the effects of cloud cover, which can reflect light back to illuminate an entire beach or wetland.

The effect of light on wildlife is a function of the animal's sensitivity and response to light, and the cues it uses during orientation, dispersal, foraging, migrating et cetera. Most wildlife appear to respond to high-intensity short-wavelength light, point sources of light, skyglow and directional light. Consequently, the information likely to be needed to monitor light for wildlife includes:

- the brightness of the entire sky from horizon to horizon
- the bearing to, intensity of and spectrum of light (point sources and skyglow) on the horizon. This will dictate the direction in which wildlife can be disoriented
- the spatial extent of glow near the horizon. A large area of glow on the horizon is likely to be more visible and disruptive to wildlife than a small area of glow
- the presence or absence of clouds. Clouds reflect light from distant sources very well, making an inland source highly visible on the coast, for example. Skyglow is a function of cloud height, albedo and thickness

- qualitative information on the light visible to wildlife. An image of light pollution visible from wildlife habitat can show the direction and spatial extent of light in the sky (see Figure 20) and in some cases provide information on the light source type (for example, orange skyglow will be caused by HPS lights or amber LEDs)
- the emission spectra (colour) of the light. It is particularly important to identify light in the UV-blue region of the visible spectrum (<500 nm) since this is the light commonly visible and disruptive to wildlife.

Measurement techniques

Currently there are no generally agreed methods for measuring biologically relevant light for wildlife or for quantifying skyglow (Barentine 2019). This is because most conventional methods of measuring light are photometric, quantifying only the light under the CIE curve that is most relevant to the human perception of light. Further, they do not consider the entire night sky.

There is a need to develop reasonably priced, repeatable, easily accessible and deployable methods for monitoring biologically relevant light that captures the whole visual field to which wildlife may be exposed (generally horizon to horizon) (Barentine 2019). These methods should be capable of quantifying all wavelengths of light equally (radiometric), including at least 380 nm to 780 nm, or capable of being calibrated over the range of wavelengths of relevance for the species of interest. Optimal methods will have the sensitivity to detect and measure change at the low light levels represented by artificial light skyglow and must have the ability to differentiate between individual point sources of light (on a local scale) and skyglow on a landscape scale (that is, over tens of kilometres).

It should be noted that measurements needed to assess the impact of skyglow on wildlife may need to be different from the measurements required to assess light for human safety.

Recognising that techniques to monitor biologically meaningful light are expected to continuously develop and improve, this section summarises the state of the science as of 2023 as an example of current techniques. It is anticipated that novel methods will be developed with time that will meet the objectives of monitoring biologically meaningful light. Where that occurs, the methods and techniques, including all the limitations and assumptions, should be clearly stated for all monitoring programs.

Recent reviews have considered various commercial and experimental instrumental techniques used around the world for quantifying skyglow (Barentine 2019; Hänel et al. 2018). The reviews assessed the benefits and limitations of the various techniques and made recommendations for measuring light pollution. Some of these instruments, and their benefits and limitations, are discussed in this section and summarised in Table 1.

Light can be measured in different ways, depending on the objective, scale and point of view, including by:

- remote sensing
- one-dimensional (single channel) instruments
- calibrated all-sky imagery (numerical and imaging)

- spectroscopy/spectroradiometry.

Remote sensing

The upward radiance of artificial light at night can be mapped via remote sensing using satellite or aerial imagery and optical sensors. This information has been used as a socioeconomic indicator to observe human activity, and increasingly as a tool to consider the impacts of artificial light on ecosystems (Levin et al. 2020). Examples are:

- the New World Atlas of Artificial Night Sky Brightness
- the interactive world Light Pollution Map application.

Benefits: The images are useful as broad-scale indicators of light pollution and for targeting biological and light monitoring programs. This technique may be a good starting point to identify potentially problematic areas for wildlife on a regional scale. Images collected via drones or aircraft may be useful for consideration of artificial light impacts on bird and bat migrations.

Limitations: Maps derived from satellite-collected information have limited value in quantifying light for wildlife. The images are a measure of light after it has passed though the atmosphere and been subject to scattering and absorption. They do not give an accurate representation of the light visible to wildlife at ground level. The annual composite images are made from images collected under different atmospheric conditions and therefore they cannot be used to confidently quantify light within or between years. The most commonly used instrument (VIIRS DNB) is not sensitive to blue light, so light in this part of the spectrum is undersampled. As satellites with more sophisticated sensors are launched, the value of this technique to biological monitoring is expected to improve.

Application to wildlife monitoring programs: While remote sensing tools may provide a good starting point for identifying artificial light that is problematic for wildlife on a regional scale, they are currently not an appropriate approach for measuring light as part of a wildlife monitoring program, as they do not accurately quantify light as observed from the ground, they underestimate the blue content of light, and results are not repeatable due to environmental conditions. Images collected via aircraft or drone may have application for monitoring impacts on airborne wildlife.

One-dimensional (single channel) instruments

These instruments measure skyglow using a single-channel detector, producing a numerical value to represent skyglow, typically at the zenith. They are generally portable and easy to use. They measure skyglow but cannot derive point source information unless they are close enough so that most of the light detected is emitted from those sources. Examples of single-channel instruments are as follows.

Sky quality meter (SQM)

This is a small handheld unit that quantifies the light in an area of sky (normally directly overhead at the zenith). Early models had a field of view of around 135°. The more recent SQM-L model has a narrower 40° diameter field of view. It measures photometric light in units of magnitude/arcsec^2 at relatively low detection limits (that is, it can measure skyglow). Instrument accuracy is reported at ±10%, though a calibration study on a group of SQM instruments in 2011 found errors ranging from –16% to +20% (den Outer et al. 2011). Long-term stability of SQMs has not been established.

Reviewers suggest that the first 3 to 4 measurements from a handheld SQM should be discarded, then the average of 4 observations should be collected by rotating the SQM 20° after each observation to obtain a value from 4 different compass directions so that the effects of stray light can be minimised or identified (Hänel et al. 2018). If the measurements vary by more than 0.2 magnitude/arcsec^2 the data should be discarded and a new location for measurements selected. Data should not be collected on moonlit nights, to avoid stray light contaminating the results.

Benefits: The SQM is cheap, easy to use and portable. Some versions have data-logging capabilities that enable autonomous operation in the field. The sensitivity of the SQM is sufficient to detect changes in overhead night-time artificial lighting under a clear sky.

Limitations: SQMs cannot be used to resolve individual light sources at a distance or identify light direction, and they cannot measure light visible to many wildlife species. The precision and accuracy of individual instruments can vary substantially and an intercalibration study is recommended to quantify the error of each instrument. Although the SQM is designed to have a photopic response, it is generally more sensitive to shorter wavelengths (that is, blue) than a truly photopic response, but this will depend on the individual instrument. It is not very sensitive to longer (orange/red) wavelengths (Hänel et al. 2018). The SQM should not be used to measure light within 20° of the horizon, as the detector is designed to measure a homogeneous sky (such as occurs at the zenith) and does not produce valid data when pointed at a heterogeneous field of view as observed at the horizon.

Application to wildlife monitoring programs: A sky quality meter can be used to measure skyglow directly overhead (zenith) at the wildlife habitat, however, it is important to recognise its limitations (such as the absence of whole of sky information and inability to measure point sources of light on the horizon) and follow methods recommended by Hänel et al. (2018) to ensure repeatability.

Dark Sky Meter

This is an iPhone app that uses the phone camera to collect light and generate a sky brightness value.

Benefits: It is cheap and easy to use.

Limitations: Dark Sky Meter is a photometric instrument. It is restricted to Apple iPhones. It will not work on iPhone models older than the 4S and cannot be used to resolve individual lights or identify light direction. It is relatively imprecise and inaccurate50 and cannot reliably measure light on the horizon.

Application to wildlife monitoring programs: Dark Sky Meter is not an appropriate tool for monitoring light impacts on wildlife as it does not measure biologically relevant light. It does not provide whole-of-sky information, cannot resolve individual light sources and is relatively imprecise and inaccurate. Dark Sky Meter should be considered more of an educational tool than a scientific instrument.

Lux meters and luminance meters

Lux meters are commercially available instruments commonly used to measure individual light sources at close range (that is, over metres rather than landscape scale). However, the inverse square law can be used to calculate the illuminance if the distance is known. Lux and luminance meters measure photometric light. Lux meters measure the light falling on a surface, and luminance meters measure the light incident from a specific solid angle.

Benefits: Both can be cheap (with more expensive models available) and easy to use.

Limitations: Both types of devices are photometric, but their measurements are weighted to human perception rather than wildlife. Depending on the sensitivity of the instrument, its detection limits may not be low enough to measure typical night sky brightness or illuminance, making it unable to measure skyglow for wildlife monitoring purposes. Lux meters have no angular resolution and luminance meters are coarse, so they cannot be used to measure distant light sources at the horizon precisely.

Application to wildlife monitoring programs: Commercial lux and luminance meters are not appropriate for the measurement of light in wildlife monitoring programs, because they have low sensitivity and low accuracy at low light levels. Expensive tailored devices with enhanced sensitivity may exist but are still not applicable to wildlife monitoring as they do not measure biologically relevant light and are not appropriate for use on a landscape scale.

Calibrated all-sky imagery

These instruments map and measure sky brightness by analysing photographic images of the whole sky. The images are processed to derive a luminance value for all or parts of the sky. One advantage of 2-dimensional (wide angle) imaging is that models of natural sources of light in the night sky can be subtracted from all-sky imagery to detect anthropogenic sources (Duriscoe 2013). Examples of devices and techniques to map and measure night sky brightness using wide-angle images are as follows.

All-Sky Transmission Monitor (ASTMON)

This charge-coupled device (CCD) astronomical camera with a fish-eye lens has been modified by the addition of a filter wheel to allow collection of data through 4 photometric bands in the visible spectrum. The spectral range of the instrument is dependent on the sensitivity of the detector and the filters used but has the advantage of being accurately calibrated on stars.

Benefits: The ASTMON was designed for outdoor installation and the Lite version is portable, with a weatherproof enclosure allowing it to remain outdoors operating robotically for weeks. It reports data in magnitude/arcsec^2 for each band and has good precision and accuracy (Hänel et al. 2018). Once the system is calibrated with standard stars, it can provide radiometric data for the whole night sky as well as resolving individual light sources.

Limitations: The ASTMON is expensive and requires specialised knowledge to operate and interpret data from. The software provided is not open source and so cannot be modified to suit individual requirements. The ASTMON may no longer be commercially available. The CCD cameras used have a limited dynamic range.

Application to wildlife monitoring programs: The ASTMON is appropriate for monitoring artificial light for wildlife as it provides whole night sky measurements that can be calibrated to give biologically relevant information that is accurate and repeatable.

Digital camera equipped with wide-angle and fish-eye lenses

This system is similar to the ASTMON, except using a commercial digital camera with an RGB matrix rather than a CCD camera with filter wheel, making it cheaper and more transportable. This system provides quantitative data on the luminance of the sky in a single image (Jechow, Kyba & Hölker 2019; Kolláth 2010).

Benefits: The cameras are easily accessible and portable. When precision is not critical, the directional distribution of night sky brightness can be obtained. At the very least, the use of a digital camera with a fish-eye lens allows for qualitative imagery data to be collected and stored for future reference and data analysis. If standard camera settings are used consistently in all surveys, it is possible to compare images to monitor spatial and temporal changes in sky brightness. This system also provides multicolour options with red, green and blue spectral bands (RGB).

Limitations: Cameras must be calibrated before use and this, together with the specific camera model, will dictate the precision of the measurements. Calibration for data processing requires lens vignetting (also known as flat fielding) and checking geometric distortion, the colour sensitivity of the camera, and the sensitivity function of the camera. Specialised knowledge is required to process and interpret these images. Also, like CCD cameras, the detectors in digital cameras have a limited dynamic range which can easily saturate in bright environments. In addition, fish-eye systems often produce the poorest quality data at the horizon, where the distortion due to the lens is the greatest.

Calibrating the camera is difficult, and standard methods have not been developed. Laboratory or astronomical photometric techniques are generally used, which require specialist knowledge and expertise. A precision of ~10% can be achieved using this technique. Standard commercial cameras are calibrated to the human eye (for example, photometric). However, the ability to obtain and process an image allows for qualitative assessment of light types (based on the colour of skyglow), which provides additional data for interpreting the biological relevance of the light.

Application to wildlife monitoring programs: A digital camera equipped with wide-angle or fish-eye lenses is appropriate for measuring light in wildlife monitoring programs, as it provides horizon-to-horizon information with enough sensitivity and accuracy to detect significant changes in low light environments. The images allow for detection of skyglow, light source type, and point source information. When the data is manually processed, biologically relevant measurements can be obtained. Because the system is fast, dynamics of skyglow and direct light can be monitored (Jechow et al. 2018).

All-sky mosaics

This technique, developed by the US National Parks Service, provides an image of the whole of the sky by mosaicking 45 individual images. The system comprises a CCD camera, a standard 50 mm lens, an astronomical photometric Bessel V filter with IR blocker, and a computer-controlled robotic telescope mount. Data collection is managed using a portable computer, commercial software and custom scripts.

Benefits: The angular resolution, precision and accuracy of the system is good, and it is calibrated and standardised on stars. The images produced have high resolution. The system is best suited for long-term monitoring from dark-sky sites. However, with the addition of a neutral density filter, the luminance or illuminance of a nearby bright light source can be measured. Also, other photometric bands can be measured with the use of additional filters.

Limitations: The system is expensive, and specialised knowledge is required to operate it and to analyse and interpret the data. The cameras are calibrated to the human eye, with the inclusion of a visible filter. However, the ability to obtain and process an image allows for qualitative assessment of light types (based on the colour of skyglow), which provides additional data for interpreting the biological relevance of the light. The measurement procedures are time consuming, and perfect clear-sky conditions and single spectral band or repeated measurements are required.

Application to wildlife monitoring programs: All-sky mosaics would be an appropriate tool for monitoring of artificial light for wildlife. They provide whole of sky images with high resolution and, with appropriate filters, can be used to measure biologically relevant wavelength regions.

Spectroscopy/spectroradiometry

Different light types produce a specific spectral signature or spectral power distribution (see Figure 26). Using a spectrometer, it is possible to separate total sky radiance into its contributing sources based on their spectral characteristics. Being able to assess the impacts of different light sources is relevant during this time of transition in lighting technology.

Where wildlife sensitivity to particular wavelength regions of light is known, being able to capture the spectral power distributions of artificial light and then predict how the light will be perceived by wildlife will be of particular benefit in assessing the likely impacts of artificial light.

This type of approach has been utilised in astronomy for a long time but only recently applied to measurement and characterisation of light pollution on earth. An example of a field-deployable spectrometer is the Spectrometer for Aerosol Night Detection (SAND).

Spectrometer for Aerosol Night Detection

SAND uses a CCD imaging camera as a light sensor, coupled with a long-slit spectrometer. The system has a spectral range from 400 nm to 720 nm and is fully automated. It can separate sampled sky radiance into its major contributing sources.

Benefits: SAND can quantify light at specific wavelengths across the spectrum (radiometric), so it can measure light visible to wildlife. It can also be used to ‘fingerprint’ different light types.

Limitations: Calibration, collection and interpretation of these data requires specialist knowledge and equipment and is expensive. SAND does not provide whole-sky information.

Application to wildlife monitoring programs: The use of a portable spectrometer that can identify light types based on their spectral power distribution or measure light at specific wavelengths of interest would be a useful contribution to a wildlife monitoring program. Unfortunately, the prototype SAND instrument is no longer in operation. However, this instrument exemplifies a type of approach that will be of benefit in measuring light for wildlife in the future.

Most appropriate instrument for measuring biologically relevant light

The most appropriate method for measuring light for wildlife will depend on the species present and the type of information required. In general, an appropriate approach will quantify light across the whole sky, across all spectral regions, differentiating point light sources from skyglow, and it will be repeatable and easy to use.

At the time of writing, the digital camera and fish-eye lens technique was recommended by Hänel et al. (2018) and Barentine (2019) as the best compromise between cost, ease of use and amount of information obtained when measuring and monitoring skyglow. Hänel et al. (2018) did, however, recognise the urgent need for the development of standard software for calibrating and displaying the results from light-monitoring instruments (Hänel et al. 2018). In the future, hyperspectral cameras with wide field of view might become available, combining the advantages of spectroradiometry and all-sky imagery. However, such devices do not currently exist.

It should be noted that this field is in a stage of rapid development. This appendix will be updated as more information becomes available.

Table 1 Examples of instrumental light measurement techniques

Type of instrument	Instrument	Measurement units	Detect skyglow	Data type	Spectrum measured	Scale	Measures biologically relevant light	Commercially available	Data quality	Price **a**
Remote sensing	Satellite imagery	Various	Yes **b**	Images + numeric value	Single band	Landscape	No	Yes	Moderate–high	Some datasets free
One dimensional	Sky quality meter (SQM)	$\mathrm{mag_{SQM}/arcsec^2}$	Yes	Numeric value	Single band	Overhead	No **c**	Yes	Moderate	<$300
One dimensional	Dark Sky Meter (iPhone)	$\sim\mathrm{mag_{SQM}/arcsec^2}$	Yes	Numeric value	Single band	Overhead	No	Yes	Low	$0
One dimensional	Luxmeter	lux	No	Numeric value	Single band	Metres	No	Yes	Low	<$300
Two dimensional	ASTMON	$\mathrm{mag_v/arcsec^2}$	Yes	Image + numeric value	Multi-band filter wheel	Whole sky	Requires calibration	No	High	>$15,000
Two dimensional	DSLR + fish-eye	$\sim\mathrm{cd/m^2}$, $\sim\mathrm{mag_v/arcsec^2}$	Yes	Image + numeric value	Multi-band RGB	Whole sky	Requires calibration	Yes	Moderate–high	>$2,500
Two dimensional	All-sky mosaic	$\mathrm{cd/m^2}$, $\mathrm{mag_v/arcsec^2}$	Yes	Image + numeric value	Single band	Whole sky	Requires calibration	No	High	~$20,000
Spectroradiometry	SAND **d**	$\mathrm{W/(m^2 nm\ sr)}$	Yes	Spectral power curve	Multi-band hyperspectral	Landscape	Yes	No	Moderate–high	$7,000

a Price as at 2018.

b Via modelling.

c Some sensitivity to short (blue) wavelengths but not to long (orange-red) wavelengths.

d Spectrometer for Aerosol Night Detection (SAND).

Modified from Hänel et al. 2018 (Hänel et al. 2018).

Modelling predicted light

Available commercial light models

Most modelling software that is currently available is problematic, as the models are weighted towards a human perception of light as represented by the CIE/photometric curve and do not account for the light to which wildlife are most sensitive. For example, most wildlife are sensitive to short-wavelength violet and blue light (Figure 17), but little or none of this light is measured by commercial instruments and consequently it is not accounted for in current light models.

A second limitation of many light models for biology is the inability to accurately account for environmental factors such as atmospheric conditions (moisture, cloud, rain, dust); site topography (hills, sand dunes, beach orientation, vegetation, buildings); other natural sources of light (moon and stars); other artificial sources of light; the spectral output of luminaires; and the distance, elevation and viewing angle of the observing species. Such a model would involve a level of complexity that science and technology has yet to deliver.

A final major limitation is the lack of biological data with which to confidently interpret a model outcome. Therefore, it is not possible to objectively estimate how much artificial light is going to cause an impact on a particular species, or age class, over a given distance and under variable environmental conditions.

Recognising these limitations, it can still be valuable to model light during the design phase of new lighting installations, to test assumptions about the light environment. For example, models could test for the potential for light spill and line-of-sight visibility of a source. These assumptions should be confirmed after construction.

Development of modelling tools that can consider broad spectral data and environmental conditions are in the early stages of development but rapidly improving (Barentine 2019).

Appendix D – Artificial light auditing

Industry best practice requires onsite inspection of a build to ensure it meets design specifications. An artificial light audit should be undertaken after construction to confirm compliance with the artificial light management plan.

An artificial light audit cannot be done by modelling the as-built design alone; it should include a site visit to:

- confirm compliance with the artificial light management plan
- check as-built compliance with engineering design
- gather details on each luminaire in place
- conduct a visual inspection of the facility lighting from the wildlife habitat
- review the artificial light monitoring at the project site
- review artificial light monitoring at the wildlife habitat.

Following the completion of a new project or the modification or upgrading of the lighting system of an existing project, the project should be audited to confirm compliance with the artificial light management plan.

Step-by-step guide

The steps to carry out an artificial light audit are:

- Review the artificial light management plan.
- Review best practice light management or approval conditions.
- Review as-built drawings for the lighting design.
- Check for compliance with the approved pre-construction (front end) lighting design.
- Conduct a site inspection both during the day and at night to visually check and measure the placement, number, intensity, spectral power output, orientation and management of each lamp and lamp type. Where possible this should be done with the lighting in operation and with all lighting extinguished.
- Take measurements in a biologically meaningful way. Where there are limitations on measurements for wildlife, these should be acknowledged.
- Record, collate and report on the findings and include any nonconformances. Consider any differences between baseline and post-construction observations. Where lighting outputs were modelled as part of the design phase, compare actual output with modelled scenarios.
- Make recommendations for any improvements or modifications to the lighting design that will decrease the impact on wildlife.

The audit should be conducted by an appropriately qualified environmental practitioner/technical specialist during a site visit. The audit should also include:

- a visual inspection of the facility lighting from the location of the wildlife habitat and, where feasible, the perspective of the wildlife (that is, sand level for a marine turtle)

- artificial light monitoring at the project site
- artificial light monitoring at the wildlife habitat.

A post-construction site visit is critical to ensure no previously unidentified lighting issues are overlooked.

Appendix E – Artificial light management checklist

Table 2 provides a checklist of issues to be considered during the environmental assessment of new infrastructure involving artificial light, or upgrades to existing artificial lighting, for both proponents and assessors. Table 3 provides a checklist of issues to be considered in assessing existing infrastructure with external lighting where listed species are observed to be affected by artificial light. Relevant sections of the main guidelines are provided for each issue.

Table 2 Checklist for new developments or lighting upgrades

Stage	Issues to be considered	Light owner or manager	Regulator	Further information
Pre-development	What are the regulatory requirements for artificial light for this project?	Is an environmental impact assessment required? What other requirements need to be addressed?	What information should be sought from the proponent as part of the assessment process?	Regulatory considerations for the management of artificial light around wildlife
Pre-development	Does the lighting design follow principles of best practice?	What is the purpose of the artificial light for this project?	Does the project use the principles of best practice light design?	Appendix A – Best practice lighting design
Pre-development	What wildlife is likely to be affected by artificial light?	Review species information within 20 km of the proposed development.	Assess species information.	Wildlife and artificial light
Pre-development	What light management and impact mitigation will be implemented?	What light mitigation and management will be most effective for the affected species?	Is the proposed management and mitigation likely to reduce the effect on listed species?	Protected matters technical appendices and species expert guidance
Pre-development	How will light be modelled?	Is light modelling appropriate? How will the model be used to inform light management for wildlife?	Are the limitations of light modelling for wildlife appropriately acknowledged?	Modelling predicted light
Pre-development	Have all lighting-relevant considerations been included in the light management plan?	Have all steps in the EIA process been undertaken and documented in the light management plan?	Does the light management plan comprehensively describe all steps in the EIA process?	Environmental impact assessment of effects of artificial light on wildlife Artificial light management plan
Pre-development	How will continuous improvement be achieved?	How will light management be evaluated and adapted?	Is a continuous review and improvement process described?	Artificial light management plan
Post-development	How will lighting be measured?	What is/are the most appropriate technique(s) for measuring biologically relevant light and what are the limitations?	Ensure appropriate light measurement techniques are used and limitations of the methods recognised.	Appendix C – Measuring biologically relevant light

Stage	Issues to be considered	Light owner or manager	Regulator	Further information
Post-development	How will lighting be audited?	What is the frequency and framework for in-house light auditing?	How will the results of light audits feed into a continuous improvement process?	Appendix D – Artificial light auditing
Post-development	Is artificial light affecting wildlife?	Does the biological monitoring indicate an effect of artificial light on fauna, and what changes will be made to mitigate this impact?	Is there a process for addressing monitoring results that indicate there is a detectable light impact on wildlife, and is it appropriate?	Wildlife and artificial light Artificial light management plan Managing existing light pollution
Post-development	What adaptive management can be introduced?	How will the results of light audits and biological monitoring be used in an adaptive management framework, and how will technological developments be incorporated into artificial light management?	What conditions can be put in place to ensure a continuous improvement approach to light management?	Artificial light management plan

Table 3 Checklist for existing infrastructure

Consideration	Light owner or manager	Regulator	Further information
Are wildlife exhibiting a change in survivorship, behaviour or reproduction that can be attributed to artificial light?	What listed species are found within 20 km of the light source? Are there dead animals or are animals displaying behaviour consistent with the effects of artificial light?	Is there evidence to implicate artificial light as the cause of the change in wildlife survivorship, behaviour or reproductive output? Review existing environmental approvals.	Describe wildlife Wildlife and artificial light Regulatory considerations for the management of artificial light around wildlife Species expert advice
Is lighting in the area best practice?	Are there modifications or technological upgrades that could be made to improve artificial light management?	Are there individual light owners or managers who can be approached to modify current lighting?	Appendix A – Best practice lighting design
Is the light affecting wildlife from a single source or multiple sources?	Are there multiple stakeholders that need to come together to address the cumulative light pollution?	Is there a role for government to facilitate collaboration between light owners and managers to address light pollution?	Managing existing light pollution Artificial light management plan
Can appropriate monitoring be undertaken to confirm the role of artificial light in wildlife survivorship or in behavioural or reproductive output changes?	How much light is emitted from my property and is it affecting wildlife?	Facilitate wildlife monitoring.	Field surveys for wildlife Appendix C – Measuring biologically relevant light Species expert advice

Consideration	Light owner or manager	Regulator	Further information
How will artificial light be audited?	What is the frequency and framework for in-house light auditing?	Can a light audit be undertaken on a regional scale?	Appendix D – Artificial light auditing
What adaptive light management can be introduced?	Are there improvements in lighting technology that can be incorporated into existing lighting?	What changes can be implemented in response to biological monitoring and light audits?	Specialist lighting engineer advice

Appendix F – Marine turtles

Key points

Marine turtles nest on sandy beaches in northern Australia. There is a robust body of evidence demonstrating the effect of light on turtle behaviour and survivorship. Light is likely to affect the turtles if it can be seen from the nesting beach, nearshore or adjacent waters.

Adult females may be deterred from nesting where artificial light is visible on a nesting beach. Hatchlings may become misoriented or disoriented and be unable to find the sea or successfully disperse to the open ocean. The effect of light on turtle behaviour has been observed from lights up to 18 km away.

Key management measures

The physical aspects of light that have the greatest effect on turtles are intensity, colour (wavelength), and elevation above beach. Management of these aspects will help reduce the threat from artificial light.

Six species of marine turtles are found in Australia: Green (*Chelonia mydas*), Loggerhead (*Caretta caretta*), Hawksbill (*Eretmochelys imbricata*), Olive Ridley (*Lepidochelys olivacea*), Flatback (*Natator depressus*) and Leatherback (*Dermochelys coriacea*) turtles.

Light pollution was identified as a high-risk threat in the Recovery Plan for Marine Turtles in Australia 2017–2027 because artificial light can disrupt critical behaviours such as adult nesting and hatchling orientation, sea-finding and dispersal, and can reduce the reproductive viability of turtle stocks (Commonwealth of Australia 2017). A key action identified in the recovery plan was the development of guidelines for the management of light pollution in areas adjacent to biologically sensitive turtle habitat.

Figure 27 Loggerhead Turtle

Photo: David Harasti.

Conservation status

Marine turtles in Australia are protected under international treaties and agreements including the Convention on the Conservation of Migratory Species of Wild Animals (CMS, Bonn 1979), the Convention on International Trade in Endangered Species of Flora and Fauna (CITES, Washington 1973), and the CMS Memorandum of Understanding on the Conservation and Management of Marine Turtles and their Habitats of the Indian Ocean and South-East Asia (IOSEA, 2005). In Australia, the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) gives effect to these international obligations.

All 6 species are listed under the EPBC Act as threatened, migratory and marine species. They are also protected under state and territory legislation.

The Recovery Plan for Marine Turtles in Australia identifies threats to marine turtles and actions required to recover these species (Commonwealth of Australia 2017). To ensure the maintenance of biodiversity, the plan considers marine turtles on a genetic stock basis rather than at the species level. It found light pollution to be a high-risk threat to 5 of 22 genetic stocks of marine turtles. The development and implementation of best practice light management guidelines was identified as a key action for promoting the recovery of marine turtles (Commonwealth of Australia 2017).

Distribution

Turtle nesting habitats include subtropical and tropical mainland and offshore island beaches extending from northern New South Wales on the east coast around northern Australia to Shark Bay in Western Australia. The extent of the known nesting range for each genetic stock can be found in the Species Profile and Threats Database and in the Recovery Plan for Marine Turtles in Australia (Commonwealth of Australia 2017).

Timing of nesting and hatching

Marine turtles nesting in the far north, between the Kimberley and Cape York, typically nest year round but have a peak during the cooler winter months, while summer nesting is favoured by turtles nesting from the Central Kimberley south in Western Australia and along the Pacific coast of Queensland and Northern New South Wales. Specific timing of nesting and hatching seasons for each stock can be found in the Recovery Plan for Marine Turtles in Australia (Commonwealth of Australia 2017).

Important habitat for marine turtles

The effect of artificial lights on turtles is most pronounced at nesting beaches and in the nearshore waters, which might include internesting areas, through which hatchlings travel to reach the ocean. For the purposes of these guidelines, important habitat for turtles includes all areas designated as **habitat critical to survival of marine turtles** and/or as **biologically important areas (BIAs)**, and areas in Queensland identified under local planning schemes as **sea turtle sensitive areas**.

- **Habitat critical to the survival of marine turtles** was identified for each stock as part of the development of the *Recovery Plan for Marine Turtles in Australia*. Nesting and internesting areas designated as habitat critical to the survival of marine turtles can be found in the recovery plan or through the department's National Conservation Values Atlas.
- **BIAs** are areas where listed threatened and migratory species display biologically important behaviour such as breeding, foraging, resting and migration. BIAs most relevant to the consideration of light impacts are nesting and internesting BIAs for each species. Marine turtle BIAs can be explored through the National Conservation Values Atlas.

  - Designation as a BIA recognises that biologically important behaviours are known to occur, but the absence of such a designation does not preclude the area from being a BIA. Where field surveys identify biologically important behaviour occurring, the habitat should be managed accordingly.
- **Sea turtle sensitive areas** have been defined in local government planning schemes in accordance with Queensland's Sea Turtle Sensitive Area Code. These may be shown in local government biodiversity of coastal protection overlay maps in the planning scheme.

Effects of artificial light on marine turtles

The effect of artificial light on turtle behaviour has been recognised since 1911 (Hooker 2011). Since then, a substantial body of research has focused on how light affects turtles and turtle populations – for reviews see Witherington and Martin (2003), Lohmann et al. (1997) and Salmon (2003). The global increase in light pollution from urbanisation and coastal development (Falchi et al. 2016) is of particular concern regarding turtles in Australia, since their important nesting habitat frequently overlaps with areas of large-scale urban and industrial development (Kamrowski et al. 2012), which have the potential to emit a large amount of light, including direct light, reflected light, skyglow and gas flares (Pendoley 2000; Pendoley 2005). Nesting areas on the North West Shelf of Western Australia and along the south-eastern coast of Queensland were found to be at the greatest risk from artificial light (Kamrowski et al. 2012).

Effect of artificial light on nesting turtles

Although they spend most of their lives in the ocean, female turtles nest on sandy tropical and subtropical beaches, predominantly at night. They rely on visual cues to select nesting beaches and orient on land. Artificial night lighting on or near beaches has been shown to disrupt nesting behaviour (Witherington & Martin 2003). Beaches with artificial light, from sources such as urban developments, roadways and piers, typically have lower densities of nesting females than dark beaches (Salmon 2003; Hu, H & Huang 2018).

Some light types do not appear to affect nesting densities: low-pressure sodium (LPS) (Witherington 1992) and filtered high-pressure sodium (HPS), which excludes wavelengths below 540 nm (Pennell 2000). On beaches exposed to light, females will nest in higher numbers in areas that are shadowed (Price et al. 2018; Salmon et al. 1995). Moving sources of artificial light (such as flash photography) may also deter nesting or cause disturbance to nesting females (Campbell 1994).

Effect of artificial light on hatchlings emerging from the nest

Most hatchling turtles emerge at night (Mrosovsky 1968) and must rapidly reach the ocean to avoid predation (Erb & Wyneken 2019). Hatchlings locate the ocean using a combination of topographic and brightness cues, orienting towards the lower, brighter oceanic horizon and away from elevated darkened silhouettes of dunes and/or vegetation behind the beach (Pendoley & Kamrowski 2015a; Lohmann et al. 1997; Limpus & Kamrowski 2013). They can also find the sea using secondary cues such as beach slope (Lohmann et al. 1997).

Sea-finding behaviour may be disrupted by artificial lights, including flares, which interfere with natural lighting and silhouettes (Witherington & Martin 2003; Kamrowski et al. 2014; Pendoley & Kamrowski 2015a). Artificial lighting may adversely affect hatchling sea-finding behaviour in 2 ways: disorientation, where hatchlings crawl on circuitous paths; and misorientation, where they move in the wrong direction, possibly attracted to artificial lights (Witherington & Martin 2003; Salmon 2006). On land, movement of hatchlings in a direction other than the sea often leads to death from predation, exhaustion, dehydration, or being crushed by vehicles on roads (Erb & Wyneken 2019).

Wavelength, intensity and direction

Brightness is recognised as an important cue for hatchlings as they attempt to orient toward the ocean. Brightness refers to the intensity and wavelength of light relative to the spectral sensitivity of the receiving eye (Witherington & Martin 2003). Both field and laboratory-based studies indicate that hatchlings have a strong tendency to orient towards the brightest direction. The brightest direction on a naturally dark beach is typically towards the ocean where the horizon is open and unhindered by dune or vegetation shadows (Limpus & Kamrowski 2013).

The attractiveness of light to hatchlings differs by species (Pendoley 2005; Horch 2008; Witherington & Bjorndal 1991), but in general, artificial lights most disruptive to hatchlings are those rich in short-wavelength blue and green light (for example, metal halide, mercury vapour, fluorescent and LED), and lights least disruptive are those emitting long-wavelength pure yellow-orange light (for example, high or low pressure sodium vapour) (Pendoley 2005; Fritches 2012). Loggerhead turtles are particularly attracted to light at 580 nm (Levenson 2004); Green and Flatback turtles are attracted to light <600 nm, with a preference for shorter wavelength light over longer wavelength light (Pendoley 2005; Fritches 2012); and many species are also attracted to light in the ultraviolet range (<380 nm) (Witherington & Bjorndal 1991; Fritches 2012).

Although longer wavelengths of light are less attractive than shorter wavelengths, they can still disrupt sea-finding (Pendoley & Kamrowski 2015a; Pendoley 2005; Robertson, Booth & Limpus 2016) and, if bright enough, can elicit a similar response to shorter wavelength light (Mrosovsky 1972; Mrosovsky & Shettleworth 1968; Pendoley & Kamrowski 2015b). Hence, the disruptive effect of light on hatchlings is also strongly correlated with intensity. Red light must be almost 600 times more intense than blue light before Green Turtle hatchlings show an equal preference for the 2 colours (Mrosovsky 1972). It is therefore important to consider both the wavelength and the intensity of the light.

Since the sun or moon may rise behind the dunes on some nesting beaches, hatchlings attracted to these point sources of light would fail to reach the ocean. Hatchlings orientate themselves by integrating light across a horizontally broad (180° for Green, Olive Ridley and Loggerhead Turtles) and vertically narrow ('few degrees' for Green and Olive Ridley turtles, and 10° to 30° for Loggerheads) 'cone of acceptance' or 'range of vision'. This integration ensures that light closest to the horizon plays the greatest role in determining orientation direction, so it is important to consider the type and direction of light that reaches the hatchling (Lohmann et al. 1997).

As a result of these sensitivities, hatchlings have been observed to respond to artificial light up to 18 km away during sea-finding (Kamrowski et al. 2014).

Shape and form

Horizon brightness and elevation are also important cues for hatchling orientation. In laboratory and field studies, hatchlings move away from elevated dark horizons and towards the lowest bright horizon (Limpus & Kamrowski 2013; Salmon et al. 1992). However, in situations where both cues are present, hatchlings are more responsive to the effects of silhouettes and darkened horizon elevation than to differences in brightness. On a natural beach this behaviour would direct the hatchlings away from dunes and vegetation and towards the more open horizon over the ocean.

This hypothesis has been supported by field experiments where hatchling sea-finding was significantly less ocean oriented when exposed to light at 2° elevation compared with 16° elevation, emphasising the importance of horizon elevation cues in hatchling sea-finding (Pendoley & Kamrowski 2015a).

Effect of artificial light on hatchlings in nearshore waters

Artificial lights can also interfere with the in-water dispersal of hatchlings (Witherington & Bjorndal 1991). Hatchlings leaving lit beaches spend longer crossing nearshore waters and can be attracted back to shore (Harewood & Horrocks 2008; Truscott, Booth & Limpus 2017). At sea, hatchlings have been reported swimming around lights on boats (Limpus et al. 2003; White & Gill 2007), and in laboratory studies lights have attracted swimming hatchlings (Salmon & Wyneken 1990). Recent advances in acoustic telemetry technology has allowed hatchlings to be passively tracked at sea, demonstrating that hatchlings are attracted to lights at sea and spend longer in the nearshore environment when lights are present (Thums et al. 2016; Wilson et al. 2018). This attraction can divert hatchlings from their usual dispersal pathway, causing them to linger around a light source or become trapped in the light spill (Wilson et al. 2018). Hatchlings actively swim against currents to reach light, which is likely to reduce survival from exhaustion and/or predation. An additional problem is that light sources are associated with structures that also attract fish (such as jetties), as there will be increased predation (Wilson et al. 2019).

Environmental impact assessment of artificial light on marine turtles

Infrastructure with artificial lighting that is externally visible should implement Best practice lighting design as a minimum. Where there is important habitat for turtles within 20 km of a project, an EIA should be undertaken.

The following sections step through the EIA process, with specific considerations for turtles.

The 20 km buffer for considering important habitat is based on skyglow approximately 15 km from the nesting beach affecting Flatback hatchling behaviour (Kamrowski et al. 2014), and light from an aluminium refinery disrupting turtle orientation 18 km away (Hodge, Limpus & Smissen 2007).

Where artificial light is likely to influence marine turtle behaviour, consideration should be given to employing mitigation measures as early as possible in a project’s life cycle, including to inform the design phase.

Associated guidance

- Recovery Plan for Marine Turtles in Australia
- Single Species Action Plan for the Loggerhead Turtle (Caretta caretta) in the South Pacific Ocean
- Sea Turtle Sensitive Area Code (Queensland)

Qualified personnel

Lighting design/management and the EIA process should be undertaken by appropriately qualified personnel. Light management plans should be developed and reviewed by appropriately qualified lighting practitioners, who should consult with an appropriately qualified marine biologist or ecologist.

People advising on the development of a lighting management plan, or the preparation of reports assessing the impact of artificial light on marine turtles, should have relevant qualifications equivalent to tertiary education in marine biology or ecology or equivalent experience as evidenced by peer-reviewed publications in the last 5 years on a relevant topic, or other relevant experience.

Step 1: Describe the project lighting

Information collated during this step should consider the Effects of artificial light on marine turtles. Turtles are susceptible to the effects of light on beaches and in the water, so the location and light source (both direct and skyglow) should be considered. Turtles are most sensitive to short-wavelength (blue/green) light and high-intensity light of all wavelengths. Hatchlings are most susceptible to light low on the horizon. They orient away from tall, dark horizons, so the presence of dunes and/or a vegetation buffer behind the beach should be considered at the design phase.

Step 2: Describe marine turtle population and behaviour

The species and the genetic stock nesting in the area of interest should be described. This should include the conservation status of the species; stock trends (where known); how widespread/localised nesting for that stock is; the abundance of turtles nesting at the location; the regional importance of the nesting beach; and the seasonality of nesting/hatching.

Relevant species and stock-specific information can be found in the Recovery Plan for Marine Turtles in Australia, the Protected Matters Search Tool, the National Conservation Values Atlas, state and territory listed species information, scientific literature, and local and Indigenous knowledge.

Where there are insufficient data to understand the population’s importance or demographics, or where it is necessary to document existing turtle behaviour, field surveys and biological monitoring may be necessary.

Biological monitoring of marine turtles

Any monitoring associated with a project should be developed and overseen and have results interpreted by appropriately Qualified personnel to ensure reliability of the data.

The objectives of turtle monitoring in an area likely to be affected by artificial light are to:

- understand the size and importance of the population
- describe turtle behaviour before the introduction or upgrading of artificial lighting
- assess nesting and hatchling orientation behaviour to determine the cause of any existing or future misorientation or disorientation.

The data will be used to inform the EIA and assess whether mitigation measures are successful. Suggested minimum monitoring parameters (what is measured) and techniques (how to measure them) are summarised in Table 4.

As a minimum, qualitative descriptive data on visible light types, location and directivity should also be collected at the same time as the biological data. Handheld-camera images can help describe the light. Quantitative data on existing skyglow should be collected, if possible, in a biologically meaningful way, recognising the technical difficulties in obtaining these data. See Appendix C – Measuring biologically relevant light for a review.

Table 4 Recommended minimum biological information necessary to assess the importance of a marine turtle population and existing behaviour

Targeted age class	Survey effort	Duration	Reference
Adult nesting	Daily track census over 1–1.5 internesting cycles at peak (Commonwealth of Australia 2017) of the nesting season (14–21 days). If the peak nesting period for this population/at this location has not been defined, then a study should be designed in consultation with a qualified turtle biologist to determine the temporal extent of activity (i.e., systematic monthly surveys over a 12-month period).	Minimum 2 breeding seasons	Eckert et al. (1999) Pendoley et al. (2016) Queensland Marine Turtle Field Guide North West Shelf Flatback Turtle Conservation Program Turtle Monitoring Field Guide Ningaloo Turtle Program Turtle Monitoring Field Guide The State of the World's Sea Turtles Minimum Data Standards for Sea Turtle Nesting Beach Monitoring
Hatchling orientation	Minimum of 14 days over a new moon phase about 50 days after the peak of adult nesting. **a** Beach: Hatchling fan monitoring. In water: Hatchling tracking	Minimum 2 breeding seasons	Pendoley (2005) Kamrowski et al. (2014) Witherington (1997) Thums et al. (2016)

a Incubation time will be stock specific. Consult the Recovery Plan for Marine Turtles in Australia for stock-specific information.

Note that the risk assessment will guide the extent of monitoring (for example, a large source of light visible over a broad spatial scale will require monitoring of multiple sites, whereas a smaller localised source of light may require fewer sites to be monitored).

To understand existing hatchling behaviour, it will be necessary to undertake monitoring (or a similar approach) to determine the ability of hatchlings to locate the ocean and orient offshore prior to construction or lighting upgrades.

A well-designed monitoring program will capture:

- hatchling behaviour (Kamrowski 2014; Pendoley 2005; Witherington 1997) at the light-exposed beach and a control/reference beach
- hatchling behaviour before project construction begins, to establish a benchmark to measure against possible changes during construction and operations
- hatchling behaviour on new moon nights, to reduce the influence of moonlight and capture any worst case scenario effects of artificial light on hatching orientation
- hatchling behaviour on full moon nights, to assess the relative contribution of the artificial light to the existing illuminated night sky.

Ideally, survey design will have been set up by a quantitative ecologist/biostatistician to ensure that the data collected provide for meaningful analysis and interpretation of findings.

Step 3: Risk assessment

The Recovery Plan for Marine Turtles in Australia states that management of light should ensure turtles are not displaced from habitat critical to their survival and that anthropogenic activities in important habitat are managed so that the biologically important behaviour can continue. These consequences should be considered in the risk assessment process. The aim of these guidelines is that light is managed to ensure that at important nesting beaches, female turtles continue to nest on the beach, post-nesting females return to the ocean successfully, emerging hatchlings orient in a seaward direction, and dispersing hatchlings can orient successfully offshore.

Consideration should be given to the relative importance of the site for nesting. For example, if this is the only site at which a stock nests, a higher consequence rating should result from the effects of artificial light.

In considering the likely effect of light on turtles, the risk assessment should consider the existing light environment, the proposed lighting design and mitigation/management, and the behaviour of turtles at the location. Consideration should be given to how the turtles will perceive light. This should include wavelength and intensity information and perspective. To assess how/whether turtles are likely to see light, a site visit should be made at night and the area viewed from the beach (approximately 10 cm above the sand), as this will be the perspective of the nesting turtles and emerging hatchlings. Similarly, consideration should be given to how turtles (both adults and hatchlings) will see light when in nearshore water.

Using this perspective, the type and number of lights should be considered to assess whether turtles are likely to be able to perceive light and what the effects of the light on their behaviour are likely to be. The risk assessment should consider proposed mitigation and management.

Step 4: Light management plan

A light management plan for marine turtles should include all relevant project information (Step 1) and biological information (Step 2). It should outline proposed mitigation. For a range of specific mitigation measures, see Marine turtle light mitigation toolbox. The plan should also outline the types of and schedule for biological and light monitoring to ensure mitigation is meeting the objectives of the plan, and triggers for revisiting the risk assessment phase of the EIA.

The plan should outline contingency options to implement if biological and light monitoring or compliance audits indicate that mitigation is not meeting objectives (for example, light is visible on the nesting beach or changes in nesting/hatchling behaviour are observed).

Step 5: Biological and light monitoring and auditing

The success of risk management and impact mitigation and light management should be confirmed through monitoring and compliance auditing. The monitoring and audit results should be used to inform continuous improvement.

Relevant biological monitoring is described in Step 2. Concurrent light monitoring should be undertaken and interpreted in the context of how turtles perceive light and within the limitations of monitoring techniques described in Appendix C – Measuring biologically relevant light. Artificial light auditing, as described in the light management plan, should be undertaken.

Step 6: Review

The EIA should incorporate a continuous improvement review process that allows for upgraded mitigations, changes to procedures, and renewal of the light management plan.

Marine turtle light mitigation toolbox

Appropriate lighting design, controls and impact mitigation will be site, project and species-specific. Table 5 provides a toolbox of management options to use around important turtle habitat. These options should be implemented in addition to the 6 Best practice lighting design principles. Not all mitigation options will be relevant for every situation. Table 6 provides a suggested list of light types appropriate for use near turtle nesting beaches and those to avoid.

Two of the most effective approaches for management of light near important nesting beaches are to ensure there is a tall, dark horizon behind the beach, such as dunes and/or a natural vegetation screen; and to ensure there is no light on or around the water through which hatchlings disperse.

Table 5 Light management options specific to marine turtle nesting beaches

Management action	Detail
Implement light management actions during the nesting and hatching season.	Peak nesting season for each stock can be found in the Recovery Plan for Marine Turtles in Australia (Commonwealth of Australia 2017).
Avoid direct light shining onto a nesting beach or out into the ocean adjacent to a nesting beach.	Adult turtles nest in lower numbers at lit beaches (Price et al. 2018).
Maintain a dune and/or vegetation screen between the nesting habitat and inland sources of light.	Hatchlings orient towards the ocean by crawling away from the tall, dark horizon provided by a dune line and/or vegetation screen.
Maintain a dark zone between the turtle nesting beach and industrial infrastructure	Avoid installing artificial light within 1.5 km of an industrial development (Pendoley & Kamrowski 2015b).
Install light fixtures as close to the ground as practicable.	Install any new lighting close to the ground. Reduce the height of existing lights to the extent practicable to minimise light spill and light glow.
Use curfews to manage lighting.	Mange artificial lights using motion sensors and timers around nesting beaches after 8 pm.
Aim lights downwards and direct them away from nesting beaches.	Aim light onto the exact surface area requiring illumination. Use shielding on lights to prevent light spill into the atmosphere and outside the footprint of the target area.
Use flashing/intermittent lights instead of fixed beam.	For example, small red flashing lights can be used to identify an entrance or delineate a pathway.
Use motion sensors to turn on lights only when needed.	For example, motion sensors could be used for pedestrian areas near a nesting beach.
Prevent indoor lighting reaching the beach.	Use fixed window screens or window tinting on fixed windows, skylights and balconies to contain light inside buildings.
Limit the number of beach access areas or construct beach access such that artificial light is not visible through the access point.	Beach access points often provide a break in dunes or vegetation that protects the beach from artificial light. Screen light spill can be mitigated by limiting the number of access points or making the access path wind through the vegetation.
Work collectively with surrounding industry/private landholders to address the cumulative effect of artificial lights.	Problematic skyglow may not be caused by any one light owner/manager. Working with other industries/stakeholders to address light pollution may be more effective in reducing the impact of artificial light.
Manage artificial light at sea, including on vessels, jetties, marinas and offshore infrastructure.	Hatchlings are attracted to, and trapped by, light spill in the water.
Reduce unnecessary lighting at sea.	Reduce vessel deck lights to the minimum required for human safety and extinguish them when not necessary. Restrict lighting at night to navigation lights only. Use block-out blinds on windows.

Management action	Detail
Avoid shining light directly onto longlines and/or illuminating baits in the water.	Light on the water can trap hatchlings or delay their transit through nearshore waters, consuming their energy reserves and increasing their exposure to predators.
Avoid lights containing short-wavelength violet/blue light.	Lumaires rich in blue light include metal halide, fluorescent, halogen, mercury vapour and most LEDs.
Avoid white LEDs.	Ask suppliers for an LED light with little or no blue in it or only use LEDs filtered to block the blue light. This can be checked by examining the spectral power curve for the luminaire.
Avoid high-intensity light of any colour.	Keep light intensity as low as possible in the vicinity of nesting beaches. Hatchlings can see all wavelengths of light and will be attracted to long-wavelength amber and red light as well as the highly visible white and blue light, especially if there is a large difference between the light intensity and the ambient dark beach environment.
Shield gas flares and locate them inland and away from the nesting beach.	Manage gas flare light emissions by reducing gas flow rates to minimise light emissions; shielding the flame behind a containment structure; elevating glow from the shielded flare more than 30o above hatchling field of view; containing the pilot flame for flares within shielding; and scheduling maintenance activity requiring flaring outside of turtle-hatching season.
Industrial/port or other facilities requiring intermittent night-time light for inspections should keep the site dark and only light specific areas when required.	Use amber/orange explosion-proof LEDs with smart lighting controls and/or motion sensors. LEDs have no warm-up or cool-down limitations, so they can remain off until needed and provide instant light when required for routine nightly inspections or in an emergency.
Industrial site/plant operators should use head torches.	Consider providing plant operators with white head torches (explosion-proof torches are available) for situations where white light is needed to detect colour correctly or when there is an emergency evacuation.
Supplement facility perimeter security lighting with computer-monitored infrared detection systems.	Perimeter lighting can be operated if night-time illumination is necessary but remain off at other times.
No light source should be directly visible from the beach.	Any light that is directly visible to a person on a nesting beach will be visible to a nesting turtle or hatchling and should be modified to prevent it being seen.
Manage light from remote regional sources (up to 20km away).	Consider light sources up to 20 km away from the nesting beach. Assess the relative visibility and scale of the night sky illuminated by the light. For example, if a regional city is illuminating a large area of the horizon, what management actions can be taken locally to reduce the effect (for example, protect or improve dune systems or plant vegetation screening in the direction of the light)?

If all other mitigation options have been exhausted and there is a human safety need for artificial light, see Table 6 for guidance on types of commercial luminaires that are more suitable for use near important marine turtle nesting habitat.

Table 6 Commercial luminaire types that are considered generally less disruptive for use near important marine turtle nesting habitat, and those to avoid

Light type	Suitability for use near marine turtle habitat
Low-pressure sodium vapour	Suitable
High-pressure sodium vapour	Suitable
Filtered LED **a**	Suitable
Filtered metal halide **a**	Suitable
Filtered white LED **a**	Suitable
Amber LED	Suitable
PC amber	Suitable
White LED	Not suitable
Metal halide	Not suitable
White fluorescent	Not suitable
Halogen	Not suitable
Mercury vapour	Not suitable

a ‘Filtered’ means LEDs can be used only if a filter approved by the manufacturer is applied to remove the short-wavelength (400 nm to 500 nm) light.

Appendix G – Seabirds

Key points

Seabirds spend most of their lives at sea, only coming ashore to nest. All species are vulnerable to the effects of lighting. Seabirds active at night while migrating, foraging or returning to colonies are most at risk.

Fledglings are more affected by artificial lighting than adults due to the synchronised mass exodus of fledglings from their nesting sites. They can be affected by lights up to 15 km away.

Key management measures

The physical aspects of light that have the greatest impact on seabirds are intensity and colour (wavelength). Consequently, management of these aspects of artificial light will have the most effective result.

Seabirds are birds that are adapted to life in the marine environment (Figure 28). They can be highly pelagic or coastal, or in some cases spend a part of the year away from the sea entirely. They feed from the ocean either at or near the sea surface. In general, seabirds live longer, breed later and have fewer young than other birds and invest a great deal of energy in their young. Most species nest in colonies, which can vary in size from a few dozen birds to millions. Many species undertake long annual migrations, crossing the equator or circumnavigating the earth in some cases (Ross et al. 1996).

Artificial light can disorient seabirds and potentially cause injury and/or death through collision with infrastructure. Birds may starve as a result of disruption to foraging, hampering their ability to prepare for breeding or migration. High mortality of seabirds occurs through grounding of fledglings as a result of attraction to lights (Rodríguez et al. 2017a) and through interaction with vessels at sea.

Figure 28 Flesh-footed Shearwater at sunset

Photo: Richard Freeman.

Conservation status

Migratory seabird species in Australia are protected under international treaties and agreements including the Convention on the Conservation of Migratory Species of Wild Animals (CMS, Bonn Convention), the Ramsar Convention on Wetlands and the Agreement on the Conservation of Albatrosses and Petrels (ACAP), and through the East Asian–Australasian Flyway Partnership. The Australian Government has bilateral migratory bird agreements with Japan (Japan–Australia Migratory Bird Agreement, JAMBA), China (China–Australia Migratory Bird Agreement, CAMBA) and the Republic of Korea (Republic of Korea–Australia Migratory Bird Agreement, ROKAMBA). In Australia the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) gives effect to these international obligations. Many seabirds are also protected under state and territory environmental legislation.

An estimated 15.5 million pairs of seabirds, from 43 species, breed at mainland and island rookeries (Rodríguez et al. 2017a). Of the 43 species, 35 are listed as threatened and/or migratory under the EPBC Act. Of the 35 EPBC Act listed species, 90% are *Procellariiformes* (petrels, shearwaters, storm petrels, gadfly petrels and diving petrels), which breed in burrows, only attend breeding colonies at night (Warham 1990) and are consequently most at risk from the effects of artificial light. Short-tailed Shearwaters comprise 77% (11.9 million pairs) of the total breeding seabird pairs.

Distribution

Seabirds in Australia belong to both migratory and residential breeding species. Most breeding species, include both temperate and tropical shearwaters and terns that undergo extensive migrations to wintering areas outside Australia's Exclusive Economic Zone (EEZ). However, there are significant numbers of residential species that remain within the EEZ throughout the year and undergo shorter migrations to non-breeding foraging grounds within the EEZ.

Timing of habitat use

Most seabird breeding occurs during the austral spring/summer (September–January), but this may extend in some species to April/May. The exceptions are the austral winter breeders, a handful of species, largely comprising petrels, that may commence nesting in June. Breeding occurs almost exclusively on many of the offshore continental islands that surround Australia. Seabirds spend most of their time flying at sea, and so are usually found on breeding islands only during the breeding season, or along mainland coastal sandbars and spits or island shorelines when roosting during their non-breeding period.

Important habitat for seabirds

Seabirds may be affected by artificial light at breeding areas, while foraging and while migrating. For the purposes of these guidelines, important habitat for seabirds includes all areas that have been designated as habitat critical to the survival of seabirds and/or as biologically important areas (BIAs), and areas designated as important habitat in wildlife conservation plans and in species-specific conservation advice.

- The National Recovery Plan for threatened albatrosses and petrels (2022)[1] lists designated habitat critical to the survival of these species. Where a recovery plan is not in force for a listed threatened species, see relevant approved conservation advice.
- Actions in Antarctica should consider important bird areas in Antarctica (Harris et al. 2015).
- BIAs are areas where listed threatened and migratory species display biologically important behaviour such as breeding, foraging, resting and migration. Seabird BIAs can be explored through the National Conservation Values Atlas.
    - Designation as a BIA recognises that biologically important behaviours are known to occur, but the absence of such a designation does not preclude the area from being a BIA. Where field surveys identify biologically important behaviour occurring, the habitat should be managed accordingly.

Effects of artificial light on seabirds

Seabirds have been affected by artificial light sources for centuries. Humans used fire to attract seabirds to hunt them for food (Murphy 1936) and reports of collisions with lighthouses date back to 1880 (Allen 1880). More recently artificial light associated with the rapid urbanisation of coastal areas has been linked to increased seabird mortality (Gineste et al. 2016), and today 56 petrel species worldwide are known to be affected by artificial lighting (Rodríguez et al. 2017a; Rodríguez et al. 2017b). Artificial light can disorient seabirds, causing collision, entrapment, stranding, grounding, and interference with navigation (being drawn off course from the usual migration route). These behavioural responses may cause injury or death.

All species active at night are vulnerable, as artificial light can disrupt their ability to orient towards the sea. Problematic sources of artificial light include coastal residential and hotel developments, street lighting, vehicle lights, sporting facility floodlights, vessel deck and search lights, cruise ships, fishing vessels, gas flares, commercial squid vessels, security lighting, navigation aids and lighthouses (Rodríguez et al. 2017b; Gineste et al. 2016; Ainley et al. 2001; Black 2005; Deppe et al. 2017; Merkel & Johansen 2011; Raine 2007; Rodríguez, Rodríguez & Lucas 2012). Seabirds, particularly petrel species in the Southern Ocean, can be disoriented by vessel lighting and may land on the deck, from which they are unable to take off. The effect of artificial light may be exacerbated by moon phase (Deppe et al. 2017), wind direction and strength (Rodríguez et al. 2014; Syposz et al. 2018), precipitation, cloud cover, and the proximity of nesting sites or migrating sites to artificial light sources (Rodríguez et al. 2015; Rodríguez, Rodríguez & Negro 2015; Troy et al. 2013). The degree of disruption is determined by a combination of physical, biological and environmental factors including the location, visibility, colour and intensity of the light, proximity to other infrastructure, landscape topography, moon phase, atmospheric and weather conditions, and species present.

Seabirds that are active at night while migrating, foraging or returning to colonies and are directly affected include petrels, shearwaters, albatross, noddies, terns and some penguin species. Less studied are the effects of light on the colony attendance of nocturnal

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[1] The recovery plan will sunset in 2032.

Procellariiformes, which could lead to higher predation risks by gulls, skuas or other diurnal predators; and the effects on species that are active during the day, including extending their activities into the night as artificial light increases perceived daylight hours.

High rates of fallout, or the collision of birds with structures, have been reported in seabirds nesting adjacent to urban or developed areas (Rodríguez et al. 2017a; Montevecchi 2006; Podolsky et al. 1998) and at sea where seabirds interact with offshore oil and gas platforms (Bourne 1979; Burke et al. 2005). A report on interactions with oil and gas platforms in the North Sea identified light as the likely cause of hundreds of thousands of bird deaths annually. It noted that this could be a site-specific impact (Ronconi, Allard & Taylor 2015).

Gas flares also affect seabirds. One anecdote describes 24 burnt carcasses of seabirds (Wedge-tailed Shearwaters) in and around an open-pit gas flare. It is likely that the birds were attracted to the light and noise of the flare and, as they circled the source, became engulfed, combusting in the super-heated air above the flame (K Pendoley pers. obs. 1992).

Mechanisms by which light affects seabirds

Most seabirds are diurnal. They rest during dark hours and have less exposure to artificial light. Among species with a nocturnal component to their life cycle, artificial light affects the adult and fledgling differently.

Adults are less affected by artificial light. Many *Procellariiformes* species (shearwaters, storm petrels, gadfly petrels) are vulnerable during nocturnal activities, which make up part of the annual breeding cycle. Adult *Procellariiformes* species are vulnerable when returning to and leaving the nesting colony. They may leave or enter to re-establish their pair bonds with breeding partners, repair nesting burrows, defend nesting sites, or forage. Adults feed their chicks by regurgitating partially digested food (Imber 1975). A recent study shows that artificial light disrupts adult nest attendance and thus affects weight gain in chicks (Cianchetti-Benedetti et al. 2018).

Fledglings are more vulnerable due to the naivety of their first flight, the immature development of ganglions in the eye at fledging, and the potential connection between light and food (Montevecchi 2006; Mitkus et al. 2016). Burrow-nesting seabirds are typically exposed to light streaming in from the burrow entrance during the day. Parents feeding their young enter the burrow from the entrance, creating an association between light and food in newly fledged birds (Rodríguez et al. 2017b). Much of the literature concerning the effect of lighting upon seabirds relates to the synchronised mass exodus of fledglings from their nesting sites (Deppe et al. 2017; Raine et al. 2007; Rodríguez et al. 2015; Rodríguez, Rodríguez & Negro 2015; Le Corre et al. 2002; Reed, Sincock & Hailman 1985). Fledging *Procellariiformes* leave the nesting colony for the sea at night (Warham 1990), returning to breed several years later. In Australia, the main fledgling period for shearwaters occurs in April/May (Serventy, Serventy & Warham 1971).

Emergence during darkness is believed to be a predator-avoidance strategy (Watanuki 1986), and artificial lighting may make fledglings more vulnerable to predation (Reed, Sincock & Hailman 1985). Artificial lights are thought to override the sea-finding cues provided by moonlight and starlight at the horizon (Telfer et al. 1987), and fledglings can be attracted back to onshore lights after reaching the sea (Rodríguez et al. 2014; Podolsky et al. 1998). It is possible that fledglings that survive their offshore migration cannot imprint their natal colony, preventing them from returning to nest when they mature (Raine et al. 2007). The consequences of exposure to artificial light on the viability of a breeding population of seabirds is unknown (Griesemer & Holmes 2011).

Eye structure and sensitivities

Seabirds, like most vertebrates, have an eye that is well adapted to see colour. Typically, diurnal birds have 6 photoreceptor cells which are sensitive to different regions of the visible spectrum (Vorobyev 2003). All seabirds are sensitive to the violet–blue region of the visible spectrum (380 nm to 440 nm) (Capuska et al. 2011). The eyes of the Black Noddy (*Anous minutus*) and Wedge-tailed Shearwater (*Puffinus pacificus*) are characterised by a high proportion of cones sensitive to shorter wavelengths (Hart 2001). This adaptation is likely due to the need to see underwater, and the optimum wavelength for vision in clear blue oceanic water is between 425 nm and 500 nm. There is no ecological advantage to having many long-wavelength-sensitive photoreceptors in species foraging in this habitat (Hart 2001).

Many diurnal birds can see in the UV range (less than 380 nm (Bowmaker et al. 1997)); however, of the over 300 seabird species, only a few have UV-sensitive vision (Capuska et al. 2011). In all seabirds, their photopic vision (daylight adapted) is most sensitive in the long-wavelength range of the visible spectrum (590 nm to 740 nm, orange to red) while their scotopic (dark adapted) vision is more sensitive to short wavelengths of light (380 nm to 485 nm, violet to blue).

Petrel vision is most sensitive to light in the short-wavelength blue (400 nm to 500 nm), region of the visible spectrum. Relative to diurnal seabirds, such as gulls and terns, petrels have a higher number of short-wavelength-sensitive cones. This is thought to be an adaptation that increases prey visibility against a blue-water foraging field favoured by petrels (Hart 2001).

Little has been published on vision in penguins. Penguins are visual foragers whose success in fish capture is linked directly to the amount of light present (Cannell & Cullen 1998). The eyes of the Humbolt Penguin (*Spheniscus humboldti*) are adapted to the aquatic environment, seeing well in the violet to blue to green region of the spectrum, but poorly in the long wavelengths (red) (Bowmaker & Martin 1985).

Wavelength, intensity and direction

The intensity of light may be a more important cue than colour for seabirds. Very bright light will attract them, regardless of colour (Raine et al. 2007). There are numerous, although sometimes conflicting, reports of the attractiveness of different wavelengths of artificial light to seabirds. White light has the greatest effect on seabirds as it contains all wavelengths of light (Rich & Longcore 2006); Deppe et al. 2017; Wiltschko & Wiltschko 1999). Seabirds have reportedly been attracted to the yellow/orange colour of fire (Murphy 1936), while white mercury vapour and broad-spectrum LED is more attractive to Barau's Petrel (*Pterodroma baraui*) and Hutton's Shearwater (*Puffinus huttoni*) than either low-pressure or high-pressure sodium vapour lights (Deppe et al. 2017). Bright white deck lights and spot lights on fishing vessels attract seabirds at night, particularly on nights with little moonlight or low visibility (Black 2005; Merkel & Johansen 2011; Montevecchi 2006).

A controlled field experiment on Short-tailed Shearwaters at Phillip Island tested the effect of metal halide, LED and HPS lights on fledging groundings (Rodríguez, Dann & Chiaradia 2017). The results suggested that the shearwaters were more sensitive to the wider emission spectrum and higher blue content of metal halide and LED lights than to HPS light. The authors strongly recommended using HPS or filtered LED and metal halide lights with purpose-designed LED filters to remove short-wavelength light for use in the vicinity of shearwater colonies (Rodríguez, Dann & Chiaradia 2017).

The first studies of penguins exposed to artificial light at a naturally dark site found they preferred lit paths over dark paths to reach their nests (Rodríguez et al. 2018). While artificial light might enhance penguin vision at night, reducing predation risk and making it easier for them to find their way, their proven attraction to light could attract them to undesirable lit areas. This study concluded that the penguins were habituated to artificial lights and were unaffected by a 15 lux increase in artificial illumination (Rodríguez et al. 2018). However, the authors were unable to rule out an effect of artificial light on penguin behaviour due to natural differences between the sites, potential complexity of penguin response to the interaction between artificial light and moonlight, and probable habituation of penguins to artificial lights.

Environmental impact assessment of artificial light on seabirds

As a minimum, infrastructure with artificial lighting that is externally visible should have Best practice lighting design implemented. Where there is important habitat for seabirds within 20 km of a project, an EIA should be undertaken. The following sections step through the EIA process, with specific considerations for seabirds.

The 20 km buffer for considering important seabird habitat is based on the observed grounding of seabirds in response to a light source at least 15 km away (Rodríguez et al. 2014).

The spatial and temporal characteristics of migratory corridors are important for some seabird species. Species typically use established migratory pathways at predictable times, and artificial light intersecting with an overhead migratory pathway should be assessed in the same way as for ground-based populations.

Where artificial light is likely to affect seabirds, consideration should be given to mitigation measures at the earliest point in project development, including to inform the design phase.

Associated guidance

- National Recovery Plan for threatened albatrosses and petrels (2022)[2]
- EPBC Act Policy Statement 3.21: Industry guidelines for avoiding, assessing and mitigating impacts on EPBC Act listed migratory shorebird species

Qualified personnel

Lighting design/management and the EIA process should be undertaken by appropriately qualified personnel. Light management plans should be developed and reviewed by appropriately qualified lighting practitioners, who should consult with an appropriately trained marine ornithologist and/or ecologist.

People advising on the development of a lighting management plan, or the preparation of reports assessing the effect of artificial light on seabirds, should have relevant qualifications

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[2] The recovery plan will sunset in 2032.

equivalent to a tertiary education in ornithology or equivalent experience as evidenced by peer-reviewed publications in the last 5 years on a relevant topic, or other relevant experience.

Step 1: Describe the project lighting

The type of information collated during this step should consider the biological Effects of artificial light on seabirds. Seabirds are susceptible when active at night while migrating, foraging or returning to colonies. The location and type of light source (both direct and skyglow) should be considered in relation to breeding and feeding areas. Seabirds are sensitive to both short-wavelength (blue/violet) and long-wavelength (orange/red) (Reed 1986) light, and some species are able to detect UV light. However, the intensity of lights may be more important than colour.

Step 2: Describe seabird population and behaviour

The species, life stage and behaviour of seabirds in the area of interest should be described. This should include the conservation status of the species; the abundance of birds; how widespread/localised the population is; the regional importance of the population; and the seasonality of seabirds utilising the area.

Relevant information can be found in the National Recovery Plan for Threatened Albatrosses and Giant Petrels 2011–2016, the Protected Matters Search Tool, the National Conservation Values Atlas, conservation advices, wildlife conservation plans, state and territory listed species information, scientific literature, and local and Indigenous knowledge.

Where there are insufficient data to understand the population's importance or demographics, or where it is necessary to document existing seabird behaviour, field surveys and biological monitoring may be necessary.

Biological monitoring of seabirds

Any biological monitoring associated with a project should be developed, overseen and have the results interpreted by an appropriately qualified biologist or ornithologist to ensure reliability of the data.

The objectives of monitoring in an area likely to be affected by light are to:

- understand the habitat use and behaviour of the population (for example, migrating, foraging, breeding)
- understand the size and importance of the population
- describe seabird behaviour prior to the introduction or upgrading of artificial lighting.

The data will be used to inform the EIA process and assess whether mitigation measures are successful. Suggested minimum monitoring parameters (what is measured) and techniques (how to measure them) are summarised in Table 7.

Table 7 Recommended minimum biological information necessary to assess the importance of a seabird population

Targeted age class	Survey effort	Duration	Reference
Adult nesting	In colonial nesting burrows or for surface nesting species with fixed or transient nesting sites, a single survey timed to coincide with predicted peak laying period. • A minimum of 3 sampling areas (transects/quadrants) appropriate for nest density to capture ~100 nests per transect. Status of nests recorded (used/unused – chick stage). For transient surface nesting species, use aerial or drone footage to estimate numbers of chicks in crèches. • A minimum of 3 sampling areas (transects/quadrants) appropriate for nest density to capture ~100 nests per transect. Status of nests recorded (used/unused – egg or chick).	Minimum 2 breeding seasons	Henderson & Southwood (2016) Surman & Nicholson (2014b) Survey Guidelines for Australia's Threatened Birds (Commonwealth of Australia 2010)
Fledgling	In colonial nesting burrows or for surface nesting species with fixed nesting sites, a single survey timed to coincide with predicted maximum fledging period.	Minimum 2 breeding seasons	Henderson & Southwood (2016) Surman & Nicholson (2014a)

Note: the information in this table is not prescriptive and should be assessed on a case-by-case basis.

Additional seabird monitoring

- Monitor fledging behaviour before a project begins, to establish a benchmark for assessing changes in fledging behaviour during construction and operations.
- Monitor fallout by assessing breeding colonies prior to fledging to assess annual breeding output/effort and measure against fallout (expecting greater fallout in years with higher reproductive output).
- Install camera traps at key locations to monitor fallout.
- Conduct nightly assessments of target lighting/areas to identify and collect grounded birds.
- Conduct observations post-dusk and pre-dawn with night vision goggles to assess activity/interactions.
- Track movement using land-based radar to determine existing flight paths (Raine et al. 2007).

As a minimum, qualitative descriptive data on visible light types, location and directivity should also be collected at the same time as the biological data. Handheld camera images can help to describe the light. Quantitative data on existing skyglow should be collected, if possible, in a biologically meaningful way, recognising the technical difficulties in obtaining these data. See Appendix C – Measuring biologically relevant light for a review.

Step 3: Risk assessment

The objective is that light should be managed in such a way that seabirds are not disrupted within or displaced from important habitat and are able to undertake critical behaviours such as foraging, reproduction and dispersal. These consequences should be considered in the risk assessment process. The aim of the process is to ensure that at important seabird rookeries, burrow usage remains constant, adults and fledglings are not grounded, and fledglings launch successfully from the rookery.

In considering the likely effect of light on seabirds, the assessment should consider the existing light environment, the proposed lighting design and mitigation/management, and the behaviour of seabirds at the location. Consideration should be given to how the birds perceive light. This should include both wavelength and intensity information and perspective. To discern how or whether seabirds are likely to see light, a site visit should be made at night and the area viewed from the seabird rookery. Similarly, consideration should be given to how seabirds will see light when in flight.

Using this perspective, the type and number of lights should be considered/modelled to determine whether seabirds are likely to perceive the artificial light and what the effects of the artificial light on their behaviour are likely to be.

Step 4: Light management plan

This should include all relevant project information (Step 1) and biological information (Step 2). It should outline proposed mitigation. For a range of seabird-specific mitigation measures see Seabird light mitigation toolbox. The plan should also outline the types of and schedule for biological and light monitoring to ensure mitigation is meeting the objectives of the plan, and triggers for revisiting the risk assessment phase of the EIA.

The plan should outline contingency options to implement if biological and light monitoring or compliance audits indicate that mitigation is not meeting objectives (for example, light is visible in seabird rookeries or fallout rates increase).

Step 5: Biological and light monitoring and auditing

The success of the impact mitigation and light management should be confirmed through monitoring and compliance auditing. The monitoring and audit results should be used to facilitate an adaptive management approach for continuous improvement.

Relevant biological monitoring is described in Step 2. Concurrent light monitoring should be undertaken and interpreted in the context of how seabirds perceive light and within the limitations of monitoring techniques described in Appendix C – Measuring biologically relevant light. Artificial light auditing, as described in the light management plan, should be undertaken.

Step 6: Review

The EIA should incorporate a continuous improvement review process that allows for upgraded mitigations, changes to procedures and renewal of the light management plan.

Seabird light mitigation toolbox

Appropriate artificial lighting design, controls and impact mitigation will be site, project and species-specific. Table 8 provides a toolbox of management options relevant to seabirds. These options should be implemented in addition to the 6 Best practice lighting design principles. Not all mitigation options will be practicable for every project. Table 9 provides a suggested list of light types appropriate for use near seabird rookeries and those to avoid.

A comprehensive review of the effects of land-based artificial lights on seabirds found that the most effective mitigation techniques were:

- turning lights off during fledging periods
- modifying light wavelengths
- removing external lights and closing window blinds to shield internal lights
- shielding the light source and preventing upward light spill
- reducing traffic speed limits and displaying warning signs
- implementing a rescue program for grounded birds (Rodríguez et al. 2017a).

Additional mitigation measures listed but not assessed for effectiveness were:

- using rotating or flashing lights, because research suggests that seabirds are less attracted to flashing lights than to constant light
- keeping light intensity as low as possible. Most bird groundings are observed in very brightly lit areas (Rodríguez et al. 2017a).

Table 8 Light management options for seabirds

Management action	Detail
Implement management actions during the breeding season.	Most seabird species nest during the austral spring and summer. Light management should be implemented during the nesting and fledgling periods.
Maintain a dark zone between the rookery and the light sources.	Avoid installing lights or manage all outdoor lighting within 3 km of a seabird rookery (Rodríguez, Rodríguez & Negro 2015). This is the median distance between nest locations and grounding locations. Avoiding the installation of lights in this zone would reduce the number of grounding birds by 50%.
Turn off lights during fledgling season.	If it is impossible to extinguish lights, consider curfews, dimming options, or changes in light spectra (preferably towards lights with low blue emissions). Fledglings can be attracted back towards lights on land as they fly out to sea.
Use curfews to manage lighting.	Extinguish lights around the rookery during the fledgling period by 7 pm, as fledglings leave their nest early in the evening.
Aim lights downwards and direct them away from nesting areas.	Aim light onto only the surface area requiring illumination. Use shielding to prevent light spill into the atmosphere and outside the footprint of the target area. This action can reduce fallout by 40% (Rodríguez et al. 2017a).
Use flashing/intermittent lights instead of fixed beam.	For example, small red flashing lights can be used to identify an entrance or delineate a pathway.
Use motion sensors to turn lights on only when needed.	Use motion sensors for pedestrian or street lighting within 3 km of a seabird rookery.
Prevent indoor lighting reaching outdoor environment.	Use fixed window screens or window tinting on fixed windows and skylights to contain light inside buildings.
Manage artificial light on jetties, wharves, marinas etc.	Fledglings and adults may be attracted to lights on marine facilities and become grounded or collide with infrastructure.
Reduce unnecessary outdoor deck lighting on all vessels and permanent and floating oil and gas installations in known seabird foraging areas at sea.	Extinguish outdoor/deck lights when not necessary for human safety and restrict lighting at night to navigation lights. Use block-out blinds on all portholes and windows.

Management action	Detail
Night fishing should only occur with minimum deck lighting. Avoid shining light directly onto fishing gear in the water. Ensure lighting enables recording of any incidental catch, including by electronic monitoring systems.	Night is between nautical dusk and nautical dawn (as defined in the Nautical Almanac tables for relevant latitude, local time and date). Light on the water at night can attract seabirds to deployed fishing gear, increasing the risk of seabird bycatch (i.e., killing or injuring birds). Minimum deck lighting should not breach minimum standards for safety and navigation. Record bird strike or incidental catch and report these data to regulatory authorities.
Avoid shining light directly onto longlines and/or illuminating baits in the water.	Light on the water can attract birds and makes it easier for them to detect and consume baits, increasing bycatch in fisheries (killing or injuring birds). Record bird strike or incidental catch and report these data to regulatory authorities.
Vessels working in seabird foraging areas during breeding season should implement a seabird management plan to prevent seabird landings on the ship, manage birds appropriately and report the interaction.	For example, see the International Association of Antarctica Tour Operators (IAATO) Seabirds landing on ships information page.
Use luminaires with spectral content appropriate for the species present.	Consider avoiding specific wavelengths that are problematic for the species of interest. In general, this would include avoiding lights rich in blue light; however, some birds are sensitive to yellow light and other mitigation may be required.
Avoid high-intensity light of any colour.	Keep light intensity as low as possible in the vicinity of seabird rookeries and known foraging areas.
Shield gas flares and locate them inland and away from seabird rookeries.	Manage gas flare light emissions by reducing gas flow rates to minimise light emissions; shielding the flame behind a containment structure; containing the pilot flame for flares within shielding; and scheduling maintenance activity requiring flaring outside of shearwater breeding season or during the day.
Minimise flaring on offshore oil and gas production facilities.	Consider reinjecting excess gas instead of flaring, particularly on installations on migratory pathways.
In facilities requiring intermittent night-time inspections, turn on lights only while operators are moving around the facility.	Use appropriate wavelength, explosion-proof LEDs with smart lighting controls. LEDs have no warm-up or cool-down limitations, so they can remain off until needed and provide instant light when required for routine nightly inspections or in the event of an emergency.
Ensure industrial site/plant operators use head torches.	Consider providing plant operators with white head torches (explosion-proof torches are available) for situations where white light is needed to detect colour correctly or in an emergency.
Supplement facility perimeter security lighting with computer-monitored infrared detection systems.	Perimeter lighting can be operated when night-time illumination is necessary but otherwise remain off.
Tourism operations around seabird colonies should manage torch usage so birds are not disturbed.	Consider installing educational signage around seabird colonies where tourism visitation is generally unsupervised.
Design and implement a rescue program for grounded birds.	This will not prevent birds grounding, but it is an important management action in the absence of appropriate light design. Rescue programs have proven useful in reducing mortality of seabirds. The program should include documentation and reporting of data about the number and location of rescued birds to regulatory authorities.

If all other mitigation options have been exhausted and there is a human safety need for artificial light, see Table 9 for guidance on types of commercial luminaires that are more suitable for use near seabird habitat.

Table 9 Commercial luminaire types that are considered generally less disruptive for use near important seabird mammal habitat, and those to avoid

Light type	**Suitability for use near marine turtle habitat**
Low-pressure sodium vapour	Suitable
High-pressure sodium vapour	Suitable
Filtered LED **a**	Suitable
Filtered metal halide **a**	Suitable
Filtered white LED **a**	Suitable
LED with appropriate spectral properties for species present	Suitable
White LED	Not suitable
Metal halide	Not suitable
White fluorescent	Not suitable
Halogen	Not suitable
Mercury vapour	Not suitable

a ‘Filtered’ means this type of luminaire can be used only if a filter approved by the manufacturer is applied to remove the problematic wavelength light.

Appendix H – Migratory shorebirds

Key points

There is evidence that night-time lighting of migratory shorebird foraging areas may benefit the birds by allowing greater visual foraging opportunities. However, where nocturnal roosts are artificially illuminated, shorebirds may be displaced, potentially reducing their local abundance if the energetic cost to travel between suitable nocturnal roosts and foraging sites is too great.

Artificial lighting could also act as an ecological trap by drawing migratory shorebirds to foraging areas with increased predation risk. Overall, the effect of artificial light on migratory shorebirds remains understudied and consequently any assessment should adopt the precautionary principle and manage potential effects from light unless demonstrated otherwise.

Shorebirds, also known as waders, inhabit the shorelines of coasts and inland water bodies for most of their lives. Most are from 2 taxonomic families, the sandpipers (*Scolopacidae*) and the plovers (*Charadriidae*). They are generally distinguished by their relatively long legs, often long bills, and most importantly their associations with wetlands at some stages of their annual cycles (van de Kam et al. 2014).

At least 215 shorebird species have been described (Colwell 2010). Their characteristics include long life span but low reproductive output, and they are highly migratory (Piersma & Baker 2000). Many species have special bills for feeding on different prey in wetlands. Their bills contain sensory organs to detect the vibrations of prey inside the substrate. Shorebirds are often gregarious during the non-breeding season, which is perhaps a mechanism to reduce individual predation risk (Cresswell 1994) and increase the chance of locating profitable feeding patches (Piersma & Baker 2000). About 62% of shorebird species migrate. Some are transoceanic and transcontinental long-distance migrants capable of flying up to 8 days non-stop. There are examples of individuals covering distances up to 11,500 km (Battley et al. 2012).

Figure 29 Curlew Sandpipers

Photo: Brian Furby.

Conservation status

Migratory shorebird species in Australia are protected under international treaties and agreements including the Convention on the Conservation of Migratory Species of Wild Animals (CMS, Bonn Convention) and the Ramsar Convention on Wetlands, and through the East Asian–Australasian Flyway Partnership. The Australian Government has bilateral migratory bird agreements with Japan (Japan–Australia Migratory Bird Agreement, JAMBA), China (China–Australia Migratory Bird Agreement, CAMBA), and the Republic of Korea (Republic of Korea–Australia Migratory Bird Agreement, ROKAMBA). In Australia, the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) gives effect to these international obligations. Many species are also protected under state and territory environmental legislation.

Thirty-seven species are listed as threatened and/or migratory species under the EPBC Act and are hence Matters of National Environmental Significance (MNES) in Australia. At least 56 transequatorial species belonging to 3 families – pratincoles (*Glareolidae*), plovers (*Charadriidae*) and sandpipers (*Scolopacidae*) have been recorded in Australia (Menkhorst et al. 2017). Thirty-six of these species and one non-transequatorial species are listed under the EPBC Act. Three species (and one subspecies) of migratory shorebird are listed as critically endangered, 2 species as endangered and one species (and one subspecies) as vulnerable under the EPBC Act.

These guidelines should be read in conjunction with EPBC Act Policy Statement 3.21: Industry guidelines for avoiding, assessing and mitigating impacts on EPBC Act listed migratory shorebird species (Commonwealth of Australia 2015a).

Distribution

Migratory shorebirds are found in Australia throughout the year and in all states and territories. Peak abundance occurs between August and April; however, sexually immature birds defer their northward migration for several years and can be found in Australia during the austral winter months.

They are predominantly associated with wetland habitats including estuaries and intertidal wetlands, coastal beaches, saltmarshes, mangrove fringes, wet grasslands, and ephemeral freshwater and salt lakes in inland Australia. Shorebirds are also opportunists and exploit artificial habitats such as pastures, tilled land, sewage treatment plants, irrigation canals, sports fields and golf courses. Of 397 internationally recognised sites considered important for migratory shorebirds along the East Asian–Australasian Flyway, 118 are found in Australia (Bamford et al. 2008).

Important habitat for migratory shorebirds

For the purposes of these guidelines, important habitat for migratory shorebirds includes all areas that are recognised or eligible for recognition as nationally or internationally important habitat. These habitats are defined in EPBC Act Policy Statement 3.21: Industry guidelines for avoiding, assessing and mitigating impacts on EPBC Act listed migratory shorebird species (Commonwealth of Australia 2015a) and the Wildlife Conservation Plan for Migratory Shorebirds (Commonwealth of Australia 2015b).

- Internationally important habitats are wetlands that support at least 1% of the individuals in a population of one species or subspecies, or a total abundance of at least 20,000 waterbirds.

- Nationally important habitats are wetlands that support at least 0.1% of the flyway population of a single species, 2,000 migratory shorebirds, or 15 migratory shorebird species.

Effects of artificial light on migratory shorebirds

Artificial light can disorient flying birds, affect their stopover selection, and cause their death through collision with infrastructure (McLaren et al. 2018). Birds may starve as a result of disruption to foraging, hampering their ability to prepare for breeding or migration. However, artificial light may help some species, particularly nocturnally foraging shorebirds, as they may have greater access to food (Rogers et al. 2006; Dwyer et al. 2013).

Annual cycle and habitat use in migratory shorebirds

Migratory shorebird species listed under the EPBC Act breed in the northern hemisphere, except the Double-banded Plover (*Charadrius bicinctus*), which breeds in New Zealand. Many of the northern hemisphere breeders nest in the arctic or subarctic tundra during the boreal summer (May to July) and spend the non-breeding season (August to April) in Australia or New Zealand. They usually spend 5 to 6 months on the non-breeding grounds, where they complete their basic (non-breeding plumage) moult, and later commence a prealternate (breeding plumage) moult prior to their northward migration. While undergoing their pre-alternate moult, shorebirds also consume a larger amount of prey to increase their fat storages, permitting them to travel greater distances between refuelling sites. Shorebirds refuel in East Asia during their northward migration. During southward migration, some individuals travel across the Pacific, briefly stopping on islands to refuel. Shorebirds migrating across the Pacific typically have non-breeding grounds in eastern Australia and New Zealand. Shorebirds returning to non-breeding grounds in western and northern Australia again pass through East Asia on their southward journey.

A common feature for many birds is their reliance on inland or coastal wetland habitats at some stages in their annual life histories. Many migratory shorebirds, despite the vast distances they cover every year, spend most of their time on coastal wetlands except for the 2 months of nesting when they use tundra or taiga habitats. However, productive coastal wetland is localised, which means that large proportions, or even entire populations, gather at a single site during a stopover or non-breeding season. The Great Knot Plover and Greater Sand Plover are examples, with 40% and 57% respectively of their entire flyway population spending their non-breeding season at Eighty-Mile Beach in Western Australia (Bamford et al. 2008). Wetlands commonly used include coastal mudflats and sandflats, sandy beaches, saltmarsh and mangrove fringes, ephemeral freshwater wetlands and damp grasslands.

The coastal intertidal wetlands favoured by many migratory shorebirds are a dynamic ecosystem strongly influenced by the tidal cycle. This is part of the critical transition zone between land, freshwater habitats and the sea. Throughout the East Asian–Australasian Flyway, intertidal wetlands have been susceptible to heavy modification for the development of farmlands, aquaculture, salt mining, ports and industry.

Daily activity pattern and habitat use of migratory shorebirds

The daily activity pattern of shorebirds at coastal wetlands is determined not only by daylight but also by tidal cycle (Colwell 2010). They feed on the exposed tidal wetland during low tide and roost during high tide as their feeding areas are inundated. The birds feed during both the day and night, especially in the lead-up to migration (Santiago-Quesada et al. 2014; Lourenço et al. 2008).

Roost site selection can vary between day and night. Shorebirds often use diurnal roosts nearest to the intertidal feeding area and may travel further to use safer nocturnal roosts – but at greater energetic cost (Dias et al. 2006; Rogers, Piersma & Hassell 2006). Roosting habitat can also vary between day and night. For example, Dunlin (*Calidris alpina*) in California make greater use of pasture (which tends to be less affected by artificial light and disturbances) at night and rely less on their diurnal roosts on islands and artificial structures such as riprap and water pipes (Conklin & Colwell 2007).

Foraging behaviours differ between day and night, and between seasons (Lourenço et al. 2008; McNeil, Drapeau & Pierotti 1993). Shorebirds typically show a preference for daytime foraging, which occurs over a greater area, and at a faster rate, than nocturnal foraging (Lourenço et al. 2008). Increased prey availability and avoidance of daytime predation and disturbance are some reasons for nocturnal foraging (McNeil, Drapeau & Pierotti 1993). Two basic types of foraging strategies have been described: visual and tactile (touch-based) foraging. Some species switch between these strategies. Tactile feeders such as sandpipers can use sensory organs in their bills to detect prey inside the substrate in the dark and can switch to a visual foraging strategy during moonlit nights to take advantage of the extra light (McNeil, Drapeau & Pierotti 1993). Visual feeders such as plovers have high densities of photoreceptors, especially the dark-adapted rods, which allow foraging under low-light conditions (McNeil, Drapeau & Pierotti 1993; Rojas et al. 1999). Plovers have been shown to employ a visual foraging strategy during both the day and the night, whereas sandpipers can shift from visual foraging during the day to tactile foraging at night, likely due to less efficient night vision (Lourenço et al. 2008).

Vision in migratory shorebirds

There is a dearth of literature on light perception in migratory shorebirds. Most studies are confined to the role of vision in foraging, with nothing on the physiology of shorebirds' eyes or their response to different wavelengths of light.

Birds in general are known to be attracted to, and disoriented by, artificial lights. This could be a result of being blinded by the intensity of light that bleaches visual pigments and therefore failing to see visual details (Verheijen 1985), or of interference with the magnetic compass used by the birds during migration (Poot et al. 2008). An attraction to conventional artificial night lighting may lead to other adverse consequences such as reducing fuel stores, delaying migration and increasing the chance of collision and thereby injury and death (Gauthreaux & Belser 2006).

Gulls and terns (*Anous minutus*, *Anous tenuirostris* and *Gygis alba*) share visual pigments that give them vision in the short-wavelength ultraviolet region of the spectrum in addition to the violet (blue) region of the spectrum. However, this sensitivity to very short wavelength light is rare in seabirds, which are characterised by photopic (daylight adapted) vision sensitivity in the mid to long wavelength range of the visible spectrum (590 nm to 740 nm, orange to red), while their scotopic (low light, dark adapted) vision is more sensitive to short wavelengths of light (380 nm to 485 nm, violet–blue) (Capuska et al. 2011).

Biological impacts on migratory shorebirds

The exponential increase in the use of artificial light over the past decade means ecological light pollution has become a global issue (Falchi et al. 2016). Although the extent to which intertidal ecosystems are being affected is unclear (Depledge, Godard-Codding & Bowen 2010), several studies have assessed both the positive and negative aspects of light pollution on migratory shorebirds.

Artificial lighting has been shown to influence the nocturnal foraging behaviour in shorebirds (Dwyer et al. 2013; Santos et al. 2010). Santos et al. (2010) demonstrated that 3 species of plovers (Common Ringed Plover, *Charadrius hiaticula*; Kentish Plover, *Charadrius alexandrina*; and Grey Plover, *Pluvialis squatarola*) and 2 species of sandpipers (Dunlin, *Calidris alpina* and Common Redshank, *Tringa totantus*) improved foraging success by exploiting sites where streetlights provided extra illumination (Santos et al. 2010).

Similarly, Dwyer et al. (2013) showed that artificial light generated from a large industrial site significantly altered the foraging strategy of Common Redshanks within an estuary. The greater nocturnal illumination of the estuary from the industrial site allowed the birds to forage for extended periods using a visual foraging strategy, which was deemed a more effective foraging behaviour than tactile foraging (Dwyer et al. 2013).

Although shorebirds may be attracted to foraging areas with greater nocturnal illumination, artificial light near nocturnal roosting sites may displace the birds. Having studied the nocturnal roosting habits of shorebirds in north-western Australia, Rogers et al. (2006) suggested that nocturnal roost sites with low exposure to artificial lighting (such as streetlights and traffic) and low perceived risk of predation were selected (Rogers et al. 2006). The study also found that nocturnal roosts spatially differed from diurnal roosts and required higher energetic cost to access, as the distance between nocturnal roosts and foraging areas was greater than the distance between diurnal roost sites and the same foraging areas (Rogers, Piersma & Hassell 2006). The overall density of shorebirds in suitable foraging areas is expected to decline with increased distance to the nearest roost, due to the greater energetic cost travelling between areas (Dias et al. 2006; Rogers, Piersma & Hassell 2006). The artificial illumination (or lack thereof) of nocturnal roost sites is therefore likely to significantly influence the abundance of shorebirds in nearby foraging areas.

Intermittent or flashing lights could flush out shorebirds and force them to leave the area, especially if the light is persistent (J Choi pers. obs. 2018; Straw pers. comm. 2018).

Artificial light can affect birds in flight. Not only can bright light attract airborne migrants (Longcore et al. 2013) but also artificial light can affect stopover selection in long-distance migrators, which can affect successful migration and decrease fitness (McLaren et al. 2018). Similarly, Roncini et al. (2015) found that interactions between offshore oil and gas platforms and birds in the North Sea were likely to include migratory shorebirds. They estimated that hundreds of thousands of birds were killed each year in these interactions and considered that light was the likely cause. The review recognised the gaps in monitoring and concluded that impacts are likely to be region, species and platform specific (Ronconi, Allard & Taylor 2015).

Environmental impact assessment of artificial light on migratory shorebirds

As a minimum, Best practice lighting design should be implemented for infrastructure with externally visible artificial lighting. Where there is important habitat for migratory shorebirds within 20 km of a project, consideration should be given to whether that light is likely to have an effect on those birds.

The following sections step through the framework for managing artificial light, with specific considerations for migratory shorebirds. The 20 km buffer is a precautionary limit based on evidence that skyglow can cause a change in behaviour in other species up to 15 km away (Rodríguez et al. 2014). Where artificial light is likely to affect migratory shorebirds, consideration should be given to mitigation measures at the earliest point in a project, including to inform the design phase.

It is important to recognise the spatial and temporal characteristics of migratory corridors for some migratory shorebird species. Species typically use established migratory pathways at predictable times, and artificial light intersecting with an overhead migratory pathway should be assessed in the same way as for ground-based populations.

Associated guidance

- Wildlife Conservation Plan for Migratory Shorebirds
- Approved conservation advice

Qualified personnel

Lighting design and management and the EIA process should be undertaken by appropriately qualified personnel. Plans should be developed and reviewed by appropriately qualified lighting practitioners, who should consult with an appropriately trained marine ornithologist or ecologist.

People advising on the development of a lighting management plan, or the preparation of reports assessing the effect of artificial light on migratory shorebirds, should have relevant qualifications equivalent to a tertiary education in ornithology or equivalent experience as evidenced by peer-reviewed publications in the last 5 years on a relevant topic, or other relevant experience.

Step 1: Describe the project lighting

Information collated during this step should consider the biological Effects of artificial light on migratory shorebirds. They can be affected by light when foraging or migrating at night. Artificial light at night may also affect their selection of roost site. The location and type of light source (both direct and skyglow) should be considered in relation to feeding and resting areas, depending on whether the birds are active or resting at night. Shorebirds are sensitive to short-wavelength (blue/violet) light, and some species are able to detect UV light. However, the intensity of lights may be more important than colour.

Step 2: Describe the migratory shorebird population and behaviour

The species and behaviour of shorebirds in the area of interest should be described. This should include the conservation status of the species; the abundance of birds; how widespread/localised the population is; the location, timing and usage of the migratory corridor; the regional importance of the population; the number of birds in the area in different seasons; and their night-time behaviour (resting or foraging).

Relevant information on shorebirds can be found in EPBC Act Policy Statement 3.21: Industry guidelines for avoiding, assessing and mitigating impacts on EPBC Act listed migratory shorebird species (Commonwealth of Australia 2015a), the Wildlife Conservation Plan for Migratory Shorebirds (Commonwealth of Australia 2015b), the Protected Matters Search Tool, the National Conservation Values Atlas, state and territory listed species information, scientific literature, and local and Indigenous knowledge.

Where there are insufficient data to understand the population’s importance or demographics, or where it is necessary to document existing shorebird behaviour, field surveys and biological monitoring may be necessary.

Biological monitoring of migratory shorebirds

Monitoring associated with a project should be developed, overseen and have the results interpreted by an appropriately qualified biologist to ensure reliability of the data (see Qualified personnel).

The objective is to collect data on the abundance of birds and their normal behaviour. See Survey guidelines for Australia's threatened birds (Commonwealth of Australia 2010).

The data will be used to inform the EIA and assess whether mitigation measures are successful. Suggested minimum monitoring parameters (what is measured) and techniques (how to measure them) are summarised in Table 10.

Table 10 Recommended minimum biological information necessary to assess the importance of a migratory shorebird population

Targeted age class	Survey effort	Duration	Reference
Adult	Four surveys of roosting birds (one in December, two in January and one in February), with an additional 3 to 4 surveys within the same neap-spring tide cycle, are recommended.	Two hours before and after predicted high tide	Industry guidelines for avoiding, assessing and mitigating impacts on EPBC Act listed migratory shorebird species (Commonwealth of Australia 2015a)
Immature	One to two surveys on roosting birds between mid-May and mid-July.	Two hours before and after predicted high tide	

Note: the information in this table is not prescriptive and should be assessed on a case-by-case basis.

Monitoring migratory shorebird populations

- Monitor the population (during different seasons) to establish a benchmark for assessing abundance before, during and after construction and during operations, to detect project-related change.
- Quantify the diurnal and nocturnal habitat use and movement in relation to tidal cycle (both high and low tides during the neap and spring tide cycles) in the area under baseline conditions to compare with light-affected conditions during construction and operations.
- Measure nocturnal light levels at foraging sites and nocturnal roost sites before and after the construction period of a project.
- Monitor nocturnal roost sites, using acoustic recording devices and/or infrared cameras, to determine nocturnal roost site use following the introduction of artificial light.

As a minimum, qualitative descriptive data on visible light types, location and directivity should also be collected at the same time as the biological data. Handheld camera images can help to describe the light. Quantitative data on existing skyglow should be collected, if possible, in a biologically meaningful way, recognising the technical difficulties in obtaining these data. See Appendix C – Measuring biologically relevant light for a review.

Step 3: Risk assessment

The objective of these guidelines is that light should be managed so that shorebirds are not disrupted within or displaced from important habitat and are able to undertake critical behaviours such as foraging, roosting and dispersal. These consequences should be considered in the risk assessment process. At important shorebird habitats, roosting and foraging numbers should remain constant and foraging birds should not be startled or at increased risk from predators as a result of increased illumination.

The assessment should consider the existing light environment, the proposed lighting design and mitigation/management, the behaviour of shorebirds at the location, and how the birds perceive light. This should include wavelength and intensity information and perspective. To understand how or whether shorebirds are likely to see light, a site visit should be made at night and the area viewed from the intertidal flats and roosting areas. Similarly, consideration should be given to how shorebirds will see light when in flight and along flyways during migration periods.

The type and number of artificial lights should then be considered to assess whether the birds are likely to perceive the light, and the possible consequences of artificial light on their behaviour.

Step 4: Light management plan

This plan should include all relevant project information (Step 1) and biological information (Step 2). It should outline proposed mitigation. For a range of shorebird-specific mitigation measures, see Migratory shorebird light mitigation toolbox. The plan should also outline the types of and schedule for biological and light monitoring to ensure mitigation is meeting the objectives of the plan, and triggers for revisiting the risk assessment phase of the EIA.

The plan should outline contingency options to implement if biological and artificial light monitoring or compliance audits indicate that mitigation is not meeting the objectives of the plan (for example, light is visible on intertidal flats, shorebirds cease using resting areas, birds are grounding or colliding with fixed or floating infrastructure, or migrating birds cease using a migratory corridor).

Step 5: Biological and light monitoring and auditing

The success of the risk mitigation and light management should be confirmed through monitoring and compliance auditing. The monitoring and audit results should be used to facilitate an adaptive management approach for continuous improvement.

Biological monitoring is described in Step 2. Concurrent light monitoring should be undertaken and interpreted in the context of how the birds perceive light and within the limitations of monitoring techniques described in Appendix C – Measuring biologically relevant light. Artificial light auditing, as described in the light management plan, should be undertaken.

Step 6: Review

The EIA should incorporate a continuous improvement review process that allows for upgraded mitigations, changes to procedures, and renewal of the light management plan.

Migratory shorebird light mitigation toolbox

All projects should incorporate the Best practice lighting design principles. Appropriate lighting controls and light impact mitigation will be site, project and species-specific. Table 11 provides a toolbox of options that would be implemented in addition to the 6 Best practice lighting design principles. Not all mitigation options will be relevant in all situations. Table 12 provides a suggested list of light types appropriate for use near rookeries or roosting sites and those to avoid.

Table 11 Light management actions specific to migratory shorebirds

Management action	Detail
Implement actions when birds are likely to be present. This includes peak migration periods (flyway locations).	Migratory shorebirds are found in Australia year round. Major movements along coastlines take place between March and April, and August and November. Between August and April, shorebird abundance peaks. Smaller numbers are found from April to August.
No light source should be directly visible from foraging or nocturnal roost habitats, or from migratory pathways.	Any light that is directly visible to a person standing in foraging or nocturnal roost habitats will potentially be visible to a shorebird and should be modified to prevent it being seen. Similarly, lights should be shielded such that they are not visible from the sky.
Do not install fixed light sources in nocturnal foraging or roost areas.	Installing light sources (for example, light poles) within shorebird habitat may permanently reduce the available area for foraging or roosting and provide vantage points for predators (for example, raptors) during the day.
Prevent mobile light sources shining into nocturnal foraging and roost habitat.	The light from mobile sources such as mobile lighting towers, head torches or vehicle headlights should be prevented from aiming into nocturnal foraging or roost areas, as this can cause immediate disturbance.
Maintain a natural barrier (for example, dunes and vegetation) between nocturnal foraging and roost areas and sources of artificial light.	Reducing the exposure of shorebirds to artificial light will reduce the risk of predation and disturbance.
Maintain a dark zone between nocturnal foraging and roost habitats and sources of artificial light.	Creating a dark zone between artificial lights and shorebird habitat will reduce disturbances to shorebirds.
Use curfews to manage lighting near nocturnal foraging and roosting areas in coastal habitats. For example, manage artificial lights by using motion sensors and timers from 7 pm until dawn.	Curfews should also consider the tidal cycle if the artificial lighting is located coastally – for example, extinguish lighting from 2 hours before high tide until 2 hours after high tide while shorebirds are potentially roosting.
Use flashing/intermittent lights instead of fixed beam.	For example, small red flashing lights can be used to identify an entrance or delineate a pathway. The timing of when lights flash must follow a predictable, well-spaced pattern.
Use motion sensors to turn lights on only when needed.	For example, installing motion-activated pedestrian lighting within 500 m of nocturnal foraging or roost areas may reduce the amount of time the habitat is exposed to artificial light.
Manage artificial light on jetties and marinas.	Shorebirds will often roost on breakwaters and jetties, so allowing dark areas in such places may provide a safe area for roosting.
Reduce deck lighting to the minimum required for human safety on vessels moored near nocturnal foraging and roost areas, and those operating offshore.	Extinguish deck lights when not necessary and restrict lighting at night to navigation lights only. Offshore vessels should direct light inwards, particularly during the migration periods when shorebirds are potentially overhead. Record bird strike or incidental capture and report these interactions to regulatory authorities
Minimise night-time flaring on offshore oil and gas production facilities.	Consider reinjecting excess gas instead of flaring. Schedule maintenance flaring during daylight hours. Record bird strike or incidental capture and report these interactions to regulatory authorities.
Use luminaires with spectral content appropriate for the species present.	Consider avoiding specific wavelengths that are problematic for the species of interest. In general, this would include avoiding lights rich in blue light; however, some birds are sensitive to yellow light and other mitigation may be required.
Avoid high intensity light of any colour.	Keeping light intensity as low as possible in the vicinity of nocturnal foraging and roost areas will minimise impact.

Management action	Detail
Prevent indoor lighting reaching migratory shorebird habitat.	Use fixed window screens or window tinting on fixed windows and skylights to contain light inside buildings.
In facilities requiring intermittent night inspections, turn lights on only while operators are moving around the facility.	Use appropriate wavelength, explosion-proof LEDs with smart lighting controls and/or motion sensors. LEDs have no warm-up or cool-down limitations, so they can remain off until needed and provide instant light when required for routine nightly inspections or in the event of an emergency.
Industrial site/plant operators are to use personal head torches.	Consider providing plant operators with white head torches (explosion-proof torches are available) for situations where white light is needed to detect colour correctly, or in the event of an emergency. Operators should avoid shining light across nocturnal foraging or roost areas, as this can cause disturbance.
Supplement facility perimeter security lighting with computer-monitored infrared detection systems.	Perimeter lighting can be operated when night-time illumination is necessary but remain off at other times.

If all other mitigation options have been exhausted and there is a human safety need for artificial light, see Table 12 for guidance on types of commercial luminaires that are more suitable for use near migratory shorebirds. The effectiveness of these luminaires will depend on which species are being considered. Careful post-installation monitoring should be undertaken to assess the success of mitigation.

Table 12 Commercial luminaire types that are considered generally less disruptive for use near migratory shorebird habitat, and those to avoid

Light type	Suitability for use near marine turtle habitat
Low-pressure sodium vapour	Suitable
High-pressure sodium vapour	Suitable
Filtered LED **a**	Suitable
Filtered metal halide **a**	Suitable
Filtered white LED **a**	Suitable
LED with appropriate spectral properties for species present	Suitable
White LED	Not suitable
Metal halide	Not suitable
White fluorescent	Not suitable
Halogen	Not suitable
Mercury vapour	Not suitable

a ‘Filtered’ means this type of luminaire can be used only if a filter approved by the manufacturer is applied to remove the problematic wavelength light.

Appendix I – Bats

Key points

Most Australian bats are nocturnal and begin foraging at or after dusk. Artificial light at night can affect bats at roost sites, along commuting corridors or when foraging. Impacts are species-specific, but can include attraction to artificial lights, changes in prey availability, habitat degradation and avoidance of artificial light. A precautionary approach should be taken when any artificial light at night changes are implemented as the physiological impacts of artificial light on many species are not fully understood.

Most Australian bats are insectivores. For these species, consideration should be given to changes in prey availability resulting from the introduction of artificial light in or near bat foraging habitat.

Key management measures

Maintaining natural darkness in and near all bat species' habitats is the most effective impact mitigation method. Where lighting exists or is introduced, effective management approaches include maintaining dark roost sites, creating dark corridors from roosts to foraging/watering sites, keeping light intensities low and redirecting light away from habitats. Longer wavelength (red) artificial light appears to have the least impact on several bat species. However, least impact does not mean no impact, and mitigation should be considered on a case-by-case basis and be specific to bat species in affected areas.

Bats around the world provide valuable ecosystem services such as pollination (estimated to be worth US$200 billion globally) and insect pest suppression (valued at US$3.7 billion to US$53 billion in the US alone) (Kasso and Balakrishnan 2013). Most of the nearly 80 bat species found in Australia are nocturnal (Churchill 2008; Van Dyck and Strahan 2008). Because bats are adapted to the night-time environment, they are particularly vulnerable to impacts from artificial light. Bats can confuse artificial lighting with natural lighting cues (for example, sunset, natural darkness, moonrise and sunrise) which influence behaviours such as roosting, emergence, feeding, torpor and commuting. Indirectly, artificial light can disrupt the life cycles or habits of food sources such as nocturnal insects – the food source of most Australian bats (Churchill 2008; Owens and Lewis 2018). Bat populations are slow to recover from disruptions due to low reproduction rates (often one pup per breeding season and only one breeding season per year for most species) and high food requirements (Voigt and Kingston 2016). They rest during daytime at roost sites to conserve energy for their energy-intensive nightly commute to areas where they forage for food and water.

Bats can present a range of responses to artificial light. They possess varying degrees of visual acuity depending on the species. Insectivorous bats use sound (through echolocation) in conjunction with sight to navigate, forage and orient themselves. Nocturnal bats have evolved traits to thrive in very low light conditions. Larger eyes in some species, particularly flying-foxes, can correlate with greater sensitivity to available light, and echolocation in other species enables orientation and location of prey in the dark.

Artificial light has been observed to cause disruption and behavioural changes in bats (Haddock et al. 2019a; Haddock et al. 2019b; Stone et al. 2015). Potential negative impacts of artificial light include delayed roost emergence, longer increased foraging commutes due to artificial light avoidance, reduced reproductive success, increased predation risk, roost abandonment, changed foraging opportunities, increased interspecific competition, and commuting route fragmentation (Stone et al. 2015). Artificial light can even lead to death, as some species that avoid artificial light can become trapped in roosts where lighting spills onto roost exits (Stone et al. 2015). Echolocating bats in particular are susceptible to disruption both through direct visual mechanisms and through the impacts of light pollution on their prey.

Some bat species may be light tolerant or even exploit artificial light where insect prey is more abundant or easier to capture. However, artificial light can affect insect community composition, resulting in food shortages for competing bat species, or may interfere with the long-term abundance of insect populations (Azam et al. 2015; Stone et al. 2015). A precautionary approach to artificial light management strategies should be taken for all Australian bat species, regardless of behavioural impact or protection status. Artificial light is known to disrupt a variety of biological functions, and a full understanding of the impacts on wildlife is still developing.

Most of what is known about bat behaviour and the effect of artificial light is derived from research on non-Australian bat species. While Australian research has corroborated some of the general principles known about bats from overseas research, it has also highlighted that impacts of artificial light at night (ALAN) are species-specific. Further research is required to understand the full scope of impacts on all species.

Figure 30 Ghost Bat pup

Photo: © Vanessa Stebbings / Taronga Zoo.

Conservation status

Noting that this appendix applies to all Australian bat species, 15 species are listed as threatened under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). Three of the EPBC Act listed species are now extinct. Many more species are protected by state and territory legislation.

For information from states and territories on protected bats see:

- Australian Capital Territory – Threatened species of the ACT

- New South Wales – Threatened biodiversity profile search
- Northern Territory – Threatened animals
- Queensland – Threatened species
- South Australia – Threatened species in South Australia
- Tasmania – List of threatened species
- Victoria – Framework for conserving threatened species
- Western Australia – Threatened species and communities.

Further information about bat species can be found in the department's Species Profile and Threats Database (SPRAT).

Distribution

Bats are distributed throughout all states and territories in Australia, except sub-Antarctic islands. They occupy almost all natural habitats in Australia, including forests, woodlands, intertidal mangroves, mountains, deserts, rural landscapes, and urban environments. Bats roost during the day and at night in solitude or in colonies in caves, trees, tree hollows, bird nests, natural cracks and crevices, disused mine adits, aqueducts, jetties, bridges, buildings and other manufactured structures. Colonies range from a handful of individuals to hundreds of thousands. Some bats regularly commute as far as 40 km from their roost sites in one night to forage (Wilson and Mittermeier 2009). However, the Southern Bent-wing Bat (*Miniopterus orianae bassanii*) has been anecdotally observed to travel over 70 km in a single night to forage (Australasian Bat Society 2018). Distribution for EPBC Act listed threatened bat species can be found in the SPRAT database.

Habitats in which species may be susceptible to light pollution

All bats require access to roost sites, foraging areas, commuting corridors, and water sources (though not all species need to drink). It is important to avoid any artificial light directed at roosts (breeding, permanent, or transitory) and entrances/exits of roost sites and the surrounding area. An ideal strategy for avoiding impacts on bat populations, particularly light-avoidant species, is to provide unlit, dark areas where they can roost, commute, forage and drink without being disrupted by artificial light. The level of importance for each habitat will depend on the species and the way the species utilises each site. There may also be a temporal dimension to important bat habitats, which may only be occupied at certain times throughout a 24-hour day or certain times of the year (see Habitat seasonality).

Some EPBC Act listed species have important populations or habitats critical to survival defined in recovery plans or conservation advices. One example is the Pilbara Leaf-nosed Bat (*Rhinonicteris aurantia*), which occupies an area in the north-west of Western Australia that is both an important population and a population of national significance (Commonwealth of Australia 2016c). Underground refuges (such as caves or mines) that are permanent diurnal roosts, non-permanent breeding roosts and transitory diurnal roosts are considered habitat critical to the survival of this species (Commonwealth of Australia 2016c).

Nationally important camps – patches of trees where protected flying-foxes roost – for the Spectacled Flying-fox (*Pteropus conspicillatus*) and Grey-headed Flying-fox (*Pteropus poliocephalus*) are identified on the department's website, including the results of quarterly population monitoring undertaken at these sites. States and territories may designate different camps as important, and the relevant jurisdictional agency should be consulted accordingly.

Habitat seasonality

Many Australian bats exhibit seasonal breeding, hibernation, migration or activity patterns. Seasonal behaviours vary between species and may even differ within the same species. The predictability and regularity of seasonal behaviours is also species dependent. The Grey-headed Flying-fox, for instance, exhibits irregular and complex migration patterns which appear to correspond with fruit and flowering availability. In comparison, migratory bat species in the northern hemisphere tend to exhibit simpler, more predictable movements from northern to southern latitudes (Roberts et al. 2012). For more predictable bat species, understanding seasonality can be helpful in managing artificial light impacts. The Ghost Bat (*Macrodema gigas*), for example, congregates at fewer roost sites during breeding season and disperses more widely at other times of the year (Commonwealth of Australia 2016b). Identifying the temporal component of bat life cycles – migration, breeding, torpor, roost emergence – can assist in determining when artificial light should be managed or avoided to minimise disturbance for those species.

Effects of artificial light on bats

Artificial light may disturb some bat species at roosting sites, affect bat foraging ecology and/or fragment commuting corridors. These impacts can reduce the capacity of a threatened species to persist or recover. As artificial light can affect different species in different ways, impacts should be considered on a case-by-case basis.

Bats are described as light tolerant if foraging behaviour is not negatively affected by artificial light. For example, many nationally important flying-fox camps and other known roost sites are located in artificially lit urban environments. Other species are considered light-intolerant or light-avoidant. Light-intolerant bats may exhibit important behaviour changes when exposed to artificial light and may actively avoid point sources of artificial light. Potential explanations of light avoidance behaviour include predator evasion, sensitivity to ultraviolet light and inability to exploit prey at light sources (Haddock 2018; Stone et al. 2015). While light-tolerant species may not change their behaviours in the presence of artificial light or may actively exploit point sources of artificial light, this does not mean there are no negative consequences. These bat species may be affected by changes in prey abundance, increased predation or physiological disturbances as have been described in other mammals (Patriarca and Debernardi, 2010; Grubisic et al., 2019). Furthermore, there may be differences in behaviours between and within species. Precautions should be taken to minimise or eliminate artificial light exposure for all bat species.

The type of light pollution known to impact bats is artificial point source light directly illuminating their habitat. The impacts of skyglow on bats are less known and represent a knowledge gap that requires further research. Direct impacts of artificial light on bats, as discussed in this appendix, are primarily referring to artificial point source light.

Roosts

Artificial light should not spill into roost sites. Artificial light can interfere with natural lighting cues and emergence routes, affect juvenile growth rates and reduce bat numbers and can even lead to roost abandonment or deaths (Stone et al. 2015; Zeale et al. 2016). Dusk is frequently a cue for bats to leave the roost and begin foraging. Artificial light may delay emergence from roosts, reducing foraging time, and may cause bats to miss peak insect abundance (Boldogh et al. 2007). These impacts may reduce bat fitness and may have consequences for populations (Stone et al. 2015). Where artificial light shines directly onto a roost site, bats may be forced to use suboptimal exits that may result in greater predation rates by predators such as cats

(Ancillotto et al. 2013; Stone et al. 2015). For example, the use of bright lights at the exits of caves when cave-roosting bats are emerging, as occurs sometimes during tourist operations, usually results in stopping or reducing the number of bats flying out (Lindy Lumsden 2020, pers. comm. to C San Miguel, 23 December). In some cases, artificial light may effectively trap bats in the roost and prevent emergence altogether (Stone et al. 2015). Long-term artificial light exposure at roost sites may cause bats to abandon a roost in favour of a suboptimal site. Negative impacts on maternity and breeding roosts could have consequences for bat populations since most bat species are slow to reproduce (Rowse et al. 2016).

Bats vary in their resilience to impacts at roost sites and some may tolerate artificial light more than others. For example, the Ghost Bat is highly susceptible to roost disturbance (Commonwealth of Australia 2016b). Flying-foxes are known to be disturbed and repelled by the consistent use of flood lights as deterrents but can habituate to other visual disturbances such as strobe lights and high-intensity sweeping floodlights (State of Queensland 2020). Regardless of the tolerance level, precaution should be taken to avoid potential impacts. Artificial light installations should be avoided at or near known roost sites. Where artificial lighting exists near roosts, light should be directed away and kept at the lowest practicable intensities.

Habitat fragmentation

Some bat species need to travel or commute between roost sites and foraging areas. Artificial light in commuting areas, particularly for light-avoidant bats, can fragment habitat, which may cause longer flight times and increase energy expenditure (Stone et al. 2015). Where bats are forced to use suboptimal flight paths they may be exposed to greater predation risk. Where there are no alternative flight paths, bats may be isolated from key food or water sources. For light-avoidant species, the habitat is considered degraded or lost where artificial light spills onto habitat (Azam et al. 2018; Haddock et al. 2019b; Spoelstra et al. 2017). Where light intrusion occurs in foraging habitats, bats may avoid the best foraging areas, instead utilising suboptimal habitat (Polak et al. 2011). Alternatively, artificial light may affect the abundance of food resources (Davies et al. 2012). In both situations, bats' ability to obtain necessary resources may be compromised.

Foraging ecology

Some behavioural generalisations can be made about bat responses to artificial light based on diet. Bats are primarily either herbivores, which are primarily frugivorous and nectarivorous, with some species also consuming leaves, and carnivores, which are primarily insectivorous, with some species also consuming small vertebrates or fish. For the purpose of these guidelines, carnivorous bats will be referred to as insectivores, as most Australian bat species feed on insects.

Insectivores

Insectivorous bats utilise vision, echolocation and passive listening to aerially orient themselves and search for food. Insectivores are likely to be affected by artificial light in multiple ways, as their primary food source, insects, may also be susceptible to impacts from artificial light, which can lead to changes in prey availability (Owens & Lewis 2018; Rowse et al. 2016). For insectivores, some generalisations about the feeding behaviour effects of artificial light can be made based on foraging ecology. Slow-flying insectivores are thought to be more light averse (presumable causes are predation risk, diminished ability to catch insects in flight or the potential impact on orientation abilities), while fast-flying might be more likely to exhibit light tolerance by opportunistically feeding around artificial lights (Azam et al. 2015; Haddock 2018;

Rowse et al. 2016; Rydell 2005; Voigt et al. 2018). However, the relationship between foraging ecology and the relative effects of artificial light needs further research for all species, which might exhibit diverse species-specific behaviours. Light exploiting or avoiding only describes feeding behaviour in response to artificial light, not whether there is a positive or negative impact. For example, a species that exploits light does not necessarily benefit from this behaviour long-term. A precautionary approach is recommended, and each species' behaviour under artificial light should be assessed on a case-by-case basis.

Artificial light may impact interspecies dynamics if more than one bat species occupies the same area, and one species is able to exploit lit areas more efficiently than the other (see Artificial light impacts on food sources for additional information) (Rydell 1992). While the recommended mitigation methods are consistent across all insectivorous bats (see Bat light mitigation toolbox), responses to artificial light are more complex than generalisations based on foraging ecology (Haddock 2018) and can vary between species. Experts should be consulted when assessing the impacts of artificial light on bats.

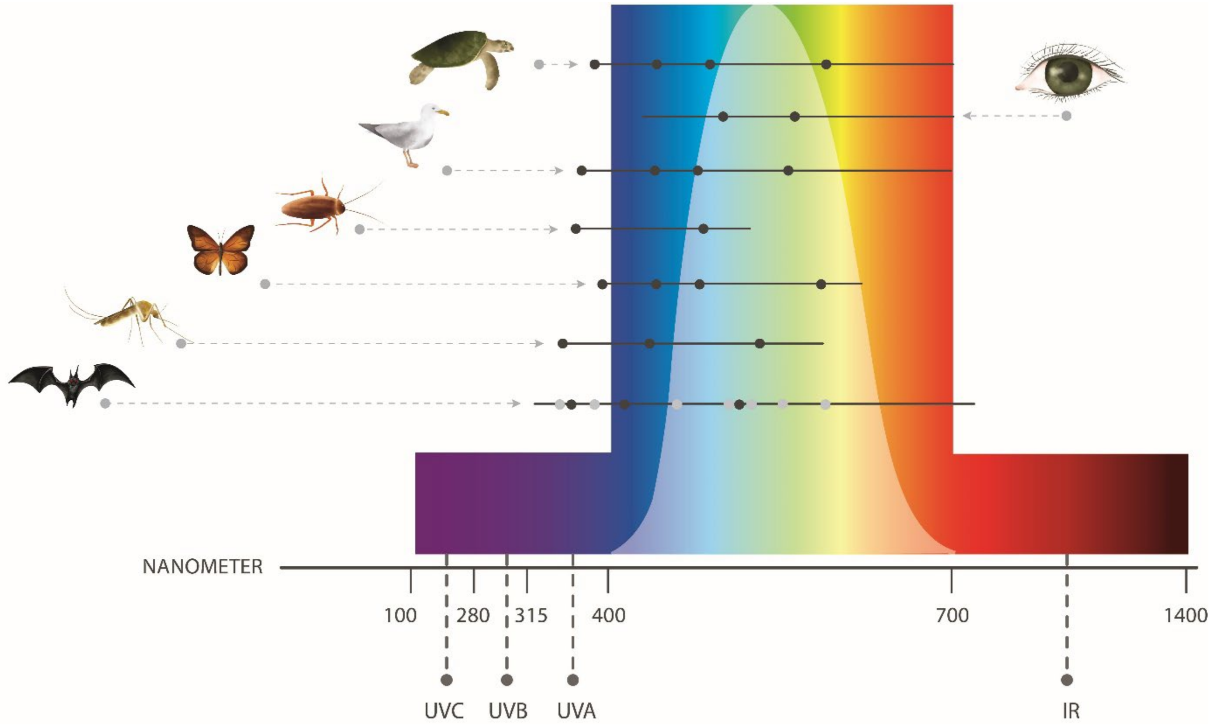
Frugivores and nectarivores

Frugivorous and nectarivorous bats heavily rely on vision and smell to orient themselves and forage (Churchill 2008). Evidence from a Central American study suggests they exhibit light avoidance (Lewanzik and Voigt 2014), though this was based on species that rely on echolocation, which the Australian frugivorous and nectarivorous species do not. Research has yet to distinguish the effects of artificial light from other human impacts such as habitat loss from urban development (Rowse et al. 2016). Some species of flying-foxes spend large portions of daytime at roost sites surveilling for predators by using visual and acoustic detection, indicating a potential light tolerance in bright conditions (Müller et al. 2007). Flying-foxes do not appear to avoid moonlit areas and are known to roost in artificial light drenched areas, suggesting little or no behavioural impact from artificial light (Lindy Lumsden 2020, pers. comm. to C San Miguel, 23 December).

When considering the introduction of, or changes to, artificial lights near important habitat, particularly roost sites, a precautionary approach that assumes a likely impact should be applied and relevant experts should be consulted.

Vision in bats

Figure 31 Comparative light perception among different species groups



Note: Horizontal lines show a broad generalisation of the ability of humans and wildlife to perceive different wavelengths. Dots represent reported peak sensitivities. Black dots for bats represent peak sensitivities in an omnivorous bat, based on Winter et al. (2003); grey dots represent potential peak sensitivities in bats, derived from Feller et al. (2009) and Simões et al. (2018). Figure adapted from Campos (2017).

Understanding how bats perceive light is important for implementing mitigations that minimise impacts where natural darkness cannot be achieved. Visual capacities and sensitivities are likely to be species or family specific. Many bat species perceive light and colours differently to humans. Some species have been reported to be sensitive to light wavelengths at around 500 nm (green), 565 nm (yellow) and 390 nm (violet) wavelengths (Eklöf 2003; Gorresen et al. 2015; Simões et al. 2018; Winter et al. 2003) (Figure 31). Unlike in humans, spectral perception in many bat species extends into the ultraviolet range (Gorresen et al. 2015; Simões et al. 2018). Pallas's Long-tongued Bat (*Glossophaga soricine*) (omnivorous bat) from South and Central America is thought to be able to detect light wavelengths between 310 nm (UV light) and 688 nm (orange/red light) and exhibit peak spectral sensitivity at 510 nm (green) and above 365 nm (UV) (Winter et al. 2003).

Narrow spectrum and longer wavelength artificial light (Table 14) at lower intensities is generally considered to have the least impact on bats (Azam et al. 2018; Haddock 2018; Spoelstra et al. 2017; Voigt et al. 2018). This is likely to apply to some slow-flying, light-averse bats but may also apply to light tolerant species. Some bat species considered more manoeuvrable and light tolerant are thought to be least affected by red wavelength illumination compared with white and green wavelengths (Haddock 2018; Spoelstra et al. 2017). Predator evasion, sensitivity to ultraviolet light and inability to exploit prey at artificial light sources may be responsible for light avoidance behaviour (Haddock 2018; Spoelstra et al. 2017). Further research is required to better understand light perception and sensitivities, and the mechanisms underlying observed artificial light impacts in Australian bat taxa.

Artificial light intensity should be considered in addition to spectral content. Nocturnal bats have evolved under conditions where the brightest source of light in the night sky was a full moon. Anthropogenic light sources, however, can produce intensities hundreds or thousands of times brighter than the moon. High artificial light intensity is known to cause light avoidance and can trespass into nearby bat habitats, contributing to habitat loss or fragmentation (Azam et al. 2018).

Where artificial lighting is necessary, the mitigation regime for bats should minimise the amount of artificial light used, using the lowest light intensity practicable and directing artificial light away from bat habitats. Mitigation approaches should be assessed on a case-by-case basis as bat species are use different strategies to orient themselves to different artificial light sources. Some species, like the Bare-rumped Sheathtail (*Saccolaimus nudicluniatus*), are known to fly high at or above tree canopy heights (Commonwealth of Australia 2016d). For these species, luminaires that are below canopy heights should have light beams directed downward and use light shields to prevent light spilling upward into habitat. Such measures may be less useful for bat species that fly low to the ground or below the height of an artificial light source but may still be useful methods for managing light spill and skyglow. Reflective surfaces can also scatter or reflect light into bat habitats, even where artificial light is directed downwards or shielded, and should also be managed. Where artificial light spills on top of, or into, bat habitats, additional mitigation considerations should include decreasing the beam area of directed artificial light, decreasing intensity, using non-reflective surfaces, using narrow wavelength (probably red) artificial light and creating dark corridors.

All mitigation measures should be accompanied by monitoring to assess the effectiveness of mitigation methods and adapt them as necessary (see Environmental impact assessment of artificial light on bats).

Artificial light impacts on food sources

When considering the impact of artificial light on bats it is important to understand the impacts of artificial light on their food sources. Artificial light impacts a wide range of flora and fauna (Gaston et al. 2013) and any impact on bat food sources – fish, plants, terrestrial vertebrates, and invertebrates – can indirectly impact bats, leading to reduced growth rates, decreased reproductive output and even death (Grubisic et al. 2019; Longcore & Rich 2006)., as Since most Australian bat species consume insect taxa (Churchill 2008), which are affected by light, insectivorous bats may be particularly vulnerable to artificial light. The following subsection provides an overview of the impact of artificial light on insects.

Insects

Artificial light may be an important driver of the global insect decline, alongside habitat loss, pesticide use, invasive species and climate change (Owens et al. 2020). Artificial light is known to elicit many responses in insects, most commonly flight-to-light. Impacts of flight-to-light on individual insects include becoming trapped by their attraction to light, disorientation, dazzle, increased predation susceptibility, and death from exhaustion and predation (Eisenbeis & Hänel 2009; Owens & Lewis 2018). Attraction to artificial light may also impact insect populations by disrupting astronomical navigation (due to artificial point source lighting and skyglow), restricting spatial distributions, altering spatial densities, increasing interspecific competition and causing long-term population declines (Adden 2020; Azam et al. 2015; Boyes et al. 2021; Sánchez-Bayo & Wyckhuys, 2019).

Many insect species (particularly moths, flies and beetles) are attracted to higher intensity and shorter wavelength light emitted by commonly used luminaires, such as high-pressure mercury vapour and LEDs (Frank 2016; Linley 2017; Owens & Lewis 2018; Voigt et al. 2018). Notably, moths – a main food source for at least 3 of the 9 insectivorous EPBC Act listed bats – have been shown to remain in artificial light pools despite the presence of bat predators (Frank 2016; Wilson & Mittermeier 2009). Some moths adapted to detecting and evading bats have reduced evasive ability when exposed to high-UV luminaires, making them easy prey (Frank 2016). Flight-to-light behaviours may result in death for 30% to 40% of insects approaching artificial light sources, due to collisions, overheating, dehydration or being eaten (Owens & Lewis 2018). This high insect mortality, while partially attributed to predation, could have significant implications for the insects' long-term availability as a food source (Azam et al. 2015) (that is, a short-term increase in availability of insects as food may cause insect populations to decline in the long-term and thereby reduce food availability for bats).

Artificial light impacts on insects can also have cascade effects on insectivorous bats. When large numbers of insects are attracted to artificial light sources, the insect distribution and concentration change is known as the 'vacuum cleaner effect' (Eisenbeis & Hänel 2009; Haddock 2018). Bats that tolerate or exploit artificial light (such as many fast-flying aerial foragers) are less likely to be negatively impacted and may even increase energy intake due to a reliable high volume of food sources at artificial lights (Haddock et al. 2019b; Rydell 1992). However, it is possible that such advantages are short lived if the increased insect predation results in fewer insect populations long-term. This is particularly relevant for macromoth species attracted to artificial lighting in Australia (Azam et al. 2015; Haddock et al. 2019a). Light-avoidant bats (including many slow-flying species) can be negatively impacted by artificial lights where insects are attracted into artificially lit areas (Haddock et al. 2019a; Haddock et al. 2019b). When artificial light attracts insect species from dark areas, light-avoidant bats may not follow them. Inability to exploit these higher densities of insects in areas drenched by artificial light may potentially disrupt coexistence between light-exploiting and light-avoidant bat taxa (Eisenbeis & Hänel 2009; Haddock et al. 2019b; Stone et al. 2015). Mitigation measures should consider the impact of artificial light on food sources as well as inter-specific dynamics of insectivorous bat species.

Environmental impact assessment of artificial light on bats

As a minimum, any planned changes to or installation of externally visible lighting should implement Best practice lighting design to reduce light pollution and minimise impacts on bats. Where protected bat species are known to occur or are likely to occur in the area, an environmental impact assessment (EIA) should be undertaken.

Bats use different parts of their habitat for roosting, foraging and commuting. Artificial light fragments and degrades bat habitat and can disrupt these critical behaviours.

Artificial light will likely be one of multiple stressors for bats that should be identified and managed in an EIA.

The following sections step through the EIA process, with specific considerations for bats. Where artificial light is likely to affect bats, consideration should be given to employing mitigation measures as early as possible in a project's life cycle, including to inform the design phase.

It is important to consider the commuting habits of bat species that utilise an area where lighting will be changed or installed. Some bat species commute distances upwards of 20 km from roosts to foraging sites. Consideration should be given to artificial light impacts within and outside roosting areas at distances relevant to the bat species.

Associated guidance

- Protected Matters Search Tool
- Species Profile and Threats Database
- Approved recovery plans for listed threatened bat species
- Approved conservation advices for listed threatened bat species
- EPBC Act Significant impact guidelines 1.1: Matters of National Environmental Significance
- Referral guideline for management actions in Grey-headed and Spectacled flying-fox camps
- Survey guidelines for Australia's threatened bats: Guidelines for detecting bats listed as threatened under the Environment Protection and Biodiversity Conservation Act 1999
- EUROBATS Guidelines for consideration of bats in lighting projects (2018)
- National Flying-fox Monitoring Viewer

Qualified personnel

Artificial lighting design/management and the EIA process should be undertaken by appropriately qualified personnel. Light management plans should be developed and reviewed by appropriately qualified lighting practitioners, who should consult with an appropriately qualified biologist or ecologist.

Experts advising on the development of an artificial lighting management plan or on the preparation of reports assessing the impact of artificial light on bats, should have knowledge of Australian bat biology and/or ecology, demonstrated through relevant qualifications or equivalent experience as evidenced by peer-reviewed publications in the last 5 years on a relevant topic, or other relevant experience.

Step 1: Describe the project lighting

Information collated during this step should consider the effects of artificial light on bats. The location of artificial light sources in relation to refuge sites, foraging areas and commuting routes should be considered at the design phase.

The existing light environment and the artificial light likely to be emitted from the site should be described during the planning phase of a project. Details should include the location and size of the project footprint; the number and type of artificial lights – their height, orientation and hours of operation; site topography; and the proximity and direction of lights compared with bats and/or their habitat. This information should include whether artificial lighting is likely to be visible from bat habitat or contribute to skyglow; the distance over which this artificial light is likely to be perceptible; shielding or light controls used to minimise artificial light spill; and spectral characteristics (wavelength) and intensity of artificial lights.

Step 2: Describe the bat population and behaviour

The species, behaviour and diet of bats roosting and foraging in the area of interest should be described. This should include the conservation status of the species; population trends (where known); how widespread/localised roosting for that population is; the abundance of bats using the location; the regional importance of the population; the seasonality of roosting and breeding; and foraging requirements and foraging range from roosting.

Species-specific information can be found in the SPRAT database, state and territory listed species information, scientific literature, recovery plans, conservation advices, and local and Indigenous knowledge.

Where there are insufficient data to understand a population's importance or demographics, or where it is necessary to document existing bat behaviour, field surveys and biological monitoring may be necessary. While bat colony roost sites may be known, commuting paths are less likely to be known (Voigt et al. 2018).

Biological monitoring of bats

Any monitoring associated with a project should be developed, overseen and have the results interpreted by appropriately qualified personnel to ensure data reliability.

The objectives of bat monitoring in an area likely to be affected by artificial light are to:

- understand the size and importance of the bat population
- understand any interspecies interactions (where multiple bat species are found at the same site)
- identify roosts, commuting routes and foraging and watering areas where artificial lighting changes may occur
- describe bat behaviour at roost sites, foraging areas and commuting routes before (to establish a baseline) and after the introduction or upgrading of artificial lighting.

The data will be used to inform the EIA and assess whether mitigation measures have the potential to be successful.

Artificial light can fragment and degrade bat habitat. Biological monitoring should include an adequate population survey to determine if there are important bat populations.

Rigorous surveys should be conducted to determine whether EPBC Act listed bats are present at the site; whether there is Habitats in which species may be susceptible to light pollution; whether bats are using habitat for roosting, foraging or commuting; and whether artificial light is likely to affect important behaviours, including beyond the site area.

To understand existing bat behaviour, it will be necessary to undertake monitoring (or a similar approach) to determine bat ability to use roost sites, forage and commute prior to the construction of or upgrades to lighting. Consideration should be given to monitoring a comparative control/reference site to ensure observed changes in bat behaviour are related to changes in the light environment and not to broader climatic or other landscape-level changes.

A well-designed behavioural monitoring program will capture the following before and after an artificial lighting design is implemented:

- behaviour of bats at roost sites – including location of roost used, type of roost used, time of first emergence, time of return to roost, and duration of rest and torpor
- foraging activity of bats – including location and type of foraging sites, time spent foraging, and prey availability
- commuting routes used by bats – including location of commuting routes, time, and duration of commuting behaviour.

Surveys should be designed in consultation with a quantitative ecologist/biostatistician to ensure that the data collected provides for meaningful analysis and interpretation of findings.

As a minimum, qualitative descriptive data on visible light types, location and directivity should also be collected at the same time as the biological data. Handheld camera images can also help describe the light. Quantitative data on existing skyglow should be collected, if possible, in a biologically meaningful way, recognising the technical difficulties in obtaining these data. See Appendix C – Measuring biologically relevant light for a review.

Step 3: Risk assessment

The objective of the Light Pollution Guidelines for Wildlife is that artificial light should be managed in such a way that bats are not disrupted within or displaced from important habitat, and that they are able to undertake critical behaviours such as roosting, foraging and commuting. The risk assessment process should assess the likelihood of artificial light affecting any of these behaviours. The aim is to ensure that important bat colonies remain constant, roosts (particularly maternity roosts) are not abandoned or disturbed, and foraging and commuting opportunities are not compromised.

When considering the likely effect of light on bats, the assessment should examine the existing artificial light environment, the proposed artificial lighting design and mitigation/management actions, and the behaviour of bats at the location. Consideration should be given to risks and impacts such as whether the bats have a direct line of sight to a given luminaire and whether they are likely to be able to see the artificial light. The assessment should include details on topography, wavelength, intensity, visibility, duration of operation, and location of the artificial light source in relation to bat presence.

To discern how or whether bats or their prey are likely to see artificial light, a site visit should be made at night and the area viewed from known bat roosts, commuting routes and foraging and watering areas. Similarly, consideration should be given to whether and how bats will perceive artificial light when in flight.

The type and number of luminaires should be considered/modelled to determine whether bats or their prey are likely to see the artificial light and whether the artificial light exposure will affect their behaviour.

Step 4: Light management plan

A light management plan should include all relevant project information (Step 1: Describe the project lighting) and biological information (Step 2: Describe the bat population and behaviour). It should outline proposed mitigation measures. For a range of bat-specific mitigation measures, see Bat light mitigation toolbox. The plan should also outline the types of and schedule for biological and light monitoring to ensure mitigation is meeting the objectives of the plan, and triggers for revisiting the risk assessment phase of the EIA. The plan should address conservation objectives, performance criteria and recovery actions, where existing government guidance exists (that is, conservation advices and recovery plans).

The plan should outline contingency options for additional mitigation or compensation if biological and light monitoring or compliance audits indicate that mitigation is not meeting objectives (for example, artificial light is visible from bat roosts or roost populations decline).

Step 5: Biological and light monitoring and auditing

The success of the impact mitigation and artificial light management should be confirmed through monitoring and compliance auditing. The monitoring and audit results should be used to facilitate an adaptive management approach for continuous improvement and contribute to scientific knowledge information baselines.

Relevant biological monitoring is described in Step 2: Describe the bat population and behaviour. Concurrent light monitoring should be undertaken and interpreted in the context of how bats and their prey perceive light and within the limitations of monitoring techniques described in Appendix C – Measuring biologically relevant light. Auditing, as described in the light management plan, should be undertaken to ensure artificial lighting at the site is consistent with the light management plan and relevant conservation objectives.

Step 6: Review

The EIA should incorporate a continuous improvement review process that allows for upgraded mitigations, changes to procedures, and renewal of the light management plan based on the outcomes of the biological monitoring program for artificial light impacts on bats.

Bat light mitigation toolbox

Appropriate artificial lighting design, controls and impact mitigation will be site, project and species-specific. provides a toolbox of management options relevant to bats. These management options should be implemented in addition to the 6 Principles of best practice lighting design. Not all mitigation options will be relevant for every project. Table 14 provides a suggested list of light types appropriate for use near bat habitat and those to avoid.

The most effective measures for mitigating the impact of artificial light on bats, in general, include:

- maintaining dark refuge sites
- avoiding, removing, redirecting or shielding artificial lights in foraging areas and along commuting routes
- keeping artificial light intensity as low as practicable, noting that low-intensity artificial light (comparable to full moon light levels) can disrupt behaviour of bats.

Other mitigation measures, which may be less effective, include:

- using narrow-spectrum, long-wavelength lighting (such as red light)
- implementing part-night lighting schemes to reduce the duration of artificial light
- using motion sensor lighting, noting that this may cause a startle response.

These measures should be assessed to determine their effectiveness as mitigation tools in each proposed project.

Table 13 Light management options specific to bats

Management action	Detail
Avoid adding artificial light to previously unlit areas.	Artificial light added to dark areas is more likely to have an impact than artificial lighting alterations or additions in areas where artificial light already exists.
Implement appropriate mitigation where and when bats are likely to be present.	Roosts, commuting routes, foraging areas and water sources are areas likely affected by artificial light. Any direct or indirect

	artificial light in foraging areas, commuting corridors or roost habitats that is visible to a person may also be perceived by bats. Modifications are encouraged to prevent the bats from perceiving this light.
Avoid artificial light directed onto roost sites and indirect spills into roosts.	Avoid installing and directing luminaires near roost sites, as this can cause roost abandonment or death. Artificial light should not be directed at, or spill onto, roost entrances or exits.
Direct artificial light downwards and/or shield luminaires near foraging areas and commuting corridors.	Vertical artificial lights should be shielded such that they are not visible from the sky or tree canopy above luminaire installations. Where lighting must be installed, it should be as low to the ground as possible to minimise light spill. Where pole lighting is used, it should be at a height sufficiently lower than tree canopies without compromising human safety. These measures allow light-avoidant species to continue using vegetated areas where artificial light offers no human utility (for example, tree canopies). Vertical artificial light spill onto vegetation should be as low intensity as possible.
Maintain darkness along commuting corridors and between roosts, water sources and foraging areas.	Artificial light sources should be at least 50 m from the edge of commuting corridors, roosts, water sources and foraging areas (Azam et al. 2018). If artificial light is too close to bat habitat, it may permanently reduce the available area for foraging or roosting (Haddock et al. 2019b), provide an advantage to predators (for example, raptors, cats, rats, foxes), or increase resource competition between bat species. Any breaks in dark corridors by artificial light may prevent the movement of bats between roosts and feeding/drinking areas or increase commuting distance for bats to cross lit areas at their darkest points (Hale et al. 2015) (See Figure 31).
Mitigate artificial light impacts for seasonal roosts.	The absence of bats does not rule out the possibility of a roost site. Some bat species may roost at certain sites at limited periods throughout the year.
Prevent indoor artificial lighting reaching the outdoor environment.	Use fixed window screens, blinds or tinting on fixed windows and skylights to contain artificial light inside buildings.
Avoid using high-intensity artificial light or unnecessary artificial light.	Keep incidental artificial light low by keeping light intensity as low as possible (without compromising human safety) in the vicinity of bat roosts and known foraging areas. Artificial light that spills into bat habitats (even from 50 m) should be kept as low as practicable. Light-sensitive species can be negatively affected by artificial light levels above natural levels of darkness. Isolated artificial light sources will typically have less effect than large arrays of high-intensity artificial lighting, except in areas where single artificial light sources are newly introduced.
Add or utilise appropriate vegetation to provide dark corridors and shield habitat from light.	Vegetation (for example, hedges and trees) can mitigate some of the negative effects of artificial light on bats by shielding against light entering their habitat or providing dark corridors. Bats can also be encouraged to utilise paths by keeping rows of trees and other vegetation unlit. Contiguous, unlit landscape features may guide them down safer or preferred commuting corridors.
Use luminaires with spectral content appropriate for the species present.	Consider avoiding specific wavelengths that are harmful for the species of interest. In general, this would include avoiding the use of artificial lights rich in UV, blue and green wavelengths. Blue and UV wavelengths are particularly attractive to insects that many bats consume. Low-pressure sodium lamps and amber LEDs are low in the blue and UV wavelength emissions that attract insects. LEDs may negatively impact some bat species (Linley 2017; Voigt et al. 2018), whereas red artificial light may have the least impact on most bat species (Haddock et al. 2019b; Spoelstra et al. 2017). Should this option be progressed, careful post-installation monitoring should be undertaken to assess the success of mitigation measures.
Implement part-night lighting schemes to reduce the amount of artificial light used throughout the night.	Consider lighting curfews to reduce lighting use throughout the night. Part-night lighting schemes will vary in effectiveness.

	Lighting curfews should be relevant to the species to maximise effectiveness (Azam et al. 2015).

If all mitigation options have been exhausted and there is a human safety need for artificial light, see Table 14 for guidance on types of commercial luminaires that are more suitable for use near bat habitat. The effectiveness of these luminaires is species-specific. Careful post-installation monitoring should be regularly undertaken to assess the effectiveness of mitigation.

Table 14 Commercial luminaire types that are considered generally less impactful for use near bat habitat, and those unsuitable

Light type	**Suitability for use near marine turtle habitat**
Low-pressure sodium vapour	Suitable
High-pressure sodium vapour	Not suitable
Filtered LED **a**	Suitable
Filtered metal halide **a**	Suitable
Filtered white LED **a**	Suitable
Amber LED	Suitable
PC amber	Suitable
White LED	Not suitable
Metal halide	Not suitable
White fluorescent	Not suitable
Halogen	Not suitable

a ‘Filtered’ means that these luminaires can only be used if a manufacturer-approved filter is applied to remove the short-wavelength light (400 nm to 500 nm).

Appendix J – Terrestrial Mammals

Key points

Most Australian terrestrial mammals are nocturnal and emerge from their refuge to begin foraging at or after dusk. Artificial light can affect terrestrial mammals at refuge sites, in foraging areas and along commuting routes. Impacts of artificial light on terrestrial mammals are species specific and include reduced activity, reduced time spent foraging, and increased predation.

Key management measures

In general, the most effective light management approaches for nocturnal and crepuscular terrestrial mammals include maintaining dark refuge sites, foraging areas and commuting routes. Artificial light intensity should be kept as low as possible near terrestrial mammal habitat. Longer wavelength (red) artificial light may be less disruptive to terrestrial mammals, however mitigation should be considered on a case-by-case basis and be specific to the terrestrial mammals in the area.

Most of Australia’s terrestrial mammals display nocturnal or crepuscular activity patterns. Nocturnal species rest during the day, begin their activity after dark and remain active throughout the night. Crepuscular species rest during the day and exhibit peak activity around dawn and dusk. Both nocturnal and crepuscular terrestrial mammals have vision that is adapted to low-light conditions (Schroer and Hölker 2016).

Almost all terrestrial mammal species listed in the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) exhibit nocturnal or crepuscular patterns of activity. This appendix will focus on the impacts of artificial light on nocturnal and crepuscular terrestrial mammals, which will both be referred to as nocturnal. This appendix does not address the impacts of artificial light on bats, marine mammals or diurnal terrestrial mammals.

Figure 32 Southern Brown Bandicoot

Photo: © Susan Flashman.

Artificial light may disrupt the behaviour and physiology of terrestrial mammals. Potential negative impacts of artificial light include reduced time spent foraging (Shier, Bird & Wang

2020; Bird et al. 2004), increased predation (Clarke 1983; Kotler et al. 1988; Kotler, Brown & Hasson 1991) and altered timing of reproduction (Le Tallec, Théry & Perret 2015; Le Tallec, Théry & Perret 2016; Robert et al. 2015).

Since nocturnal mammals have evolved to be active in naturally dark environments, they are likely vulnerable to the impacts of artificial light at night. The daily cycles of light and dark influence the behaviour of terrestrial mammals including emergence from and return to refuge sites, foraging and commuting behaviours. The onset of darkness cues activity for nocturnal terrestrial mammals. As a result, artificial light can delay the onset of activity in nocturnal species and can reduce the time they have available for critical behaviours such as finding food and commuting. Artificial light can also make nocturnal species more vulnerable to predators (Clarke 1983; Kotler, Brown & Hasson 1991) and may even allow diurnal predators to continue hunting into the night, resulting in increased predation pressure for nocturnal terrestrial mammals (Rasmussen & Macdonald 2012).

Nocturnal terrestrial mammals also respond to changes in day length across seasons (Nelson et al. 1995) and changes to moonlight levels over monthly lunar cycles. Artificial light can mask these natural light changes. It can present misleading seasonal cues preventing nocturnal mammals from adapting their behaviour and synchronising their physiology to match seasonal environmental conditions, with which can negatively impact survival (Schroer & Hölker 2016).

Artificial light may also have indirect effects on terrestrial mammals, including changes to food sources such as nocturnal insects, increased competition for space and increased road mortality.

Most of what is known about the impacts of artificial light on the behaviour of terrestrial mammals is derived from research on non-Australian species. The impact of artificial light on physiology is largely derived from laboratory studies, with limited research conducted on wild mammals. The impacts of artificial light are likely to be species-specific (Sanders et al. 2021) and further research is required to understand the extent and type of impact experienced by Australian terrestrial mammals.

Conservation status

Over 100 terrestrial mammal species were listed as threatened under the EPBC Act in May 2023. Of these EPBC Act listed terrestrial mammal species, all except the Numbat are nocturnal or crepuscular.

Details of EPBC Act listed terrestrial mammal species, their conservation status, and links to relevant conservation advices, recovery plans and other information can be found in the department's Species Profile and Threats Database (SPRAT).

For state and territory information on protected terrestrial mammals, see:

- Australian Capital Territory – Threatened species of the ACT
- New South Wales – Threatened biodiversity profile search
- Northern Territory – Threatened animals
- Queensland – Threatened species
- South Australia – Threatened species in South Australia
- Tasmania – List of threatened species
- Victoria – Framework for conserving threatened species

- Western Australia – Threatened species and communities.

Habitat use

Terrestrial mammals are found across all Australian states and territories. They occupy a range of habitats including woodlands, temperate forests, rainforests, heathlands, grasslands, coastal fringes, cliffs and rocky outcrops, coastal dunes, and mangroves. Terrestrial mammals use a wide range of permanent and temporary refuge and den sites including tree hollows, fallen logs, burrows, rock crevices, caves, dense vegetation, cracks in soil, boulder fields, and nests. Some species exhibit solitary behaviour while foraging and seeking refuge, while others live in social groups.

Terrestrial mammals use different parts of the environment and can be categorised as either ground dwelling or arboreal. Ground-dwelling terrestrial mammals seek shelter from predators, forage and commute on the ground; arboreal mammals seek shelter from predators, forage and commute in trees.

Distribution mapping of EPBC Act listed species can be found in the SPRAT database.

Habitats in which species may be susceptible to light pollution

Habitat use varies between species. Therefore, habitats in which species may be affected by light will also vary. Habitat requirements for EPBC Act listed species are defined in recovery plans or conservation advices. These habitats should be assessed to determine whether artificial light might adversely affect the species in these areas. Artificial light that reduces habitat use represents a form of habitat loss for the affected species (Bliss-Ketchum et al. 2016).

For the purposes of natural light and darkness it is important to consider areas that are necessary for a listed species to undertake important activities such as foraging, breeding, seeking refuge, commuting and dispersing.

The introduction of artificial light into areas used for critical behaviours can degrade terrestrial mammals’ habitat and reduce their area of occupancy or disrupt critical behaviours, which may affect recovery of the species. In habitats where species may be susceptible to light pollution, artificial light should be managed to preserve critical behaviours.

Refuge sites

Terrestrial mammals use a range of temporary (that is, shelter used during foraging) and permanent refuge sites. Nocturnal terrestrial mammals use refuges during the day for protection from predators and emerge after dark to avoid predators. Artificial light can disrupt the times at which terrestrial mammals enter and exit refuge sites (Barber-Meyer 2007). At worst, artificial light can degrade the habitat to the extent that these refuge sites are no longer usable. The most effective approach to artificial light management is to avoid installing and directing artificial light at refuge sites and particularly at entrances and exits of refuge sites. This is especially important for permanent refuge sites or where the refuge is a limited resource in the species’ habitat (for example, tree hollows and caves).

Foraging areas

Terrestrial mammals require foraging areas to meet their energy demands for survival. Foraging areas are species and population specific and may be seasonally driven and/or dependent on resource availability. Artificial light spilling onto foraging sites can increase the visibility of terrestrial mammals to predators (Clarke 1983). As a result of the perceived predation risk, nocturnal mammals may reduce or discontinue the use of foraging sites (Bird et al. 2004), resulting in habitat loss (Rotics, Dayan & Kronfeld-Schor 2011).

To reduce the impact of artificial light on foraging areas, the most important management approach is to avoid installing and directing artificial light near foraging areas.

Commuting routes

Terrestrial mammals use naturally dark corridors to commute between refuge sites and foraging areas. The introduction of bright artificial light into these areas can temporarily blind the low-light-adapted vision of terrestrial mammals. Artificial light that exposes terrestrial mammal commuting corridors can increase detection by predators and make them unsafe for use.

Some terrestrial mammal species always use the same commuting path, while other species use multiple routes. If commuting routes are disrupted by artificial light and alternative commuting paths are not available, the species is likely to become locally extinct.

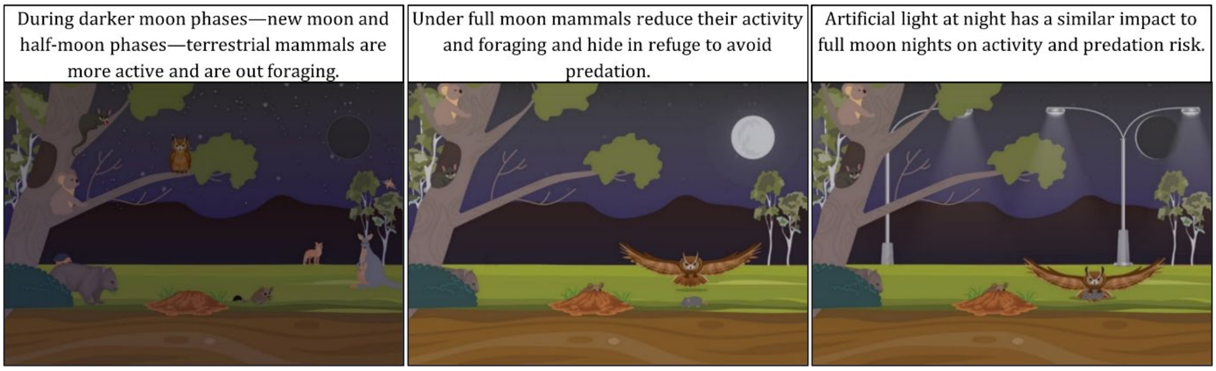
Landscapes fragmented by artificial light can lead to isolated habitat patches and consequently limit access to and between foraging and refuge sites (Bliss-Ketchum et al. 2016; Gaston & Bennie 2014). Fragmentation by artificial light can isolate individuals or populations, limiting breeding opportunities and gene flow (Hopkins et al. 2018). Artificial light spilling onto commuting routes may also provide an advantage for predators to detect and capture terrestrial mammal prey (Kotler et al. 1988; Bliss-Ketchum et al. 2016).

To prevent habitat fragmentation and disturbing commuting behaviours, artificial light should not illuminate terrestrial mammal commuting paths.

Effects of artificial light on terrestrial mammals

Artificial light can disrupt normal activity patterns, increase predation risk, and disrupt breeding and physiology of terrestrial mammals (Beier 2006). These impacts may reduce the capacity of a threatened species to persist or recover. Artificial light may affect different terrestrial mammal species in different ways and should be considered on a case-by-case basis. A species expert should be consulted where artificial light is likely to significantly impact a listed species.

Figure 33 Effects of lunar illumination and artificial light at night on activity and predation risk for nocturnal animals



During darker moon phases—new moon and half-moon phases—terrestrial mammals are more active and are out foraging.

Under full moon mammals reduce their activity and foraging and hide in refuge to avoid predation.

Artificial light at night has a similar impact to full moon nights on activity and predation risk.

Note: Natural light/dark cycles and moon phases are important cues for terrestrial mammals to determine time of day and time of month. Where there is significant artificial light at night, darker moon phases are masked, which may negatively impact important activities.

Point source artificial lighting directly illuminating habitat, and skyglow that increases ambient light levels have the potential to impact terrestrial mammals. While research has predominantly focused on direct lighting of habitat (point source lighting), the impact of skyglow on terrestrial mammals is less well known. However, changes in behaviour under moonlight conditions (Linley et al. 2020) (see Figure 33) suggests skyglow is likely to disrupt some terrestrial mammal species where it masks natural lunar cycles. Further research on the effects of skyglow on terrestrial mammals is required.

Behaviour and activity

Terrestrial mammals rely on daily and seasonal light cues (Figure 34) to anticipate favourable and unfavourable conditions for survival and reproduction and adjust their behaviour accordingly (Russart & Nelson 2018a; Le Tallec, Perret & Théry 2013). The introduction of artificial light into the night-time environment can mask these cues, leading to a shift in the timing of critical behaviours (Figure 35) and reducing the fitness of an animal (Russart & Nelson 2018b).

Exposure to artificial light at night can alter movement patterns (Rotics, Dayan & Kronfeld-Schor 2011), reduce home range (Hoffmann, Schirmer & Eccard 2019) and change individual (Hoffmann, Schirmer & Eccard 2019) or species interactions (Rotics, Dayan & Kronfeld-Schor 2011). Nocturnal mammals may reduce the duration of their activity have been shown to reduce the total duration of activity under artificial light (Barber-Meyer 2007; Bedrosian et al. 2013b; Rotics, Dayan & Kronfeld-Schor 2011; Sanders et al. 2021). For example, nocturnal rodents decrease the amount of foraging time, reducing the amount of food collected (Bird et al. 2004; Farnworth, Innes & Waas 2016; Rotics, Dayan & Kronfeld-Schor 2011; Shier, Bird & Wang 2020). These shifts in behaviour and activity might be related to the increased predation risk under artificial light (Kotler, Brown & Hasson 1991; Russart & Nelson 2018a). If artificial light is continuous throughout the night, terrestrial mammals either risk predation and forage under artificial light (Alkon & Mitrani 1988) or minimise predation risk by reducing foraging at the cost of body condition (Vásquez 1994).

Figure 34 Day length and environmental conditions, by season

Summer

Characterised by long days and short nights with warm weather, high food availability and active animals.

Autumn

Approximately equal day and night length (shorter daylength than summer). Animals put on weight before winter.

Winter

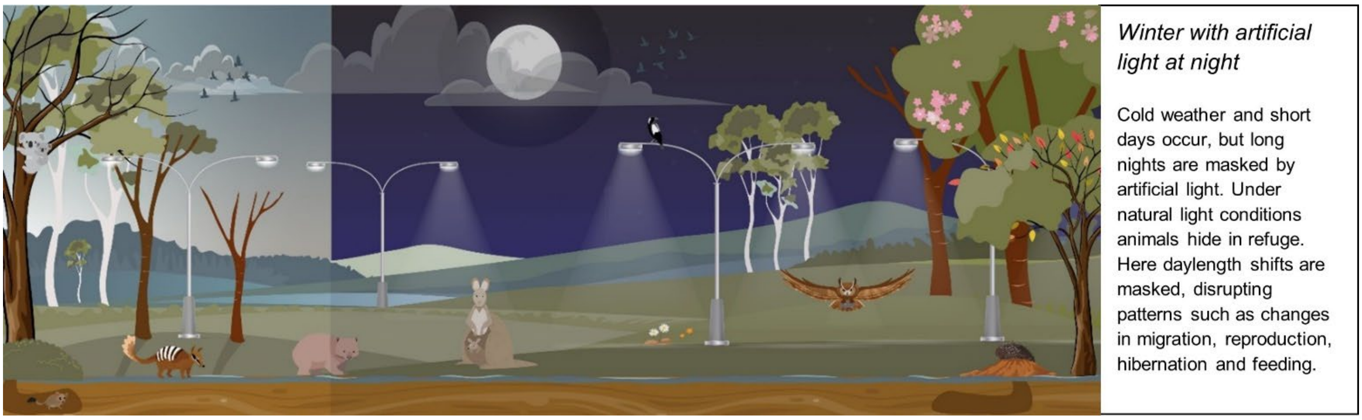
Short days and long nights accompanied by cold weather causing animals to hide in refuge.

Spring

Approximately equal day and night length (longer daylength than winter). Green vegetation following winter rain, with increases in animal activity.

Figure 34 shows natural changes in day length across the year that provide important cues for mammals to anticipate environmental conditions. Changes in day length across the year allow animals to predict favourable (for example, high food availability in spring after winter rain, and high insect abundance in summer) and unfavourable (cold, challenging winter) conditions for survival.

Figure 35 Disruption of seasonal lighting cues by artificial light at night



Winter with artificial light at night

Cold weather and short days occur, but long nights are masked by artificial light. Under natural light conditions animals hide in refuge. Here daylength shifts are masked, disrupting patterns such as changes in migration, reproduction, hibernation and feeding.

Figure 35 shows artificial light at night masking seasonal day length and interfering with seasonal lighting cues, disrupting important behaviours such as breeding, migration, feeding and hibernation.

Light avoidance behaviour occurs even under relatively low light intensity (Kramer & Birney 2001; Vásquez 1994). Terrestrial mammals reduce their activity (Falkenberg & Clarke 1998; Shier, Bird & Wang 2020; Wolfe & Summerlin 1989) and stay closer to refuge sites under the full moon (Daly et al. 1992) (Figure 33). Terrestrial mammal species like the Rufous Bettong (*Aepyprymnus rufescens*) and EPBC Act listed Southern Brown Bandicoot (*Isoodon obesulus obesulus*) and Eastern Quoll (*Dasyurus viverrinus*) show higher activity at half-moon than full moon (Linley et al. 2020). In some species, such as wallabies and rodents, this reduction in activity at full moon also leads to increased vigilance (Vásquez 1994) and decreased foraging (Carter & Goldizen 2003), resulting in less food consumed per foraging trip and an increased number of trips between refuges and foraging areas (Vásquez 1994). Consequently, the introduction of artificial light that either masks the natural changes in lunar illumination or results in a light intensity equivalent to a permanent full moon is likely to disrupt the behaviour and activity of terrestrial mammals.

Insectivorous and omnivorous EPBC Act listed mammals that rely on insects as a critical part of their diet might also experience shifts in prey availability (see Indirect impacts). A reduction in time spent foraging for herbivorous species, or shifts in prey availability for carnivorous species, could significantly disrupt the ability of these mammals to obtain sufficient resources, resulting in reduced fitness and survival.

Terrestrial mammals require access to dark refuge sites. Low light levels at or following sunset provide a cue for terrestrial mammals to exit their refuge. Artificial light directed at refuges can delay the emergence of terrestrial mammals (DeCoursey 1986), resulting in less time spent foraging and more time in shelter (Barber-Meyer 2007). Artificial light disrupts the activity of terrestrial mammals at refuge sites and foraging areas. However, consideration should also be given to proposed lighting changes along commuting routes, including those between refuge and foraging areas. The introduction of artificial light can fragment landscapes, including habitat corridors, leading to isolated habitat patches and consequently limiting access to foraging sites and dispersal of individuals (Gaston & Bennie 2014).

To minimise predation while foraging and commuting under natural illumination, terrestrial mammals use parts of their habitat (for example, under grass or between rocks) that lower the risk of detection by predators. Maintaining suitable vegetation cover, including canopy cover for arboreal species and ensuring artificial light does not spill into the habitat, can reduce the impacts of artificial light on activity and behaviour of terrestrial mammals. However, the suitability of the environment to mitigate light levels will likely depend on habitat type. For example, species living in dense bushland may experience more protection from artificial light and predation than those living in open desert or grasslands.

Mitigation of behavioural impacts of artificial light

Direct artificial light on refuges or the entrances and exits of refuge sites and foraging areas and along commuting routes should be avoided to mitigate impacts on the activity and behaviour of terrestrial mammals. Consideration should be given to whether the species of interest are ground dwelling or arboreal. Light shielding should be used to prevent artificial light spilling upward, which would contribute to skyglow and may directly enter the habitat of arboreal species. Downward light should be directed or shielded away from habitat of ground-dwelling species. See the Terrestrial mammal light mitigation toolbox in this document and Appendix A – Best practice lighting design for further details.

Physiology

Terrestrial mammals have evolved under natural light cycles of day and night. These light cues synchronise natural hormone cycles (circadian rhythms). When these light cues are altered, hormone cycles are also altered (similar to the human experience of jet lag) (Pandi-Perumal et al. 2006).

Natural changes in light and dark cycles across the year allow mammals to anticipate environmental conditions and adjust their behaviour accordingly to improve their chance of survival (Ouyang, Davies & Dominoni 2018) (see Figure 34). Natural seasonal day length changes are also responsible for synchronising the physiology of animals with seasonal environmental conditions. The introduction of artificial light at night into the habitat of terrestrial mammals can mask these natural light/dark cycles, provide misleading cues and ultimately disrupt the predictability of environmental conditions. To date most research into these effects has been conducted on only select species; however, impacts are likely to be similar across nocturnal terrestrial mammals.

Melatonin

Changes in day length are communicated through the body by the hormone melatonin. Melatonin production is suppressed by light, with peak production occurring during darkness in both diurnal and nocturnal mammals (Ouyang, Davies & Dominoni 2018; Pandi-Perumal et al. 2006). Melatonin is responsible for regulating activity patterns as well as physiological rhythms in mammals, including enhancing immune function through challenging winter conditions (Nelson et al. 1995) and synchronising the timing of reproduction with predictable changes in environmental conditions (Bartness & Goldman 1989).

The duration of melatonin production reflects the length of the night (Ouyang, Davies & Dominoni 2018) (Figure 34), conveying information about time of day and time of year. For mammals that breed at a certain time of year (seasonal breeders), melatonin production can drive changes in reproductive hormones to ensure that births occur at the most favourable time of the year to ensure survival (for example, suitable temperature, high food availability, reduced predation) (Weil et al. 2015).

Exposure to direct artificial light at night suppresses melatonin production in a range of mammals, such as Tammar Wallabies (Dimovski & Robert 2018; Robert et al. 2015). Melatonin production is particularly sensitive to short, blue wavelength light (Nelson and Takahashi 1991; Thapan, Arendt & Skene 2001) and can be suppressed by exposure to low-intensity light throughout the night (Xiang et al. 2015) or a short duration (one minute) of high-intensity light (Hoffmann, Illnerová & Vaněček 1981).

Glucocorticoids

Glucocorticoids are hormones that play an important role in coordinating an animal's response to stressors (Schoenle, Zimmer & Vitousek 2018). Increased glucocorticoid production in response to a threat or stressor results in changes in behaviour and physiology to enhance animal survival (Androulakis 2021; Schoenle, Zimmer & Vitousek 2018).

Artificial light may act as a novel stressor for terrestrial mammals, resulting in increased glucocorticoid production. If the increased glucocorticoid production is sustained, reproduction and immune function might be negatively impacted in favour of survival. Therefore, prolonged high levels of glucocorticoids can disrupt reproduction and increase the vulnerability of the animal to disease (Schoenle, Zimmer & Vitousek 2018).

For example, exposure to artificial light at night has been shown to disrupt glucocorticoid production in rodents (Bedrosian et al. 2013a; Fonken, Haim & Nelson 2012; Rahman et al. 2008; Wilson & Downs 2015). This disruption was greater following exposure to short-wavelength blue light (Rahman et al. 2008). Any disruption to the normal glucocorticoid cycle may have negative consequences for individual fitness and survival.

Immune function

Melatonin and glucocorticoids play a key role in modulating immune function in mammals (Weil et al. 2015). Maintaining adequate immune function is critical for survival through challenging winter conditions (Nelson et al. 1995) and can be considered a proxy for survival. Exposure to artificial light at night impairs the functioning of white blood cells (Aubrecht et al. 2014) and might lead to intergenerational declines in innate immunity (that is, immunity that is present at birth) (Cissé, Russart & Nelson 2020). Exposure to direct artificial light at night can also inhibit winter adaptation (Ikeno, Weil & Nelson 2014) and compromise immune function, leading to reduced individual fitness (Bedrosian et al. 2011).

The impact of artificial light on mammalian immune systems has only been described in laboratory studies. Where direct artificial lighting reaches a sufficient intensity and duration, it could cause similar disruptions to immune function in wild animals, resulting in reduced survival.

Mitigation of physiological impacts of artificial light

Artificial light consisting of short, blue wavelengths (for example, white LEDs) is known to cause the greatest disruption to the physiology of terrestrial mammals (Nelson & Takahashi 1991; Thapan, Arendt & Skene 2001). Therefore, the colour and the intensity of artificial light should be considered near terrestrial mammal habitat. To reduce the impacts on the physiology of terrestrial mammals, artificial light should be used only where required, the use of blue wavelengths (400 nm to 500 nm) should be limited, and lighting should be at the lowest intensity suitable. See the Terrestrial mammal light mitigation toolbox and Best practice lighting design for further details.

Reproduction

Some mammals are able to breed at all times of the year in response to food availability or rainfall (for example, Eastern Pygmy-possum, *Cercartetus nanus*). Other mammals restrict reproduction to certain times of year (for example, Western Ringtail Possum, *Pseudocheirus occidentalis* – noting that some populations can breed year-round) to synchronise births with predictable environmental conditions including suitable temperature, increased food availability and decreased predation rates (Schroer and Hölker 2016). Species with restricted reproduction are termed seasonal breeders. The timing of seasonal reproduction can be cued by changing light levels (see Figure 34 and Physiology) that indicate time of year, to ensure that sufficient food is available to compensate for the increased energetic demands associated with the provisioning of young (Bronson 1985). The introduction of artificial light that masks day length changes has the potential to provide misleading light cues and disrupt the timing of reproduction in seasonally reproductive terrestrial mammals. For example, artificial light can mask natural day length changes and delay reproduction in wild Tammar Wallabies (Robert et al. 2015). This shift in birth dates may result in a mismatch between the timing of births and food availability, reducing offspring survival and threatening terrestrial mammal populations (Post and Forchhammer 2008).

Altered timing of reproduction is likely to have a greater population-level impact for short-lived species that have one breeding opportunity, such as antechinus species, including threatened Fawn Antechinus (*Antechinus bellus*), Swamp Antechinus (*Antechinus minimus maritimus*), Silver-headed Antechinus (*Antechinus argentus*) and Black-tailed Antechinus (*Antechinus arktos*) (McAllan, Westman & Joss 2002). Antechinuses display a synchronous reproductive period followed by complete male mortality (Woolley 1966). If these species experience an unsuccessful breeding season or if offspring production is reduced, the persistence of the population will be threatened.

The disruption of reproductive processes caused by artificial light may be more severe for solitary species or those in isolated subpopulations. Where artificial light disrupts the reproductive timing of individuals or populations, it can cause them to be out of phase with neighbours living under natural night-time conditions (Kurvers and Hoelker 2015). This could lead to a mismatch in the timing of sexual state between males and females, or between individuals, with population-scale consequences for seasonally reproductive species (Le Tallec, Théry & Perret 2015; Le Tallec, Théry & Perret 2016).

Mitigation of reproductive impacts of artificial light

The population-scale effects of artificial light on reproduction in terrestrial mammals represents a knowledge gap. However, based on current evidence, artificial light that masks natural day length changes and disrupts physiology may disrupt reproductive cycles in seasonally reproductive terrestrial mammals. The installation or upgrade of artificial lighting should consider the wavelengths and intensity of light used near terrestrial mammal habitat. Consideration should be given to avoiding blue (400 nm to 500 nm) wavelength light as well as installing low intensity lighting. Consideration should also be given to the areas of habitat and food resources that are critical for reproduction, as well as the time of year, to avoid disturbing species during a critical reproductive period in seasonal breeders. See the Terrestrial mammal light mitigation toolbox and the guidelines on Best practice lighting design for further details.

Indirect impacts

Artificial light can have direct impacts on terrestrial mammals including disruptions to behaviour and physiology, as well as indirect impacts through changes in predation, prey availability, competition for space and increased road mortality.

Predation

Artificial light can make it easier for nocturnal predators to locate terrestrial mammals (see Figure 33). Even low levels of light at full moon can increase rates of predation and capture by predators such as owls, which are known to predate on many EPBC Act listed species (Clarke 1983; Kotler et al. 1988; Kotler, Brown & Hasson 1991).

Predation by feral cats (*Felis catus*) and Red Foxes (*Vulpes vulpes*) represents a significant threat to the recovery of many EPBC Act listed terrestrial mammals. Cats primarily use visual and auditory cues during hunting (Kronfeld-Schor et al. 2013). Low levels of artificial light, equivalent to moonlight, are sufficient to increase the visibility for cats, thereby increasing the vulnerability of their prey (Kronfeld-Schor et al. 2013). Foxes increase night-time activity at lit sites (de Molenaar et al. 2003). It is likely that artificial light would increase the vulnerability of terrestrial mammals to predation by feral cats and foxes. Future research should address this enhanced predation risk, which poses a significant threat to the recovery and persistence of EPBC Act listed terrestrial mammals.

In addition to nocturnal predators, the introduction of artificial light may result in diurnal predators extending their activity into the night, resulting in a novel predation pressure for terrestrial mammals (Kronfeld-Schor et al. 2013; Rasmussen and Macdonald 2012).

Prey availability

Indirect impacts of artificial light on terrestrial mammals can occur across large distances, including disruptions to food availability for insectivorous species.

Many nocturnal insects are attracted to artificial light sources, leading to disrupted astronomical navigation and increased mortality (Owens and Lewis 2018). The attraction of nocturnal insects to artificial light sources can draw them out of naturally dark areas or disturb them along migratory paths (Warrant et al. 2016). Insects often end up trapped in a ‘light sink’ where they are likely to face mortality from exhaustion or predation (Owens and Lewis 2018). These light sinks can alter the distribution of nocturnal insect populations, with cascade effects on their terrestrial mammal predators. Where these insects represent a critical food resource for a terrestrial mammal, light sinks could have consequences for population survival (see Box 1).

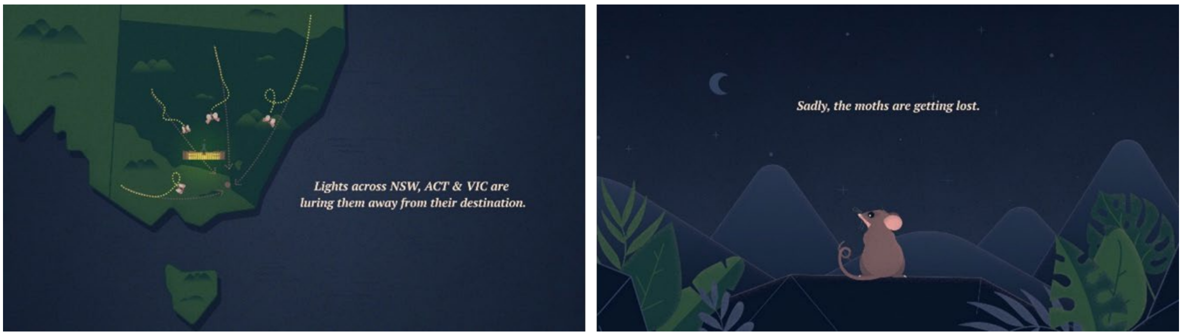
Box 1 Indirect impacts on Mountain Pygmy-possum occurring over large distances

The critically endangered Mountain Pygmy-possum (*Burramys parvus*) is a threatened terrestrial mammal inhabiting the alpine and subalpine regions of south-eastern Australia. Over winter, the Mountain Pygmy-possum enters a period of hibernation. In spring, Mountain Pygmy-possums emerge from hibernation and must find sufficient food to replenish their body's fat stores. During this time, they rely on Bogong Moths as their primary and most abundant food source to regain these fat stores and raise their young.

Each spring, Bogong Moths migrate from Queensland, New South Wales and Western Victoria to the Victorian and NSW alpine regions (Warrant et al., 2016). The moths use the Earth's magnetic field and visual cues on the horizon to navigate (Warrant et al., 2016). However, artificial lights along their migratory path can disrupt their migration, resulting in fewer moths arriving in the Victorian and NSW alps. The moths that do arrive can also be attracted and trapped by artificial lights on buildings within the ski villages in the region.

These disturbances can significantly reduce the number of Bogong Moths arriving in the boulder fields where the Mountain Pygmy-possum resides. A significant loss of this critical food resource may impact reproductive success and may have population-level consequences for the Mountain Pygmy-possum.

Figure 36 Stills from 'Lights Off for Moths' campaign, Zoos Victoria



Video stills: © Samuel Van Ingen.

Competition with invasive species

Where native species reduce their activity under artificial light it can lead to underexploited parts of habitat (Rotics, Dayan & Kronfeld-Schor 2011). Native mammals may decrease the amount of time they are active in a habitat or avoid using certain parts altogether. This type of behaviour change is effectively habitat degradation and loss.

Reduction in native mammal activity may promote invasion or competition with non-native species that are more tolerant of artificial light, for example, Black Rats (*Rattus rattus*) (Farnworth et al. 2019). Reduced activity of nocturnal mammals can also result in diurnally active species extending their activity into the night (Rotics, Dayan & Kronfeld-Schor 2011). This may lead to increased predation, competition for food and refuge, and increased disease prevalence for terrestrial mammal species.

Ecological communities

The introduction of artificial light can alter species interactions and disrupt ecological communities (Longcore & Rich 2004). For example, artificial light that disrupts the activity of insects reduces pollination rates for some plant species (Giavi, Fontaine & Knop 2021). Further studies are required to understand the impact of artificial light on complex ecosystem dynamics and ecological communities.

Terrestrial mammals provide critical ecosystem functions in ecological communities including pollination and seed dispersal. If artificial light disrupts the activity and habitat use of terrestrial mammals, it could also disrupt their critical ecosystem roles and ultimately disrupt the function of EPBC Act listed ecological communities (see Appendix K – Ecological Communities).

Road mortality

Artificial light can make it more difficult for nocturnal mammals to avoid collisions with vehicles, especially where the animal experiences a rapid shift in illumination (that is, vehicles emerging from dark bushland into bright artificial lighting) (Beier 2006). The low-light-adapted vision of nocturnal terrestrial mammals can quickly become saturated by artificial light, leaving them temporarily blinded (Beier 2006). This results in mammals becoming disoriented and unable to see the dark areas across the road. This disadvantage can remain for 10 to 40 minutes after returning to darkness (Beier 2006). As such, the use of highway illumination is an ineffective strategy to reduce mammal vehicle strikes (Reed and Woodard 1981) and may increase strike-related mortality.

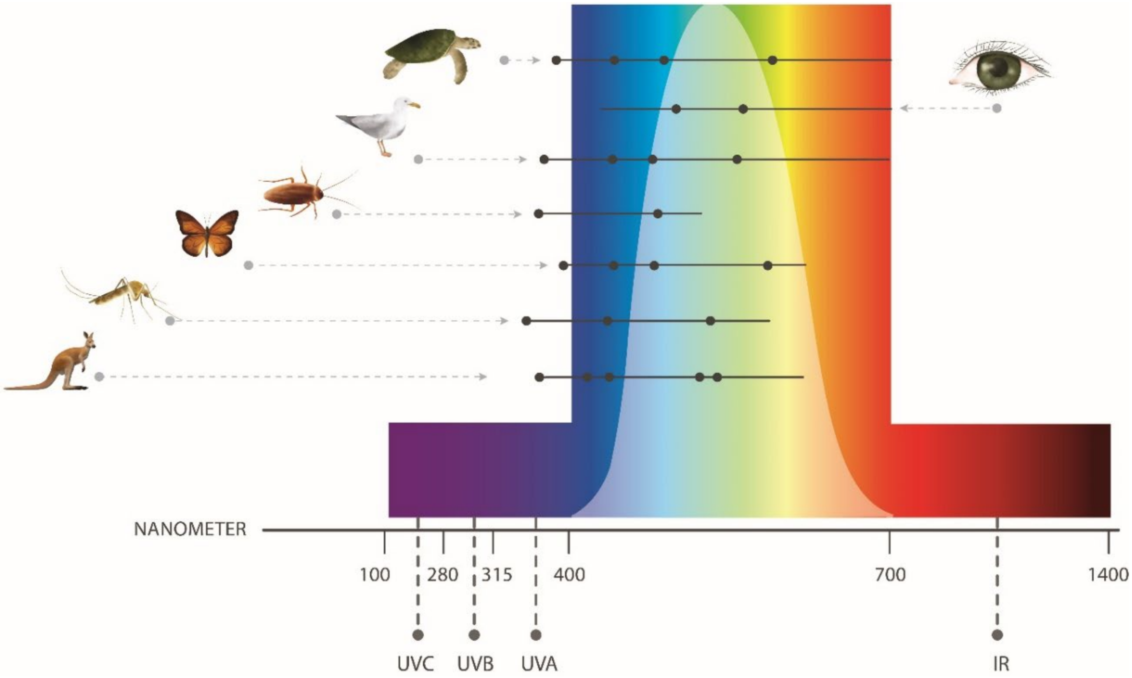
Mitigation of indirect impacts of artificial light

Direct artificial light spilling on refuge sites, foraging areas and commuting routes should be avoided to mitigate indirect impacts on terrestrial mammals. Consideration should be given to the design and shielding of artificial lights to prevent contributing to skyglow, since low levels of light can enhance the detection and predation of terrestrial mammals and increase competition with invasive species.

Disruptions to prey availability can occur over large distances. Consideration should be given to the location and direction of artificial lighting to minimise light spill outside the intended area. Where possible, outdoor lighting should be switched off during critical periods (for example, during the Bogong Moth migration in September and October) to minimise disruptions to prey availability for terrestrial mammals. See the Terrestrial mammal light mitigation toolbox and the guidelines on Best practice lighting design for further details.

Vision in terrestrial mammals

Figure 37 Comparative light perception among different species groups



Note: Horizontal lines show a broad generalisation of the ability of humans and wildlife to perceive different wavelengths. Dots represent reported peak sensitivities. Vision range for terrestrial mammals is based on limited evidence. Dots for terrestrial mammals (indicated by the kangaroo) represent peak sensitivities, based on Deakin, Waters and Graves (2010). Figure adapted from Campos (2017).

Understanding how terrestrial mammals perceive light is crucial to minimise artificial light impacts in areas where natural darkness cannot be achieved.

The vision of nocturnal mammals is characterised by scotopic vision (Appendix B – What is light and how does wildlife perceive it?). Nocturnal mammals typically have few cones (vital for colour perception during day vision) and are temporally blinded by bright light (Beier 2006). Rods (used for night vision) become blinded and unresponsive at light levels greater than that at twilight (Schroer and Hölker 2016; Beier 2006). This low-light, dark-adapted vision is more sensitive to shorter wavelengths of light, with a peak sensitivity around 496 nm (blue-green light) (Beier 2006).

Australian terrestrial mammals do not distinguish colours or perceive light the way humans do. There are also likely to be species-specific differences in the visual perception of terrestrial mammals; however, limited information is currently available. Unlike humans, terrestrial mammals are thought to be able to perceive light into the ultraviolet range. For example, the Southern Brown Bandicoot exhibits peak spectral sensitivities at 360 nm (UV light) and 551 nm (green light) (Deakin et al. 2010). Other studied terrestrial mammal species show peak spectral sensitivities ranging from 350 nm to 557 nm (Deakin et al. 2010).

If artificial light must be used in terrestrial mammal habitat it is appropriate to consider and evaluate the use of luminaires that have a spectral content outside the visual range of these animals. Further research is required to better understand light perception and sensitivities in Australian terrestrial mammals. In general, low-intensity light in the orange to red (590 nm to 740 nm) spectrum is likely to be less disruptive to terrestrial mammals.

Environmental impact assessment of artificial light on terrestrial mammals

As a minimum, any planned changes to existing lighting or installation of externally visible lighting should implement Best practice lighting design to reduce light pollution and minimise any impacts on terrestrial mammals. Where terrestrial mammals are known to occur or are likely to occur in the area, an environmental impact assessment (EIA) should be undertaken.

Terrestrial mammals use different parts of their habitat for refuge, foraging and commuting. Artificial light fragments and degrades terrestrial mammal habitat and can disrupt these critical behaviours.

Artificial light can also have Indirect impacts that can occur over a very large distance (see Box 1) and may have cascade effects on terrestrial mammals. Consideration should be given to artificial light impacts outside the site area.

It is likely that artificial light will be one of multiple stressors for terrestrial mammals that should be identified and managed through an EIA process and adaptive management framework.

The following sections step through the EIA process, with specific considerations for terrestrial mammals. Where artificial light is likely to affect terrestrial mammals, consideration should be given to employing mitigation measures as early as possible in a project's life cycle, including to inform the design phase. The efficacy of mitigation should be tested through monitoring and post-development assessment of impacts to wildlife.

Associated guidance

- Protected Matters Search Tool
- Species Profile and Threats Database
- Approved recovery plans or conservation advices for the listed threatened terrestrial mammal species

Qualified personnel

Lighting design and management and the EIA process should be undertaken by appropriately qualified personnel. Light management plans should be developed and reviewed by appropriately qualified lighting practitioners, who should consult with an appropriately qualified biologist or ecologist.

Those advising on the development of a lighting management plan, or the preparation of reports assessing the impact of artificial light on terrestrial mammals, should have knowledge of Australian terrestrial mammal biology and/or ecology, demonstrated through relevant qualifications or equivalent experience as evidenced by peer-reviewed publications in the last 5 years on a relevant topic, or other relevant experience.

Step 1: Describe the project lighting

Information collated during this step should consider the Effects of artificial light on terrestrial mammals. The location of artificial light sources in relation to refuge sites, foraging areas and commuting routes should be considered in the design phase.

The existing light environment and the artificial light likely to be emitted from the site should be described during the planning phase of a project. Information should include:

- the location and size of the project footprint;
- the number and type of artificial lights – their height, orientation and hours of operation;
- site topography;
- the proximity and direction of lights compared with terrestrial mammals and/or their habitat.
- whether artificial lighting is likely to be visible from terrestrial mammal habitat or contribute to skyglow;
- the distance over which this artificial light is likely to be perceptible;
- shielding or light controls used to minimise artificial lighting; and
- spectral characteristics (wavelength) and intensity of artificial lights.

Step 2: Describe the terrestrial mammal population and behaviour

The species and behaviour of terrestrial mammals seeking refuge, foraging and commuting in the area should be described. This should include the conservation status of the species; population trends (where known); how important that population or habitat is; the abundance of terrestrial mammals using the area; the regional importance of the population; and the seasonality of terrestrial mammals seeking refuge, foraging and commuting in the area.

Relevant species-specific information can be found in the SPRAT database, state and territory listed species information, scientific literature, recovery plans, conservation advices and local and Indigenous knowledge.

Where there are insufficient data to understand the population's importance or demographics, or where it is necessary to document existing terrestrial mammal behaviour, field surveys and biological monitoring may be necessary. While refuge and foraging areas may be known, commuting paths are less likely to be known.

Biological monitoring of terrestrial mammals

Any monitoring associated with a project should be developed and overseen and have the results interpreted by appropriately Qualified personnel to ensure reliability of the data.

The objectives of terrestrial mammal monitoring in an area likely to be affected by artificial light are to:

- understand the size and importance of the terrestrial mammal population(s)
- identify refuge sites, foraging areas and commuting routes where artificial lighting changes may occur
- describe terrestrial mammal behaviour at refuge sites, in foraging areas and along commuting routes before (establishing a baseline) and after the introduction or upgrading of artificial lighting.

The data will be used to inform the EIA and assess whether mitigation measures have the potential to be successful.

Rigorous surveys should be conducted to determine whether EPBC Act listed terrestrial mammals are present at the site, whether there are Habitats in which species may be susceptible to light pollution, whether they are using this habitat and whether artificial light is likely to affect this habitat or behaviours, including beyond the site area.

To understand existing terrestrial mammal behaviour, monitoring (or a similar approach) will be needed to determine terrestrial mammal ability to use refuge sites, forage and commute prior to construction of or upgrades to lighting. Consideration should be given to monitoring a comparative control or reference site to ensure observed changes in terrestrial mammal behaviour are related to changes in the light environment and not to broader climatic or other landscape-level changes.

A well-designed monitoring program will capture the following information before and after construction or lighting upgrades:

- behaviour of terrestrial mammals at refuge sites – including location of refuge used, type of refuge used, time of first emergence and time of return to refuge
- foraging activity of terrestrial mammals – including location and type of foraging sites, time spent foraging and time spent vigilant
- commuting routes used by terrestrial mammals – including location of commuting routes, and time and duration of commuting behaviour.

Consideration should be given to physiological impacts, particularly those affecting reproductive output. Although it may not be feasible to take invasive samples (for example, blood), collection of faecal samples may be collected for hormone analysis, and monitoring reproductive output may be relevant in some circumstances. Advice from a species expert will be required to confirm the need for monitoring and to assess the study design and appropriate monitoring methods.

Monitoring surveys should be designed in consultation with a quantitative ecologist or biostatistician to ensure reliability of the data and meaningful interpretation of the findings.

As a minimum, qualitative descriptive data on visible light types, location and directivity should also be collected at the same time as the biological data. Handheld camera images can help describe the light. Quantitative data on existing skyglow should be collected, if possible, in a biologically meaningful way, recognising the technical difficulties in obtaining these data. See Appendix C – Measuring biologically relevant light for a review.

Step 3: Risk assessment

The objective of the Light Pollution Guidelines for Wildlife is that artificial light should be managed in a way that enables terrestrial mammals to undertake critical behaviours such as seeking refuge, foraging, commuting and reproducing. The risk assessment process should consider the likelihood of artificial light affecting these behaviours. The aim of risk assessment is to ensure that important terrestrial mammal populations remain unaffected, refuge sites are not disturbed or abandoned (especially critical and limited refuge sites such as tree hollows), predation is not increased and foraging and commuting are not disrupted.

Consideration should be given to how artificial light might degrade, fragment or decrease terrestrial mammal habitat. Impacts of artificial light must be considered beyond the boundary of a proposed development. Light that spills outside a development area can result in a greater extent of habitat disturbance than light contained within a development area. Artificial light upgrades or installations should be managed to ensure the light does not extend beyond the development area, to minimise extent of habitat loss.

To understand how or whether terrestrial mammals are likely to see artificial light, a site visit should be made at night and the area viewed from known terrestrial mammal refuge sites, foraging areas and commuting routes.

Using this perspective, the type, number and location of artificial lights should be considered/modelled to determine whether terrestrial mammals are likely to perceive the artificial light (considering wavelength, intensity and location) and what the effects of the artificial light on their behaviour are likely to be.

Step 4: Light management plan

A light management plan should include all relevant project information (Step 1) and biological information (Step 2). It should outline proposed mitigation. For a range of terrestrial mammal specific mitigation measures, see Terrestrial mammal light mitigation toolbox. The plan should also outline the types of and schedule for biological and artificial light monitoring to ensure mitigation is meeting the objectives of the plan, and triggers for revisiting the risk assessment phase of the EIA.

The plan should outline contingency options to implement if biological and artificial light monitoring or compliance audits indicate that mitigation is not meeting objectives (for example, artificial light is visible in refuge, foraging and commuting areas, or changes in the use of these areas are observed).

Step 5: Biological and light monitoring and auditing

The success of the impact mitigation and light management should be confirmed through regular monitoring and compliance auditing. The monitoring and compliance audit results should be used to facilitate an adaptive management approach for continuous improvement.

Relevant biological monitoring is described in Step 2: Describe the terrestrial mammal population and behaviour. Monitoring should focus on how artificial light is perceived by terrestrial mammals at refuge, foraging and commuting areas and determine if artificial light has changed these behaviours, use of these areas or reproductive output. Consideration should be given to monitoring control sites. Monitoring should be undertaken both before and after artificial light upgrades or installations at both the affected and control sites.

Concurrent light monitoring should be undertaken and interpreted in the context of how terrestrial mammals perceive light and within the limitations of monitoring techniques described in Appendix C – Measuring biologically relevant light. Auditing, as described in the light management plan, should be undertaken to ensure artificial lighting at the site is consistent with the light management plan and is not disrupting terrestrial mammal behaviour.

Step 6: Review

The EIA should incorporate a continuous improvement review process that allows for upgraded mitigations, changes to procedures, and renewal of the light management plan based on the outcomes of the biological monitoring program for artificial light impacts on terrestrial mammals.

Terrestrial mammal light mitigation toolbox

Appropriate artificial lighting design, controls and impact mitigation will be site, project and species-specific. Table 15 provides a toolbox of management options relevant to terrestrial mammals. These options should be implemented in addition to the 6 Principles of best practice lighting design. Not all mitigation options will be relevant for every project. Table 16 provides a suggested list of light types appropriate for use near terrestrial mammal habitat and those to avoid.

The most effective measures for mitigating the impact of artificial light on terrestrial mammals include:

- maintaining dark refuge sites
- avoiding, removing, redirecting or shielding artificial lights in foraging areas and along commuting routes and keeping intensity as low as practicable, noting that low-intensity artificial light (around full moon light levels) can disrupt behaviour of terrestrial mammals.

Other mitigation measures, which may be less effective, include:

- using narrow-spectrum, long-wavelength lighting (such as red light)
- implementing part-night lighting schemes to reduce the duration of artificial light
- potentially using motion sensor lighting, noting that this may cause a startle response.

These measures should be assessed to determine their effectiveness as mitigation tools.

Table 15 Light management options specific to terrestrial mammals

Management action	Detail
Avoid adding artificial light to previously unlit areas.	Introduction of artificial light to dark areas is likely to have a greater impact than alterations or additions to areas where artificial lighting already exists.
Avoid artificial light directly onto refuge sites.	Avoid installing and directing luminaires near refuge sites as this can change terrestrial mammal refuge behaviour and use of refuge sites. Artificial light spilling onto terrestrial mammal habitat can reduce the available area for refuge.
Avoid artificial light directly onto foraging areas and commuting routes.	Avoid installing and directing luminaires near foraging areas and commuting routes. Artificial light can lead to fragmentation, degradation and loss of habitat for foraging and commuting. Artificial light in terrestrial mammal habitat can permanently reduce the available area for foraging and commuting or provide an advantage for predators.
Shield light sources to prevent artificial light spilling onto habitat for ground-dwelling species.	Where ground-dwelling terrestrial mammal species are present, artificial light should be directed onto the exact surface area requiring illumination. Use shielding on lights to prevent light spill outside the target area.
Shield light sources to prevent upward artificial light spill for arboreal species.	Where arboreal terrestrial mammal species are present, vertical light should be shielded such that it is not visible from the tree canopy above the luminaire installations. Any pole lighting should be at a height lower than arboreal mammal refuge, foraging and commuting habitat without compromising human safety.
Avoid using high intensity light.	Keep artificial light intensity as low as possible near terrestrial mammal refuge sites and known foraging areas and commuting routes. Artificial light spill into terrestrial mammal habitat should be kept at as low an intensity as practicable. For arboreal species this includes keeping the intensity of vertical artificial light spill onto vegetation as low as possible. Behaviour of terrestrial mammals can be disrupted by artificial light intensities above natural levels of darkness. Isolated artificial light sources will likely have less effect than large arrays of high-intensity artificial lighting, except in areas where single artificial light sources are newly introduced.
Prevent indoor lighting reaching the outdoor environment.	Use fixed window screens, blinds or tinting on windows and skylights to contain artificial light inside buildings.
Use luminaires with spectral content appropriate for the species present.	Consider avoiding specific wavelengths that are problematic for the species present. In general, this includes avoiding the use of artificial lights rich in blue wavelengths, which are easily perceived by terrestrial mammals. Terrestrial mammals also show a strong physiological response to blue-wavelength light. Longer wavelength artificial light (such as red light) may have less impact on terrestrial mammal species, though this may not be the case for all species. Where this option is progressed, careful post-installation monitoring should be undertaken to assess the success of mitigation.
Implement part-night lighting schemes to reduce the amount of artificial light present throughout the night.	Part-night lighting may not be an effective mitigation measure for some species. Terrestrial mammals may benefit from part-night lighting, particularly if artificial lights are turned off at times appropriate for the species in question. Where this option is progressed, careful post-installation monitoring should be undertaken to assess the success of mitigation.
Implement motion sensor lighting.	Installing motion sensor lighting may or may not be an effective mitigation measure for some species. Terrestrial mammals may benefit from motion sensor lighting, particularly if it reduces the amount of artificial light present throughout the night. Note, however, that this may cause a startle response in some species. Where this option is progressed, careful post-installation monitoring should be undertaken to assess the success of mitigation.

If all other mitigation options have been exhausted and there is still a need for artificial light, see Table 16 for guidance on types of commercial luminaires that are more suitable for use near terrestrial mammal habitat. The effectiveness of these luminaires will depend on which species are being considered. Careful post-installation monitoring should be undertaken to assess the success of mitigation.

Table 16 Commercial luminaire types that are considered generally less disruptive for use near important terrestrial mammal habitat, and those to avoid

Light type	**Suitability for use near terrestrial mammal habitat** b
Low-pressure sodium vapour	Suitable
High-pressure sodium vapour	Not suitable
Filtered LED **a**	Insufficient data to determine suitability for use near terrestrial mammals
Filtered metal halide **a**	Insufficient data to determine suitability for use near terrestrial mammals
Filtered white LED **a**	Insufficient data to determine suitability for use near terrestrial mammals
Amber LED	Suitable
PC amber	Suitable
White LED	Not suitable
Metal halide	Not suitable
White fluorescent	Not suitable
Halogen	Not suitable
Mercury vapour	Not suitable

a ‘Filtered’ means LEDs can be used only if a filter approved by the manufacturer is applied to remove the short-wavelength (400 nm to 500 nm) light.

Appendix K – Ecological Communities

Key points

An ecological community is a unique grouping of plants, animals and other organisms that exist and interact in a given habitat. Ecological communities rely on natural diurnal, lunar and seasonal light and darkness changes as important lifecycle signals. Artificial light can disrupt communities via direct impacts on individual species, including disruption of reproduction, growth, development, diet, movement or other behaviour. Artificial lighting can also indirectly disrupt ecological communities by fragmenting habitat, reducing habitat connectivity, affecting key ecological processes such as pollination, seed transport, nutrient cycling and food webs, and by facilitating survival and spread of invasive species.

The effects of light pollution on an ecological community depend on the composition of flora and fauna, and non-biological community attributes such as geography, seasonality, fire regime, presence of water bodies, natural light levels and the type and level of artificial light exposure.

Key management measures

Effective management requires restricting artificial lighting in or near habitat patches and connectivity corridors and balancing the likely impacts of light pollution on different species and ecological processes. At the community scale, reducing effects of light pollution on ecological connectivity, nutrient flows and ecosystem function may be more important than reducing adverse impacts on a single species. The best strategy usually involves limiting or eliminating the use of artificial light in sensitive habitats wherever possible to avoid impacts on ecological communities which are already trying to recover from past threats, such as fragmentation, as well as experiencing a multitude of ongoing threats.

What are ecological communities?

An ecological community (EC) is a group of plants, animals and other organisms that occur together and interact in a given habitat. Species within each ecological community interact with and depend on each other (Sanders & Gaston 2018)—for example, for food, nutrients, shelter, or reproduction, including pollination, nesting and oviposition sites. The structure, species composition and geographic distribution of an EC are determined by:

- environmental factors – climate, water availability, soil type, natural fire regime and position within the landscape/seascape (including altitude, depth and shading)
- historical factors – human landscape modifications (including burning, clearing, drainage) and the introduction of invasive species
- the nature of inter-species interactions – including mutually beneficial processes such as pollination, and antagonistic processes such as herbivory and predation (Thébault & Fontaine 2010).

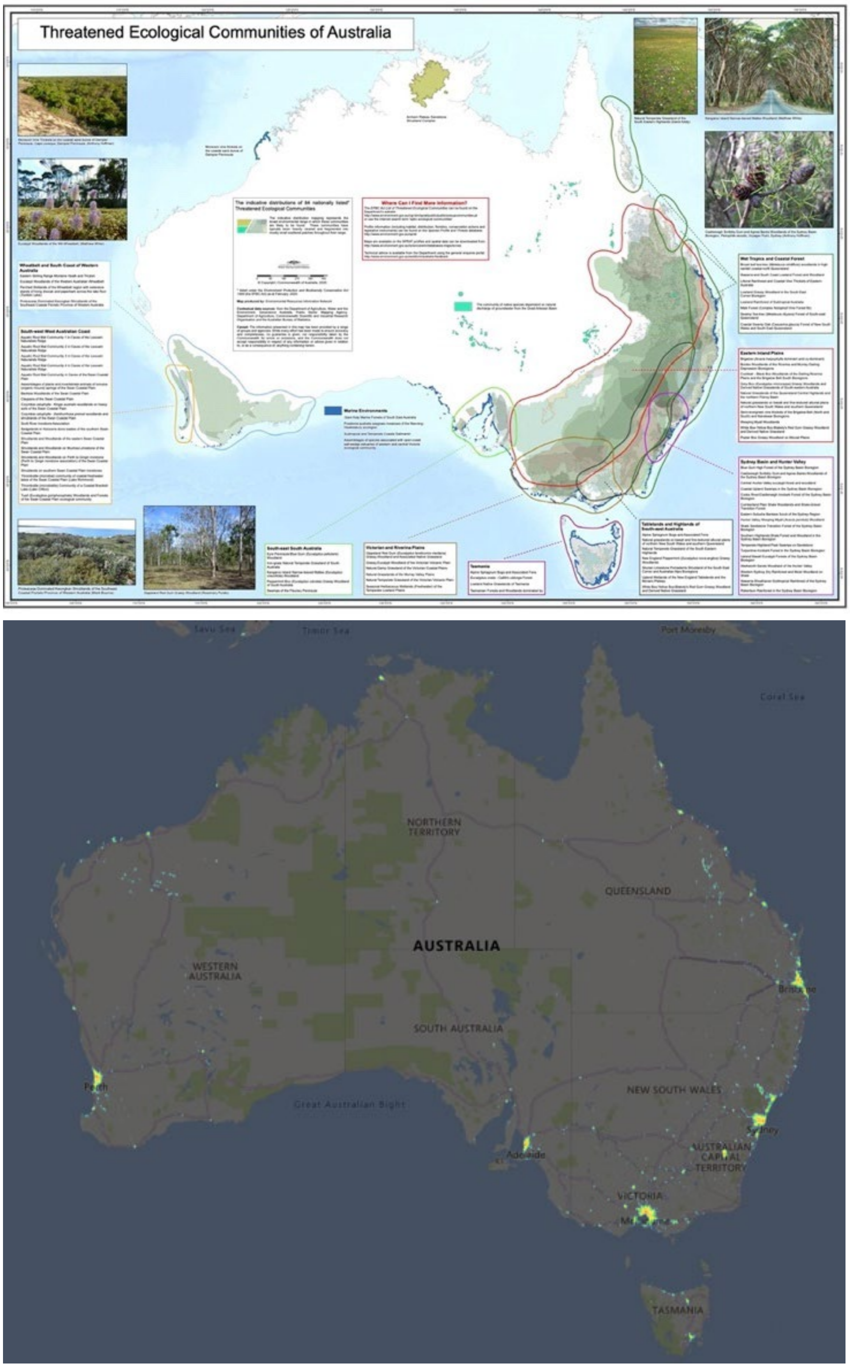
Ecological communities have strong cultural significance for both First Nations and non-indigenous Australians and support important values including native biodiversity and distinctive landscapes and seascapes. ECs also provide vital ecosystem services to both humans and wildlife, including the management of soil nutrient and water flows, purification of air and water, sediment stabilisation and salinity regulation, provision of breeding and feeding habitats, and carbon storage. These values and services in turn contribute to the tourism and recreation industries and the productivity of farmlands and fisheries.

Threatened Ecological Communities

Since European settlement, Australia's unique ecological communities have been placed under increasing strain due to land clearing, water diversion, changes in fire regime, pollution, urban development, climate change, invasive species and the introduction of other novel stressors including artificial light at night, human-generated noise and pesticides. These threats have resulted in many ECs in Australia undergoing and continuing to be affected by a rapid and significant reduction in geographic distribution and/or ecological function. When distribution and function are significantly depleted across the full range of an EC, it is at risk of extinction, and may be listed as a threatened ecological community under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). Many ECs are listed under the EPBC and/or equivalent state-based conservation legislation.

Threatened ecological communities listed under the EPBC Act occur in various habitats, including grasslands, woodlands, shrublands, mallee, forests, wetlands, marine, ground springs and cave communities. Most threatened communities include species that are listed (threatened) in their own right. The distribution of threatened ECs around Australia tends to reflect patterns of European settlement, with most concentrated around urban centres and agricultural regions. Because of this, the distribution of threatened ECs broadly coincides with areas most affected by light pollution (Map 1: Threatened ecological communities and light pollution in Australia), and many threatened ECs are exposed to light pollution across at least part of their extent.

Map 1: Threatened ecological communities and light pollution in Australia



Threatened ecological communities exist in areas most affected by light pollution.

Top: Indicative map of threatened ecological communities in Australia (as at February 2020 – additional communities have been listed since then). An enlarged, high-quality version is found at dcceew.gov.au/environment/biodiversity/threatened/communities/full-map.

Bottom: Indicative light pollution map of Australia from lightpollutionmap.info. Data: Visible Infrared Imaging Radiometer Suite (Earth Observation Group 2021).

Effects of artificial light on ecological communities

Life on Earth has evolved under predictable natural light cycles of day and night, the lunar cycle and seasonal shifts in daylength. Most organisms use these natural light signals to regulate:

- physiological processes – sleep, digestion, photosynthesis, cell expansion and repair
- life cycle events – development, growth, flowering, reproduction, hatching
- animal behaviour – resting, foraging, mating, territory defence, dispersal, migration.

In addition, light allows animals with the ability to see to find resources, navigate, avoid predators and provides energy for photosynthesis to plants and other primary producers .

The effects of light pollution

Light pollution – whether in the form of point-source light-spill from road/path or structure lighting, private interior/exterior lighting, intermittent lighting from vehicles or vessels, or indirect light pollution scattered in the atmosphere from a group of sources (skyglow) – can disrupt or mask these natural timing signals and alter the amount of light available for vision and photosynthesis. These disruptive effects can alter the life-cycle, distribution, behaviour, reproduction and survival of a large range of organisms, including: aquatic and terrestrial plants; insects and other invertebrates; terrestrial birds; frogs, toads and reptiles; fish, corals and crustaceans (see sections 3-7 below), as well as: marine turtles, seabirds, migratory shorebirds, terrestrial mammals and bats (see Appendices Appendix F – Marine turtles, Appendix G – Seabirds, Appendix H – Migratory shorebirds Appendix I – Bats and Appendix J – Terrestrial Mammals).

Artificial lighting can affect ecological communities both directly and indirectly (Sanders & Gaston 2018). Direct effects occur where light pollution acts specifically on one or more organisms that form a key part of the community; for example, by reducing the growth or productivity of grass in a grassland community or the movement or reproduction of key fauna. Indirect effects occur where light pollution impacts processes and species interactions within the ecological community, with cascading impacts on the key organisms in the community. For example, artificial light might undermine the lifecycle of pollinating insects, which in the long-term harms the recruitment of the pollinated plant species that support the community, and the food availability for key insectivorous fauna. These indirect effects can extend the effects of light pollution to the landscape scale even where the reach of the artificial light itself is more limited (Gaston et al. 2021).

The severity and nature of both direct and indirect effects will depend on community attributes, and on the type of artificial lighting, including:

- **Proximity to artificial light sources** – ecological communities near sources of artificial light such as towns, transport corridors or mine sites may be affected by direct light spill, intermittent vehicle lights and skyglow. In contrast, ecological communities in remote areas may only be affected by skyglow and, perhaps, occasional vehicular light pollution. Different parts of an ecological community may have differing exposure to light pollution; for example, tree canopies may be exposed to intense artificial light from streetlights, while accompanying understory habitat receives only weak, filtered light.
- **Intensity and duration of light sources** – Since light scatters in both air and water, the intensity of artificial light determines the distance over which its ecological effects may occur. Likewise, the duration of lighting determines the timescale over which effects may

occur, although some effects will not occur immediately. Light spill from buildings, structures and streetlighting is usually intended to illuminate over short distances at relatively low intensities, but is applied constantly – often all night, every night. In contrast, beam light from vehicle headlights or vessel floodlights is applied intermittently but at very high intensities and may reach several hundred metres (Gaston et al. 2021). The intensity and duration of lighting may also be affected by the use of adaptive lighting controls such as dimmers, timers and sensors (see Appendix A – Best practice lighting design).

- **Physical barriers to artificial light** – these might include both biotic landscape features like thick foliage, and abiotic features such as mountainous terrain. Direct artificial light spill and vehicular light pollution may impact a far greater area in open, flat communities such as grasslands compared to dense rainforest or mountain woodlands. Skyglow, on the other hand, can pervade most landscape features, although in areas with dense vegetation its effect will be filtered by the upper layers of the canopy (Endler 1993).
- **Patch size and edge effects** – human disturbance—including land clearing, artificial light, noise, pesticides and pets—at the boundary of a habitat patch has effects on plants and animals within the patch. These ‘edge effects’ can extend into the patch for up to several hundred metres (Laurance 1991) and artificial light may penetrate even further, particularly for species in or above the canopy (Gaston et al. 2021). Ecological communities confined to small patches, or narrow linear remnants—for example, along road and rail corridors—may be vulnerable to edge effects of light pollution across their entire range. In addition, light pollution may exacerbate the effects of other stressors on flora and fauna near the edges. For example, an animal stressed by increased predation pressure due to the presence of pet cats or dogs may be further stressed by artificial light disruption of behaviour or physiology, and loss of naturally dark refugia.
- **Connectivity and habitat fragmentation** – many nocturnal animals are unable or unwilling to traverse artificially illuminated areas or become trapped by light sources (Bhardwaj et al. 2020; Eisenbeis 2006; Sanders & Gaston 2018). Consequently, landscapes that might otherwise provide connectivity for animals travelling between high-value habitat patches can become less useful due to artificial lighting (Laforge et al. 2019). Light pollution can thus have a disproportionate effect on ecological communities that persist in, and are already threatened by, highly fragmented habitats. Artificial lighting in or through the middle of a patch, such as along a walking path, can also be a barrier to movement within the patch, effectively fragmenting it into smaller patches.
- **Water bodies** – the effects of light pollution on marine and freshwater communities may be as significant as the effects on terrestrial systems, given artificial light can penetrate hundreds of metres horizontally and vertically through water. Like terrestrial species, aquatic organisms regulate their growth, development, movement, and behaviour in response to light signals (see Artificial light and aquatic communities below).
- **Seasonality and fire regime** – the effect of light pollution within a given landscape or habitat patch can vary over time. Canopy, understory and groundcover vegetation may vary significantly due to annual or longer-term cycles in water availability, burning and storm damage. This in turn may affect the extent to which artificial light penetrates into habitat patches or across landscapes. Similarly, phytoplankton, algal blooms and suspended particulate levels in aquatic systems can vary substantially, altering the penetration of light below the surface (Bowmaker 1995). In alpine areas, the reflection of light from snow can significantly amplify the effects of light pollution (Jechow & Hölker 2019). Some organisms are particularly sensitive to artificial light at certain times of year or at key stages in their

life cycle. For example, many plants use changes in day-length as cues for growth or flowering (see 'Artificial light and plants' below). Similarly, natural light cues determine migration timing, navigation and the onset of reproductive behaviour in many animals, such as fish, amphibians, turtles and migratory birds (see Appendices Appendix F – Marine turtles, Appendix G – Seabirds, and Appendix H – Migratory shorebirds and relevant sections below). For a given ecological community, the effects of artificial light may vary from season to season, depending on which species are present/absent, active/dormant, reproducing or migrating. The masking of key natural light cues by artificial light may thus be more damaging at certain times of year than at others.

- **Community composition** – the effects of light pollution vary substantially between different groups of flora and fauna, and even within closely-related species. The species of plants, animals and other taxa present in an ecological community, particularly the dominant or functionally significant species, will thus affect the community's vulnerability to light pollution. The effects of light pollution on some groups such as turtles, seabirds, migratory shorebirds, bats and terrestrial mammals, are addressed in appendices Appendix F – Marine turtles, Appendix G – Seabirds, Appendix H – Migratory shorebirds Appendix I – Bats and Appendix J – Terrestrial Mammals. Groups including plants, insects and other invertebrates, birds, reptiles and amphibians, aquatic flora and fauna are addressed in more detail below. In some ecological communities, light pollution may also assist light-tolerant invasive species to out-compete native species (see Artificial light assists invasive species below).
- **Natural light levels** – in ecological communities that are exposed to very low levels of natural light, including caves, chasms, deep shaded valleys or Arctic and Antarctic winters, artificial lighting may be hundreds or thousands of times brighter than any natural light during day or night. In these communities, artificial light can have acute effects on organisms adapted to very low light (Berge et al. 2020) and lead to colonisation by more light-adapted species (Burgoyne et al. 2021), hence reducing biodiversity. Artificial light can also exacerbate changes to natural light levels from other sources, such as after a fire or storm that has removed tree canopies and/or native vegetation.

Artificial light and terrestrial plants

Note: aquatic (marine and freshwater) plants and photosynthetic organisms are addressed in the 'Artificial light and aquatic communities' section below.

Light as a signal for plants

Natural light cycles provide plants with reliable signals of time of day (light/dark), time of year (day length) and amount of shade. Plants rely on these signals to:

- regulate daily activity – photosynthesis, water and nutrient cycles, growth, rest and repair
- optimise the timing of seasonal events – germination, onset of vegetative growth, flowering, fruiting and senescence (Battey 2000)
- adjust morphology and physiology to match natural light conditions – for example by increasing leaf investment and specific leaf area in shady conditions(Coble et al. 2014; Givnish 1988; James & Bell 2000).

Changes in these light signals (for example through exposure to artificial lighting) can artificially promote shifts in growth and biomass allocation, and alter the timing of germination, flowering, fruiting, seed-set and senescence (Singhal, Kmar & Bose 2019; Sysoeva, Markovskaya & Shibaeva 2010; Velez-Ramirez et al. 2011) – see Figure 1. Even brief pulses of light at night can be enough to cause mistimed seasonal responses (Borthwick et al. 1952). Since plants use periods of natural darkness for repair and growth, exposure to artificial light at night can result in leaf damage, reduced growth and decreased productivity of fruit and seeds (Singhal et al. 2019; Sysoeva et al. 2010).

Figure 38: Artificial light masks natural daylength signal & disrupts seasonal changes in plants

The above, Figure 38, displays street lighting beside a soybean field in late summer/autumn. Plants away from the streetlight (brown in colour) have detected the shift in daylength and have shifted into the reproductive phase; withdrawing nutrients from leafy foliage and focussing investment on producing seeds. In contrast, plants near the streetlight have failed to detect the shift in natural day length and are continuing to produce vegetative growth; when winter arrives, these plants will not have produced seeds and will not reproduce. Source of images: Eddie McGriff, Alabama Extension Regional Agent, Auburn University.

Much of our knowledge of the effects of artificial lighting on plants comes from studies of agricultural and horticultural systems. The effects of light pollution on seasonal changes in wild plants are less well understood, but evidence to date suggests that they are likely to be similar, including reduced flowering density (Bennie et al. 2015) and biomass (Bennie et al. 2018), and shifts in the timing of flowering (Bennie et al. 2018; Cathey & Campbell 1975), vegetative growth (Cathey & Campbell 1975; Palmer et al. 2017), fruit-set (Palmer et al. 2017) and leaf-fall (Matzke 1936; Škvareninová et al. 2017).

The uncoupling of daily and seasonal rhythms from natural cycles may have cascading impacts on organisms that rely on or interact with plants. For example, climate-mediated shifts in plant or animal timing can result in animals breeding at times when key plant foods are not available (Post & Forchhammer, 2008). Likewise, shifts in the timing of plant flowering can result in disconnection with the presence of pollinating insects (Angilletta Jr & Angilletta 2009). Similar ecological mismatches may occur if plants, or the animals with which they interact, shift their seasonal timing in response to artificial lighting.

The timing of seasonal events in plants is largely regulated by phytochromes which respond to long-wavelength (red and near-infrared) light (Bennie et al. 2018). Amber-coloured artificial lights (which contain a relatively high proportion of longer wavelengths) can shift the timing of flowering and other seasonal events in plants (Bennie et al. 2016). Thus, while the use of longer wavelength (amber) lighting may reduce the effects of ALAN on many animals, it is unlikely to directly benefit terrestrial plants.Since biological timing in plants can be disrupted by even brief pulses of light at night (Borthwick et al. 1952), the use of lighting timers, sensors or curfews are unlikely to reduce the effects of light pollution on plants.

Light as a resource for plants

Light also provides plants with energy and carbon via photosynthesis. Plants near artificial light sources can receive sufficient light to promote photosynthesis at night when plants would ordinarily not be photosynthesizing (Bennie et al. 2016). Nocturnal photosynthesis under artificial lighting has been shown to increase overall carbon gain and growth in some species (Demers et al. 1998; Park et al. 2020; Yao et al. 2021) but can also promote responses that reduce a plant's capacity to assimilate carbon. These responses include impaired chloroplast biogenesis (Ruckle, DeMarco & Larkin 2007), reduced leaf investment, reduced daytime photosynthesis (Park et al. 2020; Pettersen, Torre & Gislerød 2010; van Gestel et al. 2005) and leaf damage or death (Cushman et al. 1995; Demers et al. 1998).

In addition, many plants close their leaf stomata and substantially reduce transpiration at night to prevent water loss and allow water potential (internal water pressure) to be restored (Phillips et al. 2010). Since photosynthesis requires gas exchange and thus open stomata, photosynthesis under artificial light at night may increase overall water loss and undermine a plant's ability to restore water potential overnight (Kavanagh, Pangle & Schotzko 2007). Because light must exceed certain thresholds to provoke a photosynthetic response, such effects are most likely for plants exposed to direct light pollution at high intensity or short distances, such as trees growing alongside streetlights (Bennie et al. 2016).

Cascading effects of light pollution in plants

Light pollution impacts on plant growth or seasonal timing are likely to have cascading impacts on herbivorous fauna and their predators (Bennie et al. 2016), and any other fauna that rely on plants – for example, as habitat and at nesting sites. Artificial light at night also disrupts nocturnal pollination networks and has negative consequences for plant reproductive success (Boom et al. 2020; Knop et al. 2017). See also 'Artificial light disrupts food webs and nutrient cycles' below.

Artificial light at night that affects plant physiology, may also change the interaction with herbivorous insects by affecting plant palatability. For example, artificial light at night exposure may increase leaf toughness by altering carbon-to-nitrogen ratios, which can affect host plant quality (Murphy et al. 2022). Streetlights have been demonstrated to directly reduce larval biomass and also indirectly affect larval growth by reducing host plant quality (Grenis and Murphy 2019). In one study, light at night of different colours changed the way that plant traits, including growth rate and leaf thickness, are related to insect herbivory damage (Cieraad et al. 2022).

Furthermore, common invasive plants may be more likely to tolerate or benefit from light pollution than native plants (Liu et al. 2022; Murphy et al. 2021). This may particularly be a concern along roadways or other locations that are frequently lit at night and have common vectors for plant invasions (Lázaro-Lobo & Ervin 2019). Artificial light may thus assist the establishment and spread of invasive weeds.

Artificial light and invertebrates

Invertebrate vision and attraction to light

Invertebrate vision is highly varied, with peak spectral sensitivities ranging from short wavelength UV-to-blue light up to long wavelength red-to-near infrared light (Davies et al. 2013; Donners et al. 2018) – see Figure 42. Among insects, sensitivity to short-wavelength UV, blue and green light is extremely common (Briscoe & Chittka 2001) and accordingly artificial light sources dominated by short-wavelength light tend to attract more insects in terms of abundance and number of species (Huemer, Kühtreiber & Tarmann 2010; Pawson & Bader 2014; van Grunsven et al. 2014; Wakefield et al. 2018).

However, replacing artificial light with longer-wavelength amber lights is not a complete solution. Some invertebrate taxa are attracted to long-wavelength lighting including some beetles, flies, ants and wasps (Deichmann et al. 2021; van Grunsven et al. 2019). Moreover, even amber lighting attracts far more invertebrates in most groups than natural darkness (Perkin, Hölker & Tockner 2014). In addition to spectrum, other factors affecting invertebrate attraction to artificial lighting include the intensity and direction of the light, the extent to which the light is filtered and muted by vegetation (Endler 1993) and its distance from sources of invertebrates. Even long-wavelength amber lighting can attract invertebrates from at least 40 metres away (Perkin et al. 2014).

Most natural light is unpolarized because waves of light can 'vibrate' in any direction as they travel outward from the light source. However, when light reflects off a flat surface, such as a body of water, it becomes polarized because light the waves can only vibrate in a single horizontal plane.

In nature, polarized light is strongly associated with water sources, and many invertebrates, as well as other animals, use polarized light from the sun or moon to identify water bodies. Artificial light from street, vehicle and building lights often strikes surfaces that reflect polarized light, including asphalt, solar panels, window glass and even dark-coloured vehicles (Blaho et al. 2014). These reflections cause invertebrates to mistake these surfaces for water, where they would normally lay their eggs. Artificial light can affect invertebrate reproduction by attracting invertebrates away from suitable habitat and by causing them to lay eggs on artificial surfaces that mimic natural water bodies (Szaz et al. 2015). Reducing such 'ecological traps' may require changing artificial lighting strategies and/or the surfaces of artificial structures (Fritz et al. 2020).

In addition, moonlight polarizing in the atmosphere provides an important navigational cue for nocturnal invertebrates, including some beetles (Dacke et al. 2003) and native bull ants (*Myrmecia midas*) (Freas et al. 2017). As polarized moonlight cues are exceptionally subtle, they are easily disrupted by light pollution, including dim skyglow, which can disorient invertebrates and disrupt normal dispersal in the landscape (Foster et al. 2021).

Artificial light is a major invertebrate stressor

Artificial light is a significant stressor of invertebrates, and a contributor to global invertebrate declines (Boyes et al. 2020; Hölker et al. 2010; Owens et al. 2020). Many invertebrates have an innate attraction to light sources called positive phototaxis or are disoriented by them (Longcore & Rich 2004) — in flying insects this is often observed as 'flight to light' behaviour (see discussion in Insects within Appendix I – Bats), and similar effects occur in ground-dwelling invertebrates (Eccard et al. 2018). Positive phototaxis can result in the death of invertebrates around light sources through impact, heat, exhaustion or increased predation (Eisenbeis 2006), while reducing important invertebrate behaviours such as feeding, mating and pollen transport (Macgregor et al. 2017). Less commonly, some invertebrates are light-avoiders, or become less active when exposed to artificial light at night (Eccard et al. 2018; Ferreira & Scheffrahn 2011; Luarte et al. 2016).

Artificial light disrupts invertebrate physiology, including melatonin cycles, immune function and oxidative stress (Joanna et al. 2020; J. Durrant et al. 2015; McLay et al. 2018). It can also disturb lifecycles at multiple points, including mating, reproduction, juvenile development, adult emergence and survival (Botha, Jones & Hopkins 2017; Boyes et al. 2020; McLay, Green & Jones 2017; McLay et al. 2018; Willmott et al. 2018). Light pollution can also interfere with short- and long-distance navigation and movement across the landscape (Eisenbeis 2006; Perkin et al. 2011). Artificial light can even affect diurnal invertebrate populations, via effects on plant reproduction (Knop et al. 2017) and the accumulation of nutrients (dead invertebrates) around outdoor lights (Davies, Bennie & Gaston 2012). In aggregate, these individual or species-level responses amount to landscape-scale shifts in invertebrate abundance, distribution and community composition (Davies et al. 2017; Desouhant et al. 2019; Lockett et al. 2021; Manfrin et al. 2017; Owens & Lewis 2018), with cascading impacts on food webs, pollination and nutrient cycling (see ‘Effects of artificial light on ecological processes’ below).

Effect on ecological communities

Insects and other invertebrates “create the biological foundation for all terrestrial ecosystems. They cycle nutrients, pollinate plants, disperse seeds, maintain soil structure and fertility, control populations of other organisms, and provide a major food source for other taxa” (Scudder 2017). Effects of artificial light on invertebrates are thus likely to have cascading effects for plants, animals and ecological processes in any ecological community.

Invertebrates provide a key trophic (energy) link between primary producers such as plants and protists, including algae, and animals. Invertebrates comprise a key food resource for most birds, reptiles, frogs, bats, and many fish, as well as terrestrial and marine mammals. Insects also convert a variety of largely indigestible plant matter (such as *Eucalyptus* sap) into widely-accessible food resources such as honeydew and lerp (Douglas 2006).

Many invertebrates are also key pollinators of terrestrial plants, and many plants have evolved to require pollination by a single or small group of insect species (Rosas-Guerrero et al. 2014). Native orchids in the genus *Caladenia* represent extreme examples of this; some species may be pollinated only by a single species of wasp (Phillips, Bohman & Peakall 2021) or even by a limited cohort within a single species of wasp (Phillips et al. 2015). Invertebrates provide other vital ecosystem services within ecological communities including decomposition and soil nutrient cycling, seed dispersal and germination, and pest control (Scudder 2017). Unsurprisingly, loss of invertebrates from a community is frequently implicated as a cause of decline in both plants (Knop et al. 2017; Ulrich et al. 2020) and higher animals including insectivorous lizards, frogs and birds (Lister & Garcia 2018).

Effects of artificial light on invertebrate assemblages are thus likely to have cascading effects on the composition and ecological functioning of many ecological communities via multiple mechanisms, including via food webs, nutrient cycling, pollination and seed dispersal.

Artificial light and terrestrial birds

Note: the effects of light pollution on seabirds and migratory shorebirds are addressed in Appendix G – Seabirds and Appendix H – Migratory shorebirds, respectively.

Seasonal light signals, reproduction and migration

Natural daylength plays a key role in regulating the breeding behaviour and physiology of birds. Shifts in daylength in the leadup to breeding season (such as the lengthening of days in spring) trigger physiological changes including increased production of key hormones (such as testosterone), increase in the size of gonads, development of breeding plumage, the onset of mating song and other reproductive behaviours (Dawson et al. 2001). At the end of breeding season, changes in daylength (such as the shortening of days in late summer or autumn) trigger a corresponding reduction in hormones, atrophy of gonads, reduction in breeding behaviours and moulting of breeding plumage.

Light pollution masks natural daylength and can result in mistimed changes in birds' physiology and behaviour. These can include mistimed changes in gonad size and testosterone production, early egg-laying, and early moulting (Dominoni, Quetting & Partecke 2013; Dominoni et al. 2020). Such changes have been observed in birds exposed to very low levels of artificial light (0.3 lux) (Dominoni et al. 2013). Birds in the tropics may be particularly sensitive to such changes due to the subtlety of seasonal changes in natural light (Hau, Wikelski & Wingfield 1998).

The timing of seasonal changes may be particularly important for migratory birds that need to reduce the weight of reproductive organs (which otherwise become a burden during migration) and replace feathers before flying long distances. In Australia, such birds include migratory shorebirds (see Appendix H – Migratory shorebirds) and other birds that migrate to the northern hemisphere (such as the white-throated needletail), and also many birds that migrate or shift range within Australia, such as the critically endangered Orange-bellied Parrot (*Neophema chrysogaster*) and Swift Parrot (*Lathamus discolor*) (Gartrell 2002), as well as many kingfishers, swallows, cuckoos, robins and silvereyes. For migratory species the seasonal change-shifting effects of artificial light may be particularly detrimental in resting and breeding habitat areas used prior to or during migration. In addition, light pollution may also distract migrating birds by imitating natural sun- or moonlight (see Appendix H – Migratory shorebirds), or by undermining the daily recalibration of birds internal magnetic 'compass' (Cochran, Mouritsen & Wikelski 2004).

Day-night cycle, sleep and cognition

At shorter time-scales, bird behaviour is often tightly regulated by the natural day-night cycle (Da Silva et al. 2014) and by the monthly waxing and waning of moonlight (Dadwal & Bhatt 2017; Dickerson, Hall & Jones 2020; Pérez-Granados & López-Iborra 2020). These responses to natural light levels represent evolutionary trade-offs between access to resources including prey, inter-specific competition, ease of movement, and risk of predation (Kronfeld-Schor et al. 2013).

Diurnal (daytime active) and nocturnal (night-time active) bird species have different physical adaptations, such as vision and hearing, that under natural conditions allow them to co-exist by exploiting the same habitat at different times, with little overlap. Light pollution can alter this balance by extending the hours of activity and spatial distribution of diurnal birds, bringing them into contact with novel prey, predators and competitors (Canário, Hespanhol Leitão & Tomé 2012; Russ, Rüger & Klenke 2015; Silva, Diez-Méndez & Kempenaers 2017). For example, the Peregrine Falcon (*Falco peregrinus*) is a diurnal predator that can adapt its foraging behaviour to use artificial light to hunt birds at night (Drewitt & Dixon 2008). Artificial light can also alter the distribution of prey and thus of nocturnal predatory birds: insects, amphibians and birds have all been observed to cluster at light sources (Baker 1990; Buchanan 2006; González-Bernal et al. 2016; Komine, Koike & Schwarzkopf 2020; Lockett et al. 2021), and at least some owls have responded by focussing their predatory efforts around those same lights (Canário et al. 2012; Rodríguez, Orozco-Valor & Sarasola 2021). Disturbance of the natural day-night cycle also has consequences for birds' sleep. Australian Magpies (*Cracticus tibicen*), Black Swans (*Cygnus atratus*) and Domestic Pigeons (*Columbia livia*) all lose sleep when exposed to streetlight-level lighting at night, although have varied sleep-recovery responses. Switching to amber lighting may reduce adverse effects on magpie sleep but does not benefit swans or pigeons (Aulsebrook et al. 2020; Aulsebrook et al. 2020).

Lunar cycle

Bird responses to moonlight are complex: many birds including Willie Wagtails (*Rhipidura leucophrys*) are more active on moonlit nights (Dickerson et al. 2020; La 2012), possibly as a means to enhance territory defence or mate attraction. Others—including the Australian Owlet-nightjar (*Aegotheles cristatus*), Blue Petrel (*Halobaena caerulea*) and Slender-billed Prion (*Pachyptila belcheri*)—reduce activity on brightly moonlit nights to reduce their risk of predation (Brigham et al. 1999; Mougeot & Bretagnolle 2000). The dawn chorus of diurnal birds typically occurs earlier on bright moonlit mornings (Bruni, Mennill & Foote 2014; Pérez-Granados & López-Iborra 2020) as its timing is dependent on ambient light levels and the visual ability of different species (Berg, Brumfield & Apanius 2006; Thomas et al. 2002). Even the full moon provides relatively faint light (typically <0.2 lux; Kyba, Mohar & Posch 2017), so artificial light can readily mask natural moonlight signals and alter the responses of birds. The nocturnal singing of male Willie Wagtails normally peaks under a full moon but decreases when artificial light is present either as a point source (for example, streetlight) or skyglow (Dickerson, Hall & Jones 2022)—this may be a response to increased predation risk under artificial light, which can be many times brighter than a full moon. In addition, dawn chorus occurs earlier in light polluted areas (Bruni et al. 2014) which may increase the predation risk for diurnal birds at times when nocturnal predators are still active (Staicer, Spector & Horn 2019).

Some urban birds appear to tolerate or even prefer artificially illuminated roosts, possibly due to improved predator detection (Daoud-Opit & Jones 2016). These include the Rainbow Lorikeet (*Trichoglossus moluccanus* – considered invasive in Western Australia and Tasmania) and the Common Myna (*Acridotheres tristis* – invasive throughout its range in Australia). Tolerance of artificial light may be one of the factors that assists these ‘urban exploiters’ to supplant less light-tolerant native bird species (Conole & Kirkpatrick 2011).

Effect on ecological communities

Birds comprise an important food source for many predators, and many are key predators of vertebrate and invertebrate prey. Birds are also responsible for many key ecological processes, including pollination (Burd et al. 2014), seed transport (Bradford & Westcott 2010; Rawsthorne, Watson & Roshier 2012), controlling invertebrates (Clarke & Schedvin 1999), nutrient cycling and fuel load reduction (Maisey et al. 2021). Taken together, the effects of artificial light on reproduction, behaviour, predator-prey dynamics, natural food webs and individual physiology of birds outlined above have the potential to reduce or fragment populations of birds, alter birds’ distribution in the landscape, or exclude them from illuminated patches altogether (Adams et al. 2021).

Loss or fragmentation of birdlife in an ecological community may in turn restrict the dispersal of pollen and seeds, reduce soil nutrient cycling, and increase invertebrate infestations, thereby limiting the reproduction and recruitment of key plant species. Where plant species rely specifically on birds for pollination or seed dispersal, such effects could result over time in substantial change in plant species composition, or reduction in the overall extent or quality of the ecological community in question.

Artificial light, reptiles and amphibians

Artificial light is known to have severe impacts on marine turtles (see Appendix F – Marine turtles), however much less is known about the effects of light pollution on other reptiles such as lizards and crocodiles, or on amphibians such as anurans (frogs and toads).

Anurans are predominantly nocturnal (Buchanan 2006), and many are known to have an innate attraction to artificial light sources, while others are light-avoiders (Jaeger & Hailman 1973). Like other insectivores, frogs may also be attracted to artificial light sources due to the concentration of insect prey nearby (Baker, 1990; Buchanan 1998; Buchanan 2006). The invasive Cane Toad (*Rhinella marina*) is also known to seek out prey concentrations around artificial lights and may benefit substantially from outdoor lighting (González-Bernal et al. 2016; Komine et al. 2020). Both light-attracted and light-avoiding responses may limit the movement of anurans in the landscape, by either concentrating individuals around light sources (Baker 1990) or preventing movement across illuminated patches (van Grunsven et al. 2017). These restrictions on movement can impact entire populations by restricting mate-choice (Rand et al. 1997) and/or preventing the dispersal of juveniles across the landscape (van Grunsven et al. 2017). Attraction to street and path lighting also exposes anurans to novel risks including vehicles and pedestrians (Baker, 1990; van Grunsven et al. 2017).

In addition to effects on movement and dispersal, light pollution can also undermine the health and reproduction of anurans. As with birds, masking of seasonal changes in daylength can result in mistimed mating and breeding behaviour in frogs (Dias et al. 2019); artificial light can also impair breeding behaviour and fertilisation success (Touzot et al. 2020), and reduce hatching success, tadpole motility, metamorphic duration, juvenile growth, immune responses to common stressors, and gene expression (Dananay & Benard 2018; May et al. 2019; Touzot et al. 2022). Light pollution can also reduce the availability of algae and other key food resources for tadpoles (Dananay & Benard 2018; Grubisic et al. 2018).

There has been little research on the effects of ALAN on terrestrial reptiles such as lizards, skinks, tortoises, snakes and crocodiles. As with birds, at least some usually diurnal squamate (scaly) reptiles may extend their hours of activity under artificial light (Garber 1978; Perry & Fisher 2006) but may suffer impaired sleep as a consequence (Kolbe et al. 2021). Like other vertebrates, reptiles have circadian rhythms and melatonin cycles, although the effect of artificial light on these is largely unknown (Grubisic et al. 2019). For nocturnal reptiles such as geckos, crocodiles and some snakes, artificial light may alter their movement in the landscape in a similar way to other wildlife, depending on whether a given species is light-attracted or light-avoidant, which in turn is affected by whether the species is predator, prey, or both. The Dubious Dtella (*Gehyra dubia*) is a native house gecko that preys on invertebrates and is preyed upon in turn by snakes and birds. It uses bright moonlight (or even dim artificial light at night) to hunt prey and identify predators (Nordberg & Schwarzkopf 2022). However, it avoids brightly lit, prey-rich spaces that are instead exploited by the invasive Common House Gecko (*Hemidactylus frenatus*) (Zozaya, Alford & Schwarzkopf 2015). By concentrating prey in spaces inaccessible to the native gecko, artificial lighting thus favours the invasive species, and may be one of the factors contributing to the decline in native geckos. Exploitation of insect concentrations around artificial light appears to be common in geckos but may result in increased risk of predation by nocturnal snakes which are attracted by the presence of geckos (Perry & Fisher 2006). As with birds, the responses of reptiles to bright moonlight are highly varied and have evolved in response to factors including predation risk, ease of foraging and prey availability (Perry & Fisher 2006). The presence of artificial light has the potential to drastically alter these behaviours and has been implicated in the decline of less light-tolerant species (Perry & Fisher 2006).

Effect on ecological communities

Reptiles and anurans perform key ecological roles, including serving as prey for birds, fish and small mammals, or being predators of insects and small vertebrates, and — in the case of tadpoles — controlling algae and cycling nutrients in freshwater systems. Where reptile and native frog populations are detrimentally affected by artificial light, this is likely to have cascading consequences for ecological communities, including altered trophic webs, changes in algal diversity and productivity, reduced aquatic nutrient cycling, and reduced energy and nutrient transfers between waterways and riparian habitats (Whiles et al. 2006).Since artificial light appears to facilitate prey capture by cane toads, it may be one factor (of many) contributing to the spread and persistence of this species in northern Australia, and the consequential loss of native fauna.

Artificial light and aquatic communities

The penetration of light pollution into aquatic habitats

The penetration of light into fresh and saltwater is determined by the colour and intensity of light as well as the turbidity of water. In clear water, short wavelength blue-green light penetrates furthest, while red light scatters and diminishes rapidly with depth (Bowmaker 1995; Davies et al. 2020; Tidau et al. 2021). Accordingly, the behaviour and physiology of many marine and freshwater organisms are regulated by natural light signals dominated by short wavelength light, often at very low intensities. Often only organisms that spend a substantial proportion of their time near the surface or on land have adapted to exploit a wide spectrum of visible light (Bowmaker 1995; Marshall et al. 2019).

Turbidity, due to fine particles of organic matter and inorganic sediment suspended in the water column, drastically alters the underwater light environment. In turbid waters short-wavelength light scatters, leaving only a small amount of mostly long-wavelength light to penetrate the depths. Accordingly, aquatic organisms that inhabit turbid waters are more likely to have visual systems and light responses that are sensitive to dim, long-wavelength light (Bowmaker 1995). In addition, the visual systems of aquatic organisms may be further complicated by behavioural requirements such as the need for an animal to distinguish food items, predators or potential mates by contrast or colour (Bowmaker 1995; Marshall et al. 2019).

Artificial light in marine and coastal environments can penetrate and have ecological impacts many tens or hundreds of metres below the surface, and over hundreds of square kilometres of area. In relatively clear marine environments, land-based light pollution can reach coral reefs greater than 30 m beneath the surface (Davies et al. 2020), while artificial light from surface vessels can affect fish behaviour at depths in excess of 200m (Berge et al. 2020) and may penetrate up to 1000 m (Tidau et al. 2021). Light pollution from onshore and offshore sources now affects around 2 million km^2 of the world’s oceans, in some cases affecting up to 100% of the territorial waters of certain nations (Smyth et al. 2021).

Effects of artificial light on aquatic organism behaviour

The daily and seasonal activity and distribution of freshwater and marine fauna follows deeply ingrained patterns driven by light availability and natural light signals. Because moonlight provides a reliable signal of tidal patterns, many aquatic invertebrates regulate important lifecycle events and related movement in response to moonlight cues. These include reproductive events, juvenile migration and moulting (Ayalon et al. 2019; Naylor, 2001).

Similarly, the natural day-night light cycle drives daily movement of freshwater and marine organisms, including the daily vertical migration of zooplankton (microinvertebrates and larval fishes) (Cisewski et al. 2010) which rise to the surface at night to feed.

The strength and timing of vertical migration can be affected by even subtle changes in ambient light; for example, upward migration is suppressed by strong moonlight but promoted by increased cloud cover (Omand, Steinberg & Stamieszkin 2021; Prihartato et al. 2016). The exposure of freshwater and marine systems to light pollution is therefore likely to mask natural light signals and suppress the upward vertical migration of zooplankton. This in turn may reduce food availability for predators of zooplankton, or cause over-predation of some species, leading to changes in community composition (Perkin et al. 2011). Even short-term lighting from passing vessels is enough to reverse upward migration of marine invertebrates(Sameoto, Cochrane & Herman 1985). Normal working lights on marine research vessels—and, by implication, lights from other sources including fishing boats, cargo vessels, recreational watercraft, jetties and oil and gas platforms—have been shown to cause zooplankton and their vertebrate predators to descend away from the surface; these effects occurred at depths of up to 200 m, and up to 200 m horizontally from the light source (Berge et al. 2020).

Since most zooplankton need to ascend to forage on phytoplankton near the water's surface, light pollution may lead to an overall reduction in zooplankton, with cascading effects on their predators and up the food chain (Figure 39).

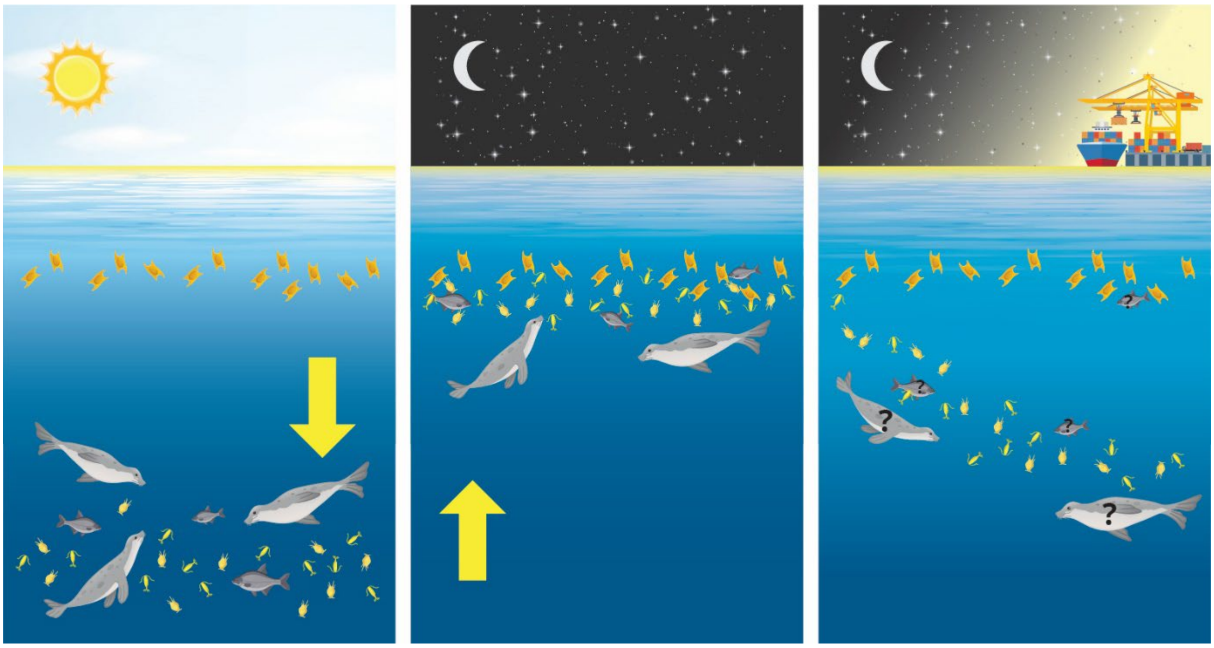


Figure 39: Effects of artificial light on vertical migration in aquatic systems

Zooplankton typically minimise their predation risk by spending daylight hours in deep, dark waters, or on the floor of rivers, lakes and oceans, and rise to the surface at night to feed on phytoplankton (microscopic photosynthesizing bacteria, cyanobacteria and algae) (Hays 2003). In response, many predators—including fish, turtles, penguins, seals, whales and dolphins—undergo their own vertical migrations, adjusting the depth and timing of foraging behaviours to locate prey which may include both zooplankton and smaller predators of zooplankton (Hays 2003; Mehner 2012). Artificial light suppresses the upward migration of many species; in doing so it may disrupt foraging by zooplankton that can no longer reach the surface, and in turn impact the movement and food availability of predators.

Some zooplankton such as marine amphipods on the Great Barrier Reef ascend at night in the usual way but, once near the surface, are attracted to brighter patches in otherwise dark waters (Navarro-Barranco & Hughes 2015). Consequently, even where light pollution doesn't mask the day-night light cycle, point-sources of light may concentrate aquatic invertebrates in a manner similar to terrestrial insects around streetlights (Navarro-Barranco & Hughes 2015), where they are easy prey for nocturnal predators (Leopold, Philippart & Yorio 2010). For amphipods in the intertidal zone (uncovered at low tide; underwater at high tide), artificial light can reduce their levels of foraging activity and thus growth by two-thirds (Luarte et al. 2016). As amphipods are responsible for breaking down dead seaweed and other beach detritus, such a large reduction in foraging activity may disrupt nutrient cycles in the intertidal zone.

In addition to interfering with daily and seasonal light cues, artificial light can directly impact the navigation, movement and behaviour of marine animals (Davies et al. 2014). Some of these changes reflect innate attraction to or repulsion by lighting, which may be highly spectrum-dependent (Marchesan et al. 2005). Other behavioural changes reflect facultative responses to enhance resource acquisition or anti-predator strategies. For example, fish behaviours, such as visually-oriented foraging, are promoted by illumination levels. Artificial light may promote these behaviours at times where they would otherwise be absent, bringing diurnal foragers into competition with their nocturnal counterparts, and increasing pressure on nocturnal and sessile (immobile) prey (Nightingale, Longcore & Simenstad 2006). In Sydney Harbour, diurnal fishes congregate at unlit wharves, which are used as habitat at night-time, when these fish are largely sedentary. The addition of LED lighting to wharves reduces fish numbers, with many presumably moving in to deeper waters to avoid the light. However, the fish that remain become highly active, foraging in a manner similar to daylight hours, and substantially increasing predation pressure on sessile invertebrates (Bolton et al. 2017). Since sessile organisms cannot move to avoid predators, natural night-time darkness often provides cover for key activities including feeding and spawning. Elimination of natural darkness increases the vulnerability of sessile marine organisms to predation and can alter the composition of nocturnally-active communities such that they more closely resemble diurnal communities (Bolton et al. 2017; Davies et al. 2015).

Effects of artificial light on flying invertebrate recruitment

Freshwater, saltmarsh and estuary systems provide key habitat for flying terrestrial invertebrates, including flies, mosquitos, mayflies, caddisflies, damselflies and dragonflies. Typically, these animals spend their entire juvenile phase underwater as aquatic nymphs, emerging from their final instar as winged adults which then use flight to disperse across the landscape to find mates and reproduction sites. In their juvenile and adult forms, these invertebrates provide a key food resource for aquatic (fish), amphibious (frogs, crabs), terrestrial (small mammals, reptiles, spiders) and airborne predators (bats, birds) (Perkin et al. 2011). Due to 'flight-to-light' behaviour and increased predation, artificial lighting strongly undermines the dispersal and survival of emergent adult invertebrates from aquatic systems (Manfrin et al. 2017; Perkin et al. 2014); this in turn impacts the size and composition of predator populations (Meyer, Mažeika & Sullivan 2013).

Effects of artificial light on aquatic plants and primary producers

Aquatic animals in communities such as the *Posidonia australis* seagrass meadows of the Manning-Hawkesbury ecoregion, giant kelp marine forests of southeast Australia, subtropical and temperate coastal saltmarshes, and the coral communities of the Great Barrier Reef, rely on aquatic plants and other primary producers to provide food shelter, breeding sites and nurseries, and on microbial assemblages to cycle nutrients and process pollutants. However, artificial light can significantly alter the abundance, composition and physiology of aquatic plants, algae and other photosynthetic organisms in marine and freshwater systems and disrupt the communities of microbes that break down sediments and pollutants and cycle carbon and nitrogen. In freshwater habitats, white (4000 Kelvin (K)) LED lighting was found to reduce the biomass of periphyton—collections of algae, microbes and detritus attaching to underwater structures—by 42 to 62% (Dananay & Benard 2018; Grubisic et al. 2018) and altered the seasonal composition of periphyton communities (Grubisic et al. 2017). In contrast, longer-wavelength sodium lighting was found to have no effect (Grubisic et al. 2018). LED lighting also causes submerged aquatic plants to undergo morphological and chemical changes normally associated with plants in the shade, including increased leaf area, higher photosynthetic capacity and reduced carbon-to-nitrogen ratio, consistent with resources being directed to photosynthetic organs rather than structural growth (Segrestin et al. 2021). Since such changes appear to be a response to perceived shading, the changes are likely to be maladaptive where plants are not, in fact, shaded during the daytime—for example, additional photosynthetic capacity may at best be under-used and at worst may increase oxidative stress. Illuminating aquatic plant patches at night may also undermine their function as a refuge for juvenile fish, since artificial light provides increased predation opportunities for visually-oriented predators (Bolton et al. 2017).

Application of long-wavelength sodium lighting (2000 K) to agricultural drainage ditches increases the presence of photoautotrophic (photosynthesizing or similar) microbes but reduces the presence of heterotrophic microbes (those that consume organic matter) and reduces overall respiration (CO_2 production) (Hölker et al. 2015). This suggests that long-wavelength lighting may increase carbon sequestration but reduces the breakdown of detritus and the cycling of carbon and nitrogen in aquatic systems. This may be because even long-wavelength lighting imposes increased physiological stress on detritivore microinvertebrates, increasing energy budgets but slowing growth and overall activity (Czarnecka et al. 2021). Broad-spectrum white, and narrow spectrum red and green lights have also been linked to potential increases in cyanobacteria (blue-green ‘algae’) and algal blooms (Diamantopoulou et al. 2021; Poulin et al. 2013), which can reduce oxygen and sunlight levels and increase water toxicity for fish and other aquatic and terrestrial fauna.

In coral reefs, artificial light can undermine photosynthesis in dinoflagellates, change their concentrations of chlorophyll, disrupt the coral-dinoflagellate symbiosis, increase oxidative stress and oxidative damage and lead to coral bleaching (Ayalon et al. 2019; Levy et al. 2020). These effects are much greater under short wavelength luminaires (6000-10,000 K) than under long wavelength luminaires (2000 K) (Ayalon et al. 2019). Moreover, other physiological disruptions, including bleaching because of artificial light, have been observed in coral species that are relatively resistant to thermal stress (Levy et al. 2020). Artificial light may thus increase the vulnerability of corals to bleaching.

Effects of artificial light on reproduction and fitness of aquatic animals

The impacts of artificial light on aquatic species might be of similar magnitude to impacts on terrestrial species. As with terrestrial fauna, the daily and seasonal rhythms of aquatic species are closely tied to natural light cycles (Falcón et al. 2010), and masking of sun- and moonlight signals can disrupt or suppress reproductive physiology, processes and behaviours, including the production of female sex hormones required to produce eggs in freshwater fish (Brüning et al. 2016); the nocturnal hatching of marine fish, timed to avoid diurnal predators (McAlary & McFarland 1993) and the production of coral sperm and egg cells, which is timed to allow spawning in response to optimal moonlight (and thus tidal) conditions (Ayalon et al. 2021).

Effects of artificial light on coral gamete production and spawning have been observed regardless of whether cool white (5300 K) or warm white (2700 K) lighting was used. In shallow coastal reefs, the reproduction of Ocellaris Clownfish (*Amphiprion ocellaris*) is drastically impacted by light pollution. For example, spawning frequency halves, embryo quality is reduced and hatching success reduces by 85%. Cool white lighting has a stronger effect on hatching success, but less impact on embryo quality, compared to warmer yellow lighting (Fobert, Schubert & Burke da Silva 2021). Since hatching time in these and other common reef fish is timed to avoid visual predators, very low light levels (<0.03 lux) may be required to induce normal hatching (McAlary & McFarland 1993).

Even where light pollution doesn't impact hatching, it can significantly reduce the survival of juvenile animals due to predation; in coastal saltmarshes, survival of juvenile Intertidal Burrowing Crabs (*Neohelice granulata*) was 61% lower under artificial light compared to natural darkness (Nuñez et al. 2021). Saltmarsh crabs play a key role as prey for birds and fish, and as ecosystem engineers whose burrowing oxygenates and regenerates intertidal mudflat soils, benefiting microorganisms, sediment decomposition and plant productivity; accordingly, population pressures due to increased juvenile mortality may have severe cascading effects on saltmarsh ecological communities (Nuñez et al. 2021).

Impacts on aquatic communities

Artificial light has the potential to disrupt aquatic ecosystems, including animal behaviour, plant and algal growth, predator-prey interactions, daily and seasonal movement, reproduction, development, and decomposition. These disruptions may have cascading impacts on aquatic community food webs, nutrient flows and cycling, and overall population abundance and species diversity.

In addition, effects on coral, such as coral bleaching and disrupted reproduction, can undermine reef-building and affect the physical structures on which reef communities depend. Further research should examine the direct and indirect impacts of light pollution in freshwater and marine communities.

Effects of artificial light on habitat fragmentation

Habitat fragmentation caused by land clearing or urbanisation reduces ecosystem function and biodiversity through multiple mechanisms (Fischer & Lindenmayer 2007), including reduced ecological connectivity (Amos et al. 2014) and increased edge effects (Laurance 1991; Laurance et al. 2002), both of which may be exacerbated by the effects of light pollution.

Artificial light reduces effective patch size

Edge effects describe the differences in community composition, structure or ecological function that occur at the edges of habitat patches, that is, at transition points between habitats of different types, such as where woodland transitions to open grassland, or between habitat and non-habitat landscapes, and, for example, at urban boundaries (Harper et al. 2005). Habitat edges are exposed to different pressures and processes to those that occur at the centre of habitat patches. For example, edges of woodland or forest patches may be exposed to increased wind, sunlight, evaporation, pollutants, disturbance of vegetation and soil, and entry of propagules (pollen, seeds), as well as increased predation and competitive pressures due to the presence of species from both adjacent habitats (Harper et al. 2005; Ries et al. 2004). Edge effects are common in both terrestrial and aquatic systems, including at the boundary between sandy seafloor and seagrass patches (Smith et al. 2011; Tanner 2005).

Increased penetration of natural light, especially sunlight, is a frequent and well-established effect of habitat edges (Haddad et al. 2015; Harper et al. 2005; Ries et al. 2004), particularly at the edge of woodland or forest habitat where light can penetrate horizontally from a cleared boundary. For the same reasons, artificial light at night might be expected to have greater penetration, and thus stronger ecological effects, when it occurs at habitat edges. Light pollution may compound existing pressures such as predation and competition at habitat boundaries; alternatively, it may create new edge-affected areas—for example, where a path through habitat is illuminated (Figure 40)—thereby reducing the size of intact habitat and reducing connectivity between the remnant patches.

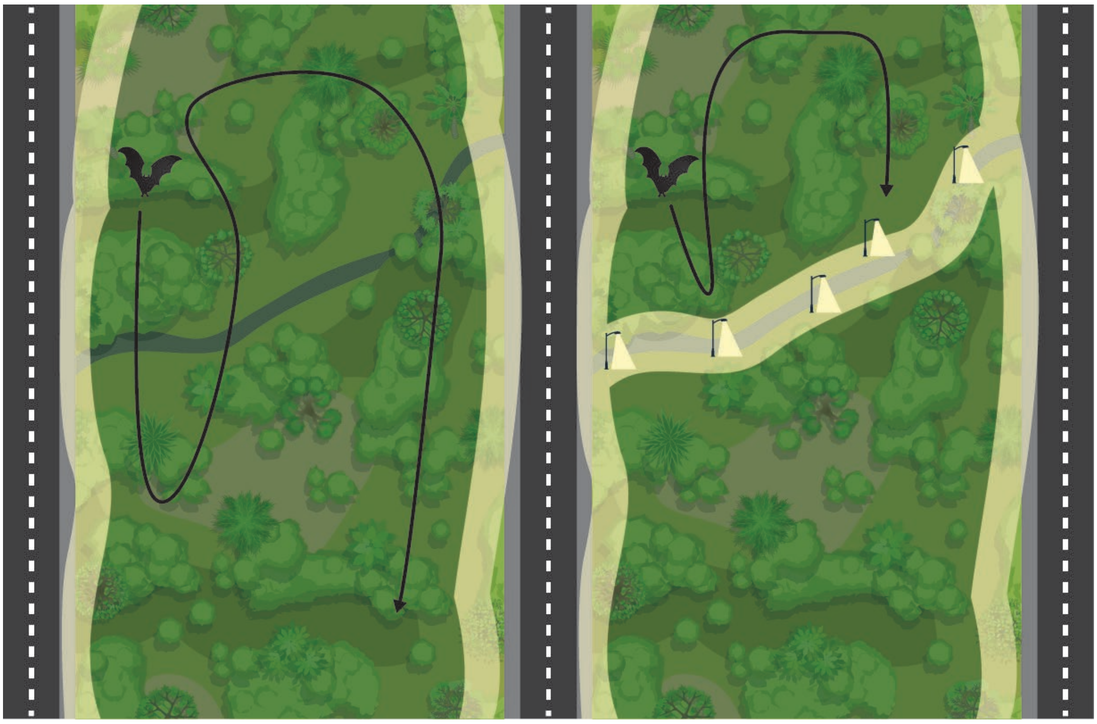


Figure 40: Effects of artificial light on habitat fragmentation and edge effects

Left: Habitat patch prior to introduction of artificial light. Dark green is intact habitat; light-green is habitat subjected to existing edge effects; grey is unlit path, presenting a narrow barrier between top and bottom of intact habitat patch.

Right: Habitat patch after lighting added to path. The additional edge-effected habitat represents a corresponding reduction in total intact habitat, and a substantial barrier to movement between the top and bottom intact patches which are now increasingly isolated.

Artificial light reduces ecological connectivity

Ecological connectivity is the ability of organisms, propagules, genes and energy to move between habitat patches within the landscape or seascape. Connectivity is important on multiple spatial and temporal scales, from daily short-distance travel between foraging patches, to long-distance migration on annual (or longer) cycles (Cosgrove, McWhorter & Maron 2018). The benefits of ecological connectivity include:

- increased biodiversity in an ecological community, including genetic diversity due to gene flow between populations
- increased foraging and mating opportunities

- ability to move between habitat patches in response to population pressures or habitat changes such as fire or drought
- re-colonisation of habitat patches following fire, drought, storms or other disturbance
- seasonal migration in response to changes in temperature or resource availability
- long-term migration in response to climate change or habitat loss

Where connectivity is reduced in a landscape, isolated populations of plants, animals and other organisms are at increased risk of local extinction due to interactions between environmental (fire, drought, habitat changes), demographic (age and sex ratios) and genetic factors (the loss of genetic diversity from inbreeding or genetic drift) (Benson et al. 2016). Loss of connectivity also makes it less likely that a habitat patch will be recolonized.

Human activity creates barriers to movement across land and water that undermine ecological connectivity, including cleared land, roads, buildings, dams, breakwaters and marinas (Bishop et al. 2017; Caplat et al. 2016). For nocturnal species, artificial light can produce a barrier effect that reduces movement as effectively as any physical barrier (Sordello et al. 2022). Light barriers increase mortality, decrease foraging and breeding opportunities, reduce gene flow between patches and prevent recolonisation of unoccupied habitat after fires, storms or other disruption (Hölker et al. 2021). Many invertebrate, mammal and anuran species will not cross artificially illuminated areas (Bhardwaj et al. 2020; Farnworth et al. 2018; Hale et al. 2015; Threlfall, Law & Banks 2013; van Grunsven et al. 2017)—where these are extensive—for example, along a highway—populations on either side of the barrier may be effectively isolated from each other, or may incur greatly increased travel distances in order to forage or mate (Soanes et al. 2018).

For nocturnal invertebrates such as moths, rows of streetlights present a substantial and often fatal barrier to landscape movement (Eisenbeis 2006). Since nocturnal invertebrates are important pollinators for many plants (Knop et al. 2017), artificial light barriers can also prevent dispersal of pollen in the landscape, undermining gene flow in plant communities (Macgregor et al. 2017). Similar mechanisms may operate to reduce plant recruitment where light barriers prevent the transport of other propagules (fruits, seeds) by animals. For aquatic fauna, light barriers may also restrict vertical movement, for example by restricting upward diel migration (see Effects of artificial light on aquatic organism movement).

Areas set aside for biodiversity are also often designated for recreation (including walking, wildlife watching, cycling, camping, fishing, boating, off-road driving), resulting in tensions between biodiversity values and recreational infrastructure (roads, paths, carparks, boat ramps, lighting) that creates barriers to the movement of organisms. Ecological connectivity can sometimes be improved, although not completely restored, by ‘piercing’ these barriers to movement, for example by providing wildlife bridges across or under roads, fish ladders at dams or habitat corridors or ‘stepping stones’ across cleared landscapes. Likewise, connectivity for nocturnal species may be improved by providing naturally dark corridors or unlit patches through which light-sensitive species may move (Sordello et al. 2022). Removing or reducing artificial lighting within and around existing dark corridors should also be a priority for improving landscape connectivity (Laforge et al. 2019).

Effects of artificial light on ecological processes

The ecological effects of light pollution are rarely restricted to a single organism or species. This is because organisms in a community interact and depend on each other for resources including food, shelter, pollination, decomposition and reproduction sites. As discussed in the preceding sections, where artificial light increases the mortality of a particular insect, that may have consequences for insectivorous animals that prey on the insect; plants that are pollinated or consumed by the insect; other invertebrates that are controlled (preyed on) by the insect and so on. The insect itself may in turn be affected by artificial light effects on the behaviour of its predators, the growth of a plant where it lays its eggs and other effects. Many of these interactions can be conceptualised as ecological processes: functions or flows or energy, matter or propagules which are commonly found in most ecosystems. Artificial light has the capacity to disrupt several key ecological processes including:

- Pollination, seed dispersal and soil nutrient cycling
- The consumption of energy and nutrients and their transfer between organisms through predation and herbivory (‘food webs’)

Artificial light reduces pollination, seed dispersal and soil nutrients

Many plants rely on animals to transport pollen or disperse seeds across the landscape. Pollination typically involves collection of pollen on hairs/feathers by nectarivorous fauna—including birds, bats, arboreal mammals and insects—and subsequent transport from one flower to another (Bradford et al. 2022; Goldingay, Carthew & Whelan 1991; Paton & Ford 1977). Seed dispersal occurs via multiple mechanisms; some are relatively straightforward, such as the attachment of ‘hooked’ or ‘hairy’ seeds to fur/feathers, while others involve complex species-specific mutualisms wherein both plant and animal benefit from the seed transport. Examples include the ingestion of seed-bearing fruit and subsequent excretion of viable seeds by Mistletoebirds (*Dicaeum hirundinaceum*) and Southern Cassowaries (*Casuarius casuarius*) (Bradford & Westcott 2010; Rawsthorne et al. 2012); the deliberate collection and transport of seeds by ants (myrmecochory) in order to provisions nests with ant-attractive food rewards (elaiosomes), which is a common reproductive strategy in Australian desert plants (Berg 1975); the transport and scattering of Eucalyptus seeds by native bees collecting resin for hive construction (Heard 2016); and the collection and storage of rainforest tree seeds by Giant White-tailed Rats (*Uromys caudimaculatus*) (Theimer, 2001).

As described in this and other appendices, members of animal groups responsible for pollen and seed transport (birds, bats, mammals and insects) may be vulnerable to effects of light pollution, such as restricted movement in the landscape. Artificial light can significantly reduce nocturnal pollination by insects (Macgregor et al. 2017), with cascading effects for plant reproduction and productivity (Knop et al. 2017; Ulrich et al. 2020). Adverse effects of artificial lighting on nocturnal vertebrate pollinators, such as flying-foxes, possums and native rats, are likely to have similar cascading effects on plants that rely on them for pollination or seed transport. Further, since non-native fauna (such as the Black Rat, *Rattus rattus*) are generally less well-adapted than the native species they supplant (such as the Brown Antechinus (*Antechinus stuartii*) or Eastern Pygmy-possums (*Cercartetus nanus*)) for pollinating native plants (O’Rourke et al. 2020), light pollution may further undermine pollination by assisting non-native urban adaptors to displace native pollinators.

Soil nutrient cycling may be a further indirect mechanism through which artificial light impacts plant reproduction, growth or productivity. Across many terrestrial communities, soil health and nutrient cycling depends on the foraging behaviour of small mammals such as bandicoots, bettongs and bilbies, and ground-dwelling birds such as lyrebirds, which turn over huge amounts of soil each year (Davies et al. 2019; Maisey et al. 2021). At smaller scales, nutrient cycling relies on the action of invertebrate detritivores including terrestrial, freshwater and marine amphipods (Czarnecka et al. 2021; Davies et al. 2012; Luarte et al. 2016) and saltmarsh crabs (Nuñez et al. 2021). If artificial light reduces the population size or movement of ecosystem engineers, it may alter the soil quality and nutrient availability for plants across a range of ecological communities from woodland to coastal to desert habitats (Fleming et al. 2014).

Reduction in pollination, seed dispersal or nutrient cycling due to light pollution can have flow-on effects for entire ecological communities, including plants (reduced reproduction and recruitment) and the animals that rely on them (reduced food, shelter, habitat structure and nesting resources) (Knop et al. 2017).

Artificial light disrupts food webs and nutrient cycles

Many of the direct effects of light pollution described in this and other appendices involve disruption of organisms' access to energy and nutrients. In the case of plants and other photosynthetic organisms, this includes changes to the amount of light available for photosynthesis, and potential shifts in soil nutrition (see 'Light as a resource for plants' and 'Artificial light reduces pollination, seed dispersal and soil nutrients' above). In the case of fauna, this may include changed herbivory due to shifts in plant growth, fruit-set and recruitment, altered ability to distinguish prey and predators, altered predation risk, changed foraging opportunities—such as prey concentrations around light sources—and increased interaction with novel prey, predators and competitors due to diurnal species extending their foraging activity into the night (see this appendix and Appendix F – Marine turtles, Appendix G – Seabirds, Appendix H – Migratory shorebirds Appendix I – Bats and Appendix J – Terrestrial Mammals).

These shifts in the availability and distribution of energy and nutrients mean that even species not directly affected by light pollution may be affected by its cascading effects (Knop et al. 2017); for example, herbivores may be affected where light reduces the productivity of a key food plant (Bennie et al. 2015). In turn, predators may be affected by subsequent decreases in herbivore abundance (Lister & Garcia 2018). These 'trophic cascades' can translate into community-level changes in the flow of energy and nutrients, which in turn affect the composition of species in the community. For example, in freshwater aquatic systems, microinvertebrates consume algae and organic sediments and are in turn consumed by nymphs of flying insects. The subsequent emergence of adult insects from the water and their dispersal onto land represents a substantial flow of energy and nutrients from the aquatic to the terrestrial sphere (Manfrin et al. 2017). Artificial light might disrupt this flow at multiple levels (Figure 41). Such disruptions in turn may drive changes in both the aquatic and terrestrial systems, including shifts in the body size and diversity of both emergent insects and their terrestrial predators (Manfrin et al. 2017; Meyer et al. 2013), and changes to the composition of faunal assemblages around light sources, including increased numbers of predators and scavengers (Davies et al. 2012).

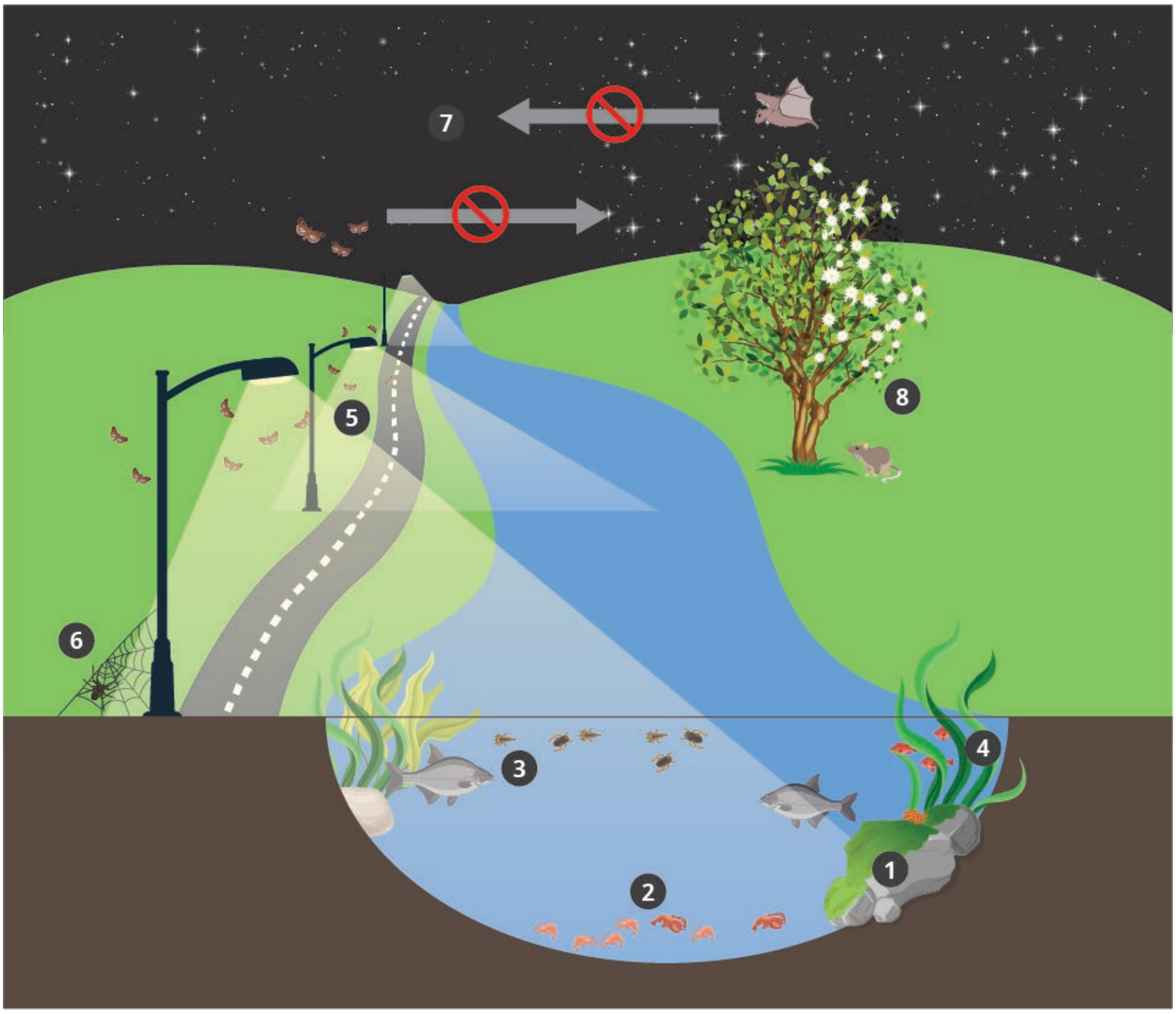


Figure 41: Effects of artificial light on food webs, pollination and seed dispersal

Artificial light can disrupt the flow of energy and nutrients in waterways and terrestrial ecosystems by (1) reducing the biomass of algae available to for microinvertebrates to forage on (Grubisic et al. 2017; Grubisic et al. 2018); (2) suppressing the upward migration of microinvertebrates and thus depriving insect nymphs, fish and other predators of prey (Hays 2003); (3) by increasing predation pressure on insect nymphs by fish or birds (Bolton et al. 2017; Leopold et al. 2010); (4) by preventing fish from hatching and depriving them of natural dark refuges (Bolton et al. 2017; Fobert et al. 2021); (5) by drawing flying insects away from water bodies and concentrating them (and thus the nutrients they represent) at particular points in the landscape (Manfrin et al. 2017; Meyer et al. 2013; Perkin et al. 2014); (6) by altering the size and composition of predator and scavenger assemblages around artificial light sources. In addition, artificial light barriers can (7) prevent the dispersal of faunal pollinators and seed dispersers across the landscape, thereby (8) reducing plant reproduction and the availability of fruit and seed as food resources.

Artificial light assists invasive species

Invasive species are organisms - including plants, invertebrates and vertebrates – that, because of human activities, occur beyond their accepted normal distribution, and threaten valued environmental, agricultural or other values. There is growing evidence that, like other natural and human-made disturbances, light pollution may assist the spread of invasive species, including by suppressing native counterparts or providing additional resources.

Three of Australia's most damaging invasive vertebrates—Cane Toads (*Rhinella marina*), Feral Cats (*Felis catus*) and Red Foxes (*Vulpes vulpes*)—have been shown to prefer or benefit from artificially illuminated hunting grounds (see 'Artificial light, reptiles and amphibians' above, and 'Appendix I – Terrestrial Mammals'). These three species represent a significant threat to several EPBC Act listed species, including small terrestrial mammals and reptiles.

Cane toads, along with invasive Common House Geckos (*Hemidactylus frenatus*), can thrive in part by exploiting insect concentrations around outdoor lighting – a resource that appears to be under-exploited by native geckos and anurans. In contrast, Feral Cats and Red Foxes are visual predators and likely benefit from increased night-time illumination from artificial lights to distinguish and capture prey.

Invasive birds such as the Common Myna (*Acridotheres tristis*) and Rainbow Lorikeet (*Trichoglossus moluccanus* – invasive in Western Australia and Tasmania) have readily colonised urban areas, including because they can tolerate (or even prefer) some level of artificial light at night (Daoud-Opit & Jones 2016). Even invasive plants may be better than natives at exploiting artificial light to grow and spread (Liu et al. 2022; Murphy et al. 2021).

The mechanisms by which artificial light may assist plant and animal invasions represents a knowledge gap that should be addressed in future research. In the meantime, there are sufficient examples of light pollution assisting invasive species that its potential to do so should be considered in assessing its likely effects on ecological communities. At a minimum, where artificial light facilitates the spread of invasive species it is likely to alter the composition of ECs, and potentially undermine the integrity of ECs via the suppression of native prey or competitors.

Environmental impacts assessment of artificial light on ecological communities

Planned changes to, or installation of, externally visible artificial light should implement Best practice lighting design (Appendix A – Best practice lighting design; Environmental impact assessment of effects of artificial light on wildlife) to minimise effects on threatened ecological communities from fixed (structure and road) lighting both permanent and temporary. Early consideration should also be given to the ecological effects of intermittent vehicular or vessel lighting where a project is likely to result in increased land or water traffic at night—for example, construction of a new road or jetty, even if not illuminated itself. Most lighting projects will have adverse impacts of some kind on nearby ecological communities. Even in highly modified urban areas, the addition of lighting is likely to adversely affect invertebrates, birds, bats and other small mammals. Even where an EC is not threatened and does not contain threatened species, the ecological effects of artificial lighting should also be minimised. This includes considering whether the project lighting is likely to reduce landscape connectivity — for example, new lighting in previously dark spaces—or substantially alter the overall intensity or spectrum of light entering the local environment.

Artificial lighting can have ecological effects many kilometres from its source. Artificial light can deeply penetrate a habitat patch and threaten the integrity and quality of ecological communities at the landscape scale. In addition, artificial light might occur together with other anthropogenic impacts, such as noise, increased human traffic, increased pollution and litter, increased hard surfaces and so on. Accordingly, there can be no one-size-fits-all rule as to the circumstances in which an Environmental Impact Assessment should be undertaken in connection with lighting projects near threatened ECs. Instead, planners should be alert to the potential for artificial light to impact ECs at the landscape scale; for example, if the project introduces new barriers to movement between isolated patches.

Since any artificial light is likely to affect an EC, consideration should be given to lighting objectives, design and mitigation measures as early as possible in a project's life cycle and used to inform the design phase. These may include measures that are only indirectly related to lighting, such as closing a carpark in a sensitive area at night to eliminate vehicular headlights or lowering speed limits on a new road to allow lower intensity lighting to be employed without increasing risks to drivers.

A person who proposes to take an action that will have, or is likely to have, a significant impact on a threatened ecological community or nationally protected species, must refer that action to the minister for a decision on whether assessment and approval is required under the *Environment Protection and Biodiversity Conservation Act 1999*.

Associated guidance

- Matters of National Environmental Significance Significant Impact Guidelines 1.1 Environment Protection and Biodiversity Conservation Act 1999
- Approved conservation advices for threatened ecological communities and threatened species
- Approved recovery plans for threatened ecological communities and threatened species
- State-based species recovery programs and conservation planning documents and advices
- Local government environmental planning advices
- Wildlife conservation plans for migratory species
- Threat abatement plans
- Species Profile and Threats Database (SPRAT)
- Other appendices in this document: Appendix F – Marine turtles; Appendix G – Seabirds; Appendix H – Migratory shorebirds; Appendix I – Bats; Appendix J – Terrestrial Mammals
- Ramsar Information Sheets and Ecological Character Descriptions
- Landscape based management plans, strategies and policies such as aquatic and terrestrial park plans of management

Qualified personnel

Artificial lighting design/management and the EIA process should be undertaken by appropriately qualified personnel. Light management plans should be developed and reviewed by appropriately qualified lighting practitioners who should consult with an appropriately qualified ecologist(s).

People advising on the development of artificial lighting management plans, or the preparation of reports assessing the impact of artificial light on ecological communities, should have knowledge of Australian ecology demonstrated either through relevant tertiary qualifications or equivalent experience as evidenced by peer reviewed publications in the last five years on a relevant topic, or other relevant experience.

Step 1: Describe the project lighting

Information collated during this step should consider the Effects of artificial light on ecological communities. The existing light environment and characterise the additional artificial light likely to be emitted at the site. Information should include (but not be limited to):

- the location and size of the project footprint
- the number and type of luminaires (existing and proposed)
- artificial light fixture height, orientation and hours of operation
- site topography and proximity to potential habitat and threatened EC patches
- whether artificial lighting may fragment existing habitat, or disrupt connectivity between habitat patches
- whether artificial lighting will be directly visible from affected patches, or contribute to skyglow
- the distance over which artificial light is likely to be perceptible
- shielding or artificial light controls used to minimise impacts
- spectral characteristics (wavelength) and intensity of luminaires
- effects of mobile and incidental artificial light sources—for example additional night-time vehicular or vessel traffic arising from the project
- effects of light at multiple relevant levels of habitat structure, including undergrowth, canopy level, above canopy level; or water surface, sub-surface, sea floor
- timing of construction and effects of lighting used during the construction phase

Step 2: Describe the ecological community

The species, distribution and abundance/density of key flora and fauna comprising, or dependent upon, the community should be described. For threatened ECs, the community descriptions found in listing advices, conservation advices and/or recovery plans in the SPRAT database provide a good starting point. These resources will provide guidance as to the most important species likely to be found in affected patches. However additional data will be required to identify the distribution and abundance/density of each species in the patches affected by the proposed project. Where there is insufficient data available for an affected patch, field surveys and ecological monitoring may be necessary.

Surveys and monitoring of communities

Surveys and monitoring associated with a project should be developed, overseen and results interpreted by appropriately qualified personnel to ensure reliability of the data. The nature of monitoring required will be community-specific and is likely to include surveys or monitoring of at least some of the: vegetation, invertebrate assemblages, reptiles and anurans, birds, fish, aquatic and marine flora and fauna, terrestrial mammals and bats.

The objectives of monitoring key species in an area likely to be affected by artificial light are to:

- understand the size and importance of the populations of key species within the EC
- understand interspecies interactions, including herbivory, predation, pollination, seed dispersal, shelter and sites for reproduction
- identify potential impacts of artificial light on:

  - key species and inter-specific interactions
  - habitat fragmentation, including connectivity, patch size and edge effects (see Effects of artificial light on ecological communities)
  - ecological processes, including pollination, seed transport, nutrient cycling and food webs (see Effects of artificial light on ecological processes)
- describe the responses of flora and fauna before and after the introduction/upgrade of artificial light

Monitoring may need to be repeated multiple times to achieve the objectives above if the taxonomic composition of the community varies over time—for example, due to migration, seasonal breeding or feeding patterns, irruptive breeding, or responses to drought, storms or fire.

The data will be used to inform the EIA and assess whether mitigation measures have the potential to be successful. Expert advice should be sought regarding appropriate monitoring parameters and techniques for each flora and fauna type. These will vary with community type and composition.

As a minimum, qualitative descriptive data on visible light types, location and directivity should also be collected at the same time as the ecological data. Handheld-camera images can assist with describing the intensity of the light source. Quantitative data on existing skyglow should be collected, if possible, in a biologically meaningful way, recognising the technical difficulties in obtaining these data. See Measuring Biologically Relevant Light (Appendix C – Measuring biologically relevant light) for a review.

Identify community vulnerabilities to artificial light

Identify the attributes of the community and its key species that may make them vulnerable to the effects of artificial light. In particular:

- Of the taxa identified in Step 2, are any known to be vulnerable to direct artificial light effects? ('known' should be interpreted broadly to encompass recognised impacts on taxonomically or functionally similar organisms)
- Of the taxa identified in Step 2, are any dependent upon or affected by other species or processes that are known to be affected by artificial light—such as pollination, seed transport, nutrient cycling, predation, herbivory, competition with other native or invasive species—this will nearly always be yes.
- What are the attributes of the landscape(s)/ecosystem(s) the community sits within and how might these amplify or reduce the spread and effect of artificial light?
- Are there other community attributes, such as seasonality, fire regime, topography, low natural daylight, habitat fragmentation, connectivity or patch size, that may indicate whether artificial light is:
  - more or less likely to impact the community?
  - likely to have different impacts at different times?

Table 17: Community attributes and corresponding direct and indirect vulnerabilities to the effects of artificial light sets out some of the major direct and indirect vulnerabilities to artificial light that arise in relation to ecological community landscape types or species groups.

Table 17: Community attributes and corresponding direct and indirect vulnerabilities to the effects of artificial light

Community includes:	Direct effects	Indirect effects
LANDSCAPE ATTRIBUTES		
Grassland	• Generally flat or undulating landscape with few topographical impediments to light spill. • Little or no shade or filtering by canopy trees; skyglow is likely to affect entire landscape • Filtering/shade effects of vegetation may change dramatically following drought/fire/storm/grazing	• Pollination of many grass and forb species relies on invertebrates and birds; effects of light on fauna are likely to disrupt pollination • Artificial light may facilitate predation, including by invasive species, especially when vegetation is reduced by fire, drought, storm etc • Artificial light may favour colonisation by invasive grass species over native species • Soil nutrient cycling relies on digging by small mammals and large birds; artificial light effects on these animals may undermine soil quality
Woodland & Rainforest	• Light penetration will be greater at edges than in centre of patch (edge effects) • Lighting intensity of skyglow may be relatively high at canopy level but much lower in understorey	• Pollination and seed transport for many tree and understorey species relies on invertebrates, birds and small mammals; effects of light on fauna are likely to disrupt pollination • Soil nutrient cycling relies on digging by small mammals and large birds; artificial light effects on these animals may undermine soil quality
Water bodies	• Artificial light penetrates deep into water (at least 200m) • Water and sediment filter light, altering spectral qualities (which may change with daily or seasonal changes in sediment) • Light barriers can be both horizontal and vertical (suppressing diel migration)	• Artificial light can interrupt nutrient transfers between aquatic and terrestrial systems via effects on invertebrates, including spatial concentration and the strength and timing of zooplankton vertical migration, on periphyton (increasing carbon sequestration, but reducing the breakdown of detritus and the cycling of carbon and nitrogen in aquatic systems) and on the predators reliant on them • Potential increases in cyanobacteria (blue-green ‘algae’) and toxic algal blooms are associated with white light. These types of artificial light can reduce sunlight and oxygen levels and increase toxicity of water.

Alpine areas	• Reflective properties of snow and ice will increase spread of light during winter • Lighting on high points (hilltops) can spread over large distances; lighting in valleys will have only limited spatial effect	• Effects of artificial light on invertebrate migration (Bogong moths) in other regions can disrupt food webs in alpine areas, and flow of nutrients from non-alpine to alpine regions
Caves	• Natural light is limited or absent, so any introduction of ALAN is likely to have significant effects on resident flora and fauna • Artificial light facilitates colonisation by lampenflora including taxa such as cyanobacteria, algae and bryophytes	• Artificial light effects on plant investment and morphology may reduce root growth (with consequences for root mat communities)
Linear patches	• Any lighting is likely to affect a large proportion of patch, especially where a linear patch follows or contains transport corridors (roads, rail, shared paths) • Edge effects of lighting are thus likely to substantially reduce the effective patch size for light-sensitive organisms, or eliminate them entirely from the patch	• Linear patches are often vectors for invasive plant and animal species. Many of these benefit from or tolerate light pollution, including weeds (increased growth), cane toads (food aggregations at streetlights) and invasive birds and geckos (more light tolerant than native competitors)
Small patches	• Edge effects of lighting are likely to substantially reduce the effective patch size for light-sensitive organisms	
SPECIES ATTRIBUTES		
Terrestrial plants	• Artificial lighting (including both cool white and amber lighting) may mask seasonal lighting cues, leading to mistimed seasonal changes in growth and reproduction • Night-time photosynthesis may undermine water status and tree health	• Loss of invertebrate and vertebrate pollinators and seed transporters may affect reproduction • Loss of digging mammals and large terrestrial birds may reduce nutrient cycling in soil
Aquatic plants, algae and periphyton	• White lighting may reduce biomass of algae and periphyton substantially • White lighting may cause morphological and chemical changes in plants consistent with daytime shading • Both broad spectrum (white) and narrow spectrum (red, green) lighting may increase growth of cyanobacteria species responsible for toxic algal blooms	• Effects of lighting on zooplankton may reduce grazing and cause algae to become overabundant • Loss of heterotrophic microbes may reduce nutrient cycling in aquatic systems • Increases in photoautotrophic microbes may lead to increased carbon sequestration however there may be reductions in the breakdown of detritus and the cycling of carbon in aquatic systems

Aquatic fauna (See also: Corals)	• Artificial light may suppress diel vertical migration reducing opportunities for zooplankton to feed at the surface • Artificial light may concentrate the spatial distribution of zoo plankton and thereby impact predator movement and behaviours • Light may alter predation interactions amongst fish, and between fish and sessile invertebrates • Light may reduce spawning frequency, embryo quality and hatching success in fish (both white and amber lighting is implicated in different effects) • Predation of juvenile crabs massively increases under artificial light	• White lighting may reduce the biomass of algae and periphyton available as food resources for aquatic predators • Loss of juvenile crabs and other invertebrates can reduce oxygenation of mudflats, sediment decomposition and plant productivity
Corals	• Artificial light can lead to mistimed breeding that fails to synchronize with appropriate conditions • Longer-wavelength (amber) lighting that helps some marine species (for example turtles – Appendix F – Marine turtles) does not appear to prevent breeding failure in corals (but does reduce light-induced bleaching)	• Artificial light can undermine dinoflagellate photosynthesis and ultimately lead to coral bleaching • Artificial light may increase the vulnerability of corals to bleaching through cumulative stressors (for example, artificial light plus heat stress)
Insects and other invertebrates	• Artificial lighting traps many flying and ground-dwelling insects, increasing mortality and reducing dispersal, foraging and breeding • Other invertebrates avoid illuminated areas, or become less active under lights, reducing dispersal, foraging and breeding	• Diurnal birds can extend foraging activity into the night-time, increasing predation pressure on nocturnal invertebrates • Decreased plant growth due to artificial light may reduce food resources and breeding sites available to herbivorous insects
Frogs and reptiles	• Lights may attract frogs to paths and roads, resulting in increased mortality due to predation or vehicles • Light patches or barriers (roads, paths) may reduce dispersal of juveniles across the landscape and limit the breeding options for light-sensitive species	• Artificial light may reduce invertebrate abundance with impacts on frog food resource • Artificial light sources may assist invasive cane toads by aggregating invertebrate prey and making them easier to capture
Marine turtles	• Artificial light at beaches may displace adult turtles and deprive them of nesting sites • Hatchlings crawl towards artificial light sources, rather than the ocean, leading to death through	

	predation, vehicle strike or dehydration	
Nocturnal birds	• Lights may cause smaller nocturnal birds (for example, owlet nightjars) to reduce foraging due to predation risk • Spatial distribution of some nocturnal birds (for example, owls and frogmouths) may be altered by artificial light to take advantage of prey aggregations (insects, bats) around light sources • Artificial light may disrupt seasonal physiological and behavioural cues, undermining reproduction	• Artificial light may reduce invertebrate abundance with impacts on food resource of nocturnal birds including nightjars, owls and frogmouths
Diurnal birds	• Artificial light may disrupt seasonal physiological and behavioural cues, undermining reproduction • Artificial light may extend foraging behaviour into the night-time • Artificial light may assist visual predators (including exotic species such as cats and foxes), leading to increased predation at roosting and nesting sites	• Artificial light may reduce invertebrate abundance with impacts on birds' food resource
Seabirds	• Artificial light masks natural navigation cues (moon and stars), causing seabirds to become disoriented • Fledglings leaving burrows for the first time are particularly prone to disorientation • Artificial lights can cause seabirds to become stranded on structures or vessels	
Migratory shorebirds	• Artificial light at roosting sites may displace birds elsewhere and deprive them of access to nearby foraging sites • Artificial light at foraging sites may increase susceptibility to predation • Migrating birds may be disoriented or killed by artificially lit structures on migration routes	
Bats	• Artificial light may delay nightly departure from roost, and disrupt foraging and commuting behaviour • Rows of lighting may present a barrier to landscape connectivity	• Artificial light may reduce invertebrate abundance with impacts on bats' food resource • Aggregations of insects at light sources may assist some (light-tolerant) bat species in the short term and disadvantage others
Terrestrial mammals	• Most native mammals are active in low light to avoid predators. Artificial lighting can restrict	• Artificial light may reduce invertebrate abundance with

	movement in the landscape and increase predation risk • Vehicle headlights can disorient and temporarily blind native mammals • Artificial light masks natural seasonal cues (daylength), causing mistimed reproduction	impacts on insectivorous mammals' food resource

Step 3: Risk assessment

Artificial light should be managed so that: the ecological functioning of an ecological community is not impaired; key species within the community are able to survive, disperse and reproduce, and are not exposed to additional stresses; existing habitat patches do not decline in quality or size; connectivity between patches is maintained or enhanced; and energy and nutrient flows within the community are not disrupted. The risk assessment process should consider the likelihood of artificial light affecting any of these objectives. The aim of risk assessment is to ensure that important ecological communities remain unaffected and intact.

Consideration should be given to how artificial light might degrade, fragment or decrease relevant habitat. Impacts of artificial light impacts must be considered beyond the direct footprint of the proposed development. Light that spills outside the development area will represent a greater extent of habitat disturbance than what is described by the development area. Artificial light upgrades or installations should be managed to ensure the light does not extend beyond the development area to minimize the extent of habitat loss. The effect of mobile and intermittent light sources including vehicular or vessel lighting should be specifically considered.

To understand how or whether artificial light is likely to spill into or be visible from a habitat patch, site visits should be made at night and—if the extent of foliage changes seasonally or following fire or storms—on multiple occasions to consider the effect of light under all conditions. Particular attention should be paid to naturally dark habitat corridors or refugia that facilitate connectivity between habitat patches.

Using this perspective, the type, number and location of artificial lights, and the effect of mobile light sources, should be considered and/or modelled to determine the potential effect of lighting on the EC and its key species, considering wavelength, intensity, duration and location.

The nature of consideration required will be highly community- and project-specific, but should include:

3) the threatened status of any taxa identified at Step 2: Describe the ecological community

4) the proportion of the EC landscape that will be impacted by artificial light, and the distribution of organisms within that proportion. For example, roadside remnants may be of particularly high quality and thus both species-rich and highly exposed to artificial light

5) the synchronicity of high artificial light periods (long nights, lack of dense growth) with light-sensitive developmental stages of key taxa (flowering, migration, reproduction)

6) the distribution of light sources within the landscape with regard to the potential fragmentation of habitat, reduction in connectivity, increase in edge effects or reduction in patch size

7) whether the ecological community sits on or near land or waters protected by state or Commonwealth environmental legislation; for example, a listed Ramsar site, a National Park or state protected land

8) consideration of context-specific planning and regulatory guidance including Ecological Character Description (ECD) and Ramsar Information Sheet (RIS) for Ramsar wetlands; National Park Management Plans; Nature Reserve Management Plans; Biosphere Reserve plans; local government reserve plans or planning regulations; regional environmental plans.

Step 5: Light management plan

This should include all relevant project information (Step 1: Describe the project lighting), biological and abiotic community information (Step 2: Describe the ecological community) and attributes that make the EC or its key species vulnerable to light pollution effects (Step 3: Risk assessment), and should outline proposed mitigation of any such effects. For a range of taxon- and landscape-specific mitigation measures please see Ecological communities light mitigation toolbox. The plan should also outline the type and schedule for biological and artificial light monitoring to ensure mitigation is meeting the objectives of the plan, and triggers for revisiting the risk assessment phase of the EIA. The plan should outline contingency options if biological and artificial light monitoring or compliance audits indicate that mitigation is not meeting objectives; for example, if artificial light is affecting key species or ecological processes, or substantial changes in community composition or habitat structure are observed.

Consideration should be given to monitoring control sites. Monitoring should be undertaken both before and after artificial light upgrades or installations occur at both the affected and control sites. Concurrent light monitoring should be undertaken and interpreted in the context of how key species within the EC perceive or use light and within the limitations of monitoring techniques described in Appendix C – Measuring biologically relevant light.

Monitoring, as described in the light management plan, should be undertaken to ensure artificial light at the site is consistent with the light management plan and is not disrupting the ecological function of the EC or the behaviour, survival, dispersal and reproduction of key species.

Monitoring of species' movement and distribution in the landscape should also be undertaken to ensure that artificial light is not fragmenting patches of any ecological community or reducing connectivity between existing patches.

Step 6: Review

The EIA should incorporate a continuous improvement review process that allows for upgraded mitigations, changes to procedures and renewal of the light management plan based on the outcomes of the biological monitoring program of artificial light impacts on the EC and its key species. This process should include periodic assessment of improvements in lighting and light-mitigation technology, with a view to implementing new technology where it helps reduce the effects of artificial light on the EC.

Ecological communities light mitigation toolbox

Appropriate artificial lighting design, controls and mitigation will be site, project, community and often species-specific. Table 18: Artificial light management options for ecological communities provides a toolbox of management options relevant to ecological communities. These options should be implemented in addition to the six best practice light design principles. Not all mitigation options will be relevant for every project. Where artificial lighting must be used, the most appropriate colour of lights will depend on the organisms that are most likely to be exposed to the lighting and/or most severely affected. There is unlikely to be any single ideal lighting solution for any EC (Figure 42), and choice of lighting spectrum will usually involve trade-offs between benefits to some organisms and adverse effects on others. The most effective measures for mitigating the impact of artificial light on ecological communities include:

- maintaining naturally dark habitat patches and connecting corridors whenever possible
- avoiding the creation of 'light barriers' that can fragment an intact habitat patch and prevent movement of species within the patch, or than can reduce connectivity between neighbouring patches
- piercing light barriers by providing natural or near-naturally dark corridors wherever possible
- avoiding, removing, redirecting or shielding artificial lights within and close to habitat patches wherever possible, and keeping intensity as low as practicable, noting that low artificial intensity light (well below full moon light levels) can disrupt terrestrial and aquatic flora and fauna
- minimizing effects of intermittent mobile light sources, such as vehicle headlights and vessel deck lights.

Other mitigation measures that may be less effective include:

- using narrow spectrum, long wavelength amber or red lighting; this is likely to benefit most invertebrates and some algae, but its effects on other animal groups (fish, birds, amphibians, mammals) is highly variable (Alaasam et al. 2021), and it can disrupt seasonal shifts in terrestrial plant physiology via effects on phytochromes.
- implementing part-night lighting schemes to reduce the duration of artificial light
- using motion sensor lighting or dimmers may reduce the overall amount of light emitted.

These mitigation measures should be assessed on a case-by-case basis to determine their effectiveness.

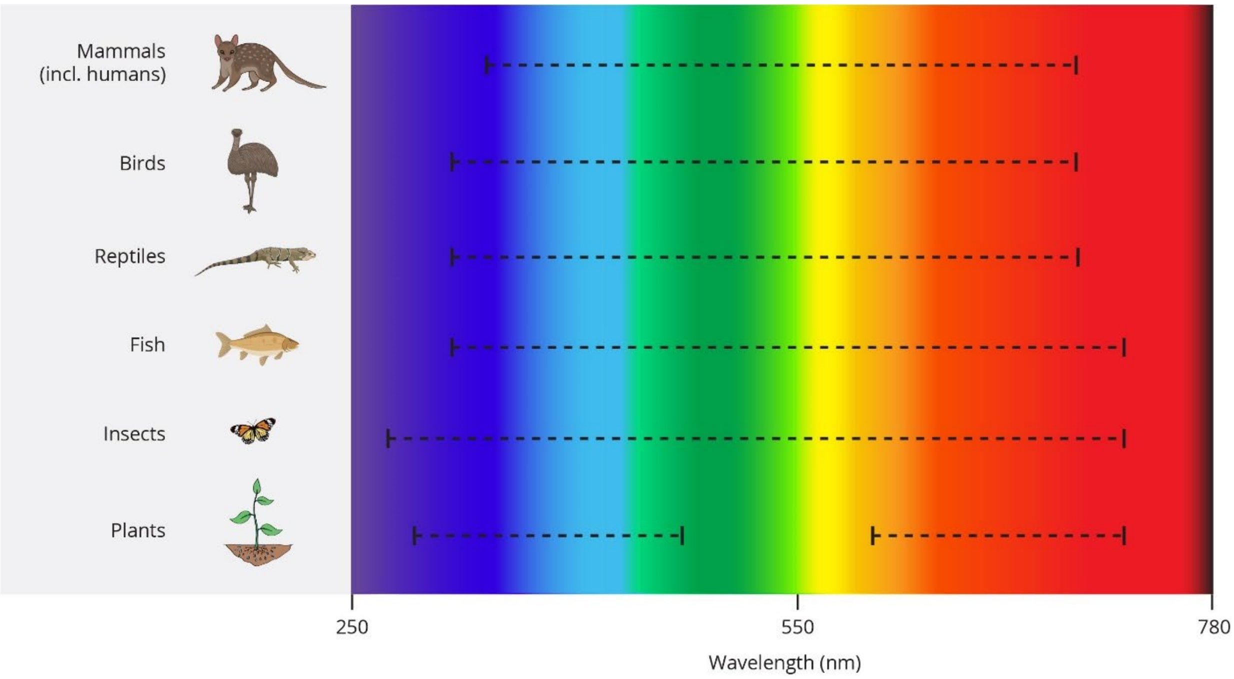
Table 18: Artificial light management options for ecological communities

Management action	Detail	Groups likely to benefit
Avoid adding artificial light to previously unlit areas.	Introduction of artificial light to dark areas is likely to have a greater impact than alterations or additions to areas where artificial lighting already exists.	All ecological communities and species
Avoid fragmenting existing habitat with lighting 'barriers'	Introduction of artificial light into the centre of naturally dark habitat (for example, by lighting a road or path) will create a barrier to movement for many species, and effectively fragment the existing patch into multiple small patches.	All ecological communities and species

Management action	Detail	Groups likely to benefit
Avoid artificial light directly onto habitat patches.	Avoid installing and directing luminaires near habitat patches as this can impose edge effects which reduce the area of intact habitat and add to existing edge effects on key species.	All ecological communities and species
Avoid artificial light directly onto connectivity corridors.	Avoid installing and directing luminaires near corridors or habitat 'stepping stones' connecting important habitat patches. Artificial light can lead to reduced connectivity, fragmentation, degradation and loss of habitat.	All ecological communities and species
Limit infrastructure that increases vehicular and vessel lighting.	Focussed beam lighting from vehicle headlights or vessel floodlights can penetrate hundreds of metres into habitat patches (Gaston et al. 2021), and even brief pulses of light can disrupt biological timing in plants (Borthwick et al. 1952). The construction of roads, carparks, jetties, boat ramps etc in or close to important patches of ecological communities might lead to increased vehicular or vessel traffic. If such facilities must be constructed, consider reducing operations and access at night.	All ecological communities and species
Shield light sources to prevent artificial light spilling onto habitat for algae, grasses, understory plants and ground-dwelling and aquatic animals.	Where algae, grass, understorey plants or ground-dwelling or aquatic animals are present, artificial light should be directed onto only the surface area requiring illumination. Use shielding on lights to prevent light spill outside the target area.	Aquatic flora and fauna; understory plants, grassland plants, ground-dwelling fauna
Shield light source to prevent upward artificial light spill for trees, arboreal animals, bats and birds.	Where trees, arboreal species (including roosting birds and arboreal mammals), nocturnal birds or bats are present, vertical light should be shielded such that it is not visible from the tree canopy above the luminaire installations. Any pole lighting should be at a height lower than tree canopy height without compromising human safety.	Bats, nocturnal and roosting diurnal birds, arboreal mammals, trees
Avoid lighting above or spilling onto water bodies (including from vessels).	Lighting water bodies disrupts the diel vertical migration of zooplankton and their predators, disrupting the natural distribution of aquatic fauna and potentially undermining food webs. Vessel working lights can alter the movement of fauna 200 m below the surface and up to 200 m away from the light source. Lights near waterways can disrupt the emergence and dispersal of flying invertebrates.	All aquatic fauna, flying invertebrates and their predators, and plants pollinated by flying invertebrates
Avoid lighting under wharves, jetties, bridges or other structures over water.	Dark patches in water under structures provide important night-time rest areas for fish, and dark spaces within which sessile aquatic organisms can feed and spawn with reduced predation risk. Dark underpasses also provide important connectivity for bats and riparian animals.	Fish, sessile aquatic organisms, bats, riparian animals
Use the lowest intensity lighting suitable for the objective.	Keep artificial light intensity as low as possible near habitat patches. Artificial light spill into habitat should be kept as low an intensity as practicable. For trees and arboreal species, this includes keeping the intensity of vertical artificial light spill onto vegetation as low as possible.	All ecological communities and species
Prevent indoor lighting reaching the outdoor environment.	Use fixed window screens, blinds or tinting on windows and skylights to contain artificial light inside buildings.	All ecological communities and species
Use luminaires with spectral content appropriate for the species present.	Considerations should be given to avoiding specific wavelengths that are problematic for the species present. In general, this includes avoiding the use of artificial lights rich in blue wavelengths which are easily perceived by	Most species, but especially insects and other invertebrates,

Management action	Detail	Groups likely to benefit
	most animals. Longer wavelength artificial light (such as red light) may have less impact on most insects, but its effects on other animal groups (fish, birds, amphibians, mammals) is highly variable, and it can disrupt seasonal shifts in terrestrial plant physiology via effects on phytochromes. Where this option is progressed, careful post-installation monitoring should be undertaken to assess the success of mitigation.	coral and aquatic primary producers
Implement part-night lighting schemes to reduce the amount of artificial light present throughout the night.	Part-night lighting will increase the available hours of darkness but may not be an effective mitigation measure for some species, such as those active at the beginning of the night, including many flying invertebrates. Where this option is progressed, careful post-installation monitoring should be undertaken to assess the success of mitigation.	Some nocturnal species
Implement motion sensor lighting.	Installing motion sensor lighting may be an effective mitigation measure for certain species. Animals that are too small to trigger sensors may benefit from motion sensor lighting, particularly if it reduces the amount of artificial light present throughout the night. Note however that activated sensor lighting may cause a startle response in some species (particularly those large enough to trigger lighting), and even short lighting pulses can disrupt biological timing in plants (Borthwick et al. 1952). Where this option is progressed, careful post installation monitoring should be undertaken to assess the success of mitigation.	Some nocturnal species
Implement seasonal lighting restrictions to coincide with light-sensitive life history events.	Some species are particularly vulnerable to the effects of artificial light at certain times of year, such as when mating, spawning, migrating or dispersing. Dimming or turning off artificial lighting during these periods may be particularly beneficial. For example, the bridge to Phillip Island in Victoria sits across a major migration route for shearwaters. During peak migration periods all lighting is turned off, and speed limits are reduced to ensure driver safety and reduce shearwater mortality.	Migratory birds, dispersing frogs, spawning corals and fish, nesting and hatching marine turtles and potentially most species
Use physical barriers to prevent light spreading across the landscape.	In habitats with little understorey and few landscape features (such as grasslands), direct artificial light spill can be relatively uninterrupted over hundreds of metres. If lighting must be used, consider adding additional barriers (such as earthworks, fences, or screening plants) to reduce the spread of light. Consideration should be given to the potential for such infrastructure to create additional barriers to movement in the landscape.	Most organisms except those that can see lighting from above the light source (such as bats, birds, arboreal fauna, flying invertebrates)

Figure 42: Indicative light spectral range to which major groups of organisms found in ecological communities can respond to or detect.



In Figure 42, arrows indicate the range of spectra that can be detected by representative taxa. This demonstrates artificial light luminaires of any spectral composition will likely impact or be perceived by some wildlife. Note that most or all species within each faunal group do not have the full range of spectral sensitivity displayed; rather, this figure is intended to reflect the complete range of spectral sensitivities across all species within a given group. For plants, there are two separate perception ranges as plants use light shorter wavelengths for photosynthesis and longer wavelengths for the detection of the light environment. In addition, sensitivity is species-specific and not equal across all parts of the spectrum: humans can see in violet or red light, but spectral sensitivity peaks toward the centre of the spectrum.

Glossary

ACAP is the Agreement on the Conservation of Albatrosses and Petrels.

ALAN is artificial light at night. It refers to artificial light that is visible outdoors at night.

Albedo is the proportion of the incident light or radiation that is reflected by a surface, typically that of a planet or moon.

Artificial light is composed of visible light, ultraviolet (UV) and infrared (IR) radiation derived from an anthropogenic source.

Artificial skyglow is the part of the skyglow that is attributable to human-made sources of light (see also **skyglow**).

Baffle is an opaque or translucent element to shield a light source from direct view, or to prevent light reflecting from a surface like a wall.

Biologically important area (BIA) is a spatially defined area where aggregations of individuals of a species are known to display biologically important behaviour, such as breeding, feeding, resting or migration.

Biologically relevant describes an approach, interpretation or outcome that considers the species to which it refers or factors in biological considerations.

Brightness is the strength of the visual sensation on the naked eye when lit surfaces are viewed.

Bulb means the source of electric light and is a component of a luminaire.

CAMBA is the China–Australia Migratory Bird Agreement.

Candela (cd) (a **photometric term**) is a photometric unit of illumination that measures the amount of light emitted in the range of a (3-dimensional) angular span. Luminance is typically measured in candela per square meter (cd/m^2).

Charge coupled device (CCD) is the sensor technology used in digital cameras. It converts captured light into digital data (images), which can be processed to produce quantifiable data.

CIE is the Commission Internationale de l'Éclairage (International Light Commission), which sets most international lighting standards.

CMS is the Convention on the Conservation of Migratory Species of Wild Animals, also known as the Bonn Convention.

Colour temperature is the perceived colour of a light source, ranging from cool (blue) to warm (yellow), measured in Kelvin (K). A low correlated colour temperature, such as 2,500 K, will have a warm appearance, while a high colour temperature, such as 6,500 K, will appear cold.

Commuting routes are paths that are used regularly by bats or nocturnal mammals to move from a roost to a foraging area (and back) or to move between foraging areas or roosts.

Correlated colour temperature (CCT) is a simplified way to characterise the spectral properties of a light source, correlated to the response of the human eye. Colour temperature is expressed in Kelvin (K).

Cumulative light refers to increased sky brightness due to light emissions from multiple light sources. It is measured as **skyglow**.

Disorientation refers to any species moving in a confused manner – for example, a turtle hatchling circling and unable to find the ocean.

EEZ is the Australian Exclusive Economic Zone.

EIA means environmental impact assessment.

Electromagnetic radiation is a kind of radiation – including visible light, radio waves, gamma rays, and X-rays – in which electric and magnetic fields vary simultaneously.

EPBC Act is the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*.

Fallout refers to birds colliding with human-made structures when disoriented.

Footcandle (fc or ftc) (a **photometric term**) is a unit of light intensity used in America. It is based on the brightness of one candle at a distance of one foot. Measured in lumens per square foot, one ftc is equal to approximately 10.7639 lux. This measure is not appropriate for understanding how animals perceive light.

FMP is the Field Management Program.

Genetic stock is a discrete grouping within a species by genetic relatedness. Management of the species may be undertaken on a genetic stock basis because each genetic stock represents a unique evolutionary history, which if lost cannot be replaced.

Grounding refers to birds failing to take their first flight from the nest or (adults and juveniles) colliding with a structure and being unable to launch back into the air.

Habitat critical to the survival of the species is an area defined in a recovery plan for a listed threatened species that provides for the recovery of the species.

Habitat patch is any discrete area with a definite shape, spatial and configuration used by a species for breeding or obtaining other resources.

Horizontal plane, in relation to a light fitting, means the horizontal plane passing through the centre of the light source (for example, the bulb) of the light fitting.

HPS means high-pressure sodium. An HPS lamp produces a characteristic wavelength near 589 nm.

IAATO is the International Association of Antarctica Tour Operators.

Incident light is the light that hits a surface.

Illuminance is a **photometric** measure of the total luminous flux incident on a surface, per unit area. Illuminance represents how much the incident light illuminates a surface and is wavelength-weighted to correlate with human brightness perception. Illuminance is measured in **lux** (lx) or equivalently in **lumens** per square metre (lm/m^2).

Important habitats are areas that are necessary for an ecologically significant proportion of a listed species to undertake important activities such as foraging, breeding, roosting or dispersal. Important habitats are species-specific and depend on their listing status. They include areas that have been designated as **habitat critical to survival** of a threatened species.

Incandescent bulb means a bulb that provides light by a filament heated by an electric current to a high temperature.

Intensity is the amount of energy or light in a given direction. As a general term, “intensity” can be used as a surrogate for illuminance or luminance, irradiance and all qualities related to light. Intensity per se is not a defined lighting term and should be avoided as soon as specific quantities (including units) need to be used or if specific effects of light are discussed. Intensity can be used in a descriptive way but not as a formal quantity.

Internationally important refers to wetland habitat for migratory shorebirds that supports at least 1% of the individuals in a population of one species or subspecies, or a total abundance of at least 20,000 shorebirds.

IR is infrared radiation. It represents a band of the electromagnetic spectrum with wavelengths from 700 nm to 1 mm.

Irradiance (a **radiometric term**) is a measurement of radiant flux at or on a known surface area, W/m^2. This measure is appropriate for understanding animal perception of light.

IUCN is the International Union for the Conservation of Nature.

JAMBA is the Japan–Australia Migratory Bird Agreement.

Kelvin (K) is the absolute unit for temperature. It is equal in magnitude to 1°C. Kelvin is typically used to describe **correlated colour temperature (CCT)**.

Lamp is a generic term for a source of optical radiation (light), often called a ‘bulb’ or ‘tube’. Examples are incandescent, fluorescent, high-intensity discharge (HID) and low-pressure sodium (LPS) lamps and light-emitting diode (LED) modules and arrays.

LED means light-emitting diode, a semiconductor light source that emits light when current flows through it.

Light fitting (luminaire) means the complete lighting unit. It includes the bulb, reflector (mirror) or refractor (lens), ballast, housing and attached parts.

Light is the radiant energy that is visible to humans and wildlife. Light stimulates receptors in the visual system. Those signals are interpreted by the brain, making things visible. Light may also be detected by other biological mechanisms, such as photosynthesis and other light detection in plants.

Light pollution refers to **artificial light** that alters the natural patterns of light and dark in ecosystems.

Light spill is the light that falls outside the boundaries of the object or area intended to be lit. Spill light serves no purpose and, if directed above the horizontal plane, contributes directly to **artificial skyglow**. Light spill is also called spill light, obtrusive light or light trespass.

Lighting controls are devices used for turning lights on and off, or for dimming.

Listed species are species listed under the **EPBC Act** or under relevant state or territory environment/conservation legislation. Species may be listed as threatened, migratory, or part of a listed threatened ecological community.

Light sources are any mechanisms that emit **light** visible to humans and wildlife. There are many natural light sources—the moon, the sun, stars, lightning, fires, etc. However, for managing the impacts of light, this document primarily refers to **light sources** generated by human activity that are visible outdoors at night. Light sources include street lights, building lights, façade lights, vehicular and vessel lights, gas flares, phosphorescent technologies and light reflected from artificial satellites.

LNG is liquefied natural gas.

LPS means low-pressure sodium. An LPS lamp produces a characteristic wavelength near 589 nm.

Luminaire means the complete lighting unit (fixture or light fitting), consisting of a lamp or lamps and ballast(s) (when applicable), together with the parts designed to distribute the light (reflector, lens, diffuser), to position and protect the lamp(s), and to connect the lamp(s) to the power supply.

Luminous flux is the total light emitted by a bulb in all directions. It is measured in **lumen**.

Lumen (lm) (a **photometric term**) is the unit of **luminous flux**, a measure of the total quantity of visible light emitted by a source per unit of time. This is a **photometric** unit, weighted to the sensitivity of the human eye. If a light source emits one **candela** of luminous intensity uniformly across a solid angle of one steradian, the total **luminous flux** emitted into that angle is 1 lumen.

Luminance (cd/m^2) is a **photometric** measure of the luminous intensity per unit area of light travelling in a given direction, wavelength-weighted to correlate with human brightness perception. Luminance is measured in candela per square metre (cd/m^2). Luminance and **illuminance (lux)** are related, in the sense that luminance is a measure of light emitted from a surface (either because of reflection or because it is a light-emitting surface), and illuminance is a measure of light hitting a surface.

Lux (lx) is a **photometric** measure of illumination of a surface. The difference between lux and **candela** is that lux measures the illumination of a surface, instead of that of an angle. Lux is not an appropriate measure for understanding how animals perceive light.

Magnitudes per square arc second (mag/arcsec^2) (a **radiometric term**) is a term used in astronomy to measure sky brightness within an area of the sky that has an angular area of 1 second by 1 second. It means that the brightness in magnitudes is spread out over a square arcsecond of the sky. Each magnitude lower (numerically) means just over 2.5 times more light is coming from a given patch of sky. A change of 5 magnitude/arcsec^2 means the sky is 100x brighter.

Misorientation occurs when a species moves in the wrong direction, for example, when a turtle hatchling moves toward a light and away from the ocean.

MNES means Matters of National Environmental Significance as defined by the **EPBC Act**. MNES include EPBC Act listed threatened and listed migratory species.

Mounting height is the height of the fitting or bulb above the ground.

Nanometre (nm) is the unit used for wavelength. 1 nm = 10-9 m. = 1 billionths of a metre or 1 millionth of a millimetre. It is used as the unit for the wavelength of optical radiation.

Nationally important refers to wetland habitat for migratory shorebirds that supports at least 0.1% of the flyway population of a single species of migratory shorebird, or 2,000 migratory shorebirds or 15 migratory shorebird species.

Natural skyglow is the part of the **skyglow** that is attributable to radiation from celestial sources and luminescent processes in the earth's upper atmosphere.

Outdoor lighting is the night-time illumination of an area by any form of outside light fitting (luminaire).

Outside light fitting means a light fitting (luminaire) that is attached or fixed outside or on the exterior of a building or structure, whether temporary or permanent.

Photocells are sensors that turn lights on and off in response to natural light levels. Some advanced modes can slowly dim or increase the lighting (see also **smart controls**).

Photometric terms refer to measurements of light that are weighted to the sensitivity of the human eye. They do not include the shortest or the longest wavelengths of the visible spectrum and so are not appropriate for understanding the full extent of how animals perceive light.

Photometry is a subset of radiometry. It is the measurement of light weighted to the sensitivity of the human eye.

Photopic vision refers to vision under well-lit conditions. It allows colour perception.

Phototaxis is the tendency of an organism to move in a certain direction depending on the light distribution at its place. This is equivalent to orientation on the direction of light incident. Positive phototaxis means that movement goes towards increased brightness, resulting in attraction by light. This is the most common case and found in many insects. Negative phototaxis is also possible, resulting in avoidance of light.

Point source means light from an unshielded lamp (that is, directly visible).

Radiance (a **radiometric term**) is a measure of radiant intensity emitted from a unit area of a source, measured in W/m^2.

Radiant flux/power (a **radiometric term**) is the total optical power of a light source, expressed in watts (W). It is the radiant energy emitted, reflected, transmitted or received, per unit time. Sometimes called radiant power, it can also be defined as the rate of flow of radiant energy.

Radiant intensity (a **radiometric term**) is the amount of flux emitted through a known solid angle, W/steradian. It has a directional quantity.

Radiometric terms refer to measurements of light across the entire visible spectrum (not weighted to the human eye). Radiometric terms are appropriate for understanding how animals perceive light.

Radiometry is the measurement of all wavelengths across the entire visible spectrum (not weighted to the human eye).

Reflected light is light that bounces off a surface. Light-coloured surfaces reflect more light than darker coloured surfaces.

ROKAMBA is the Republic of Korea–Australia Migratory Bird Agreement.

Scotopic vision refers to vision during low-light or dark conditions.

Shielded light fittings are light fittings with a physical barrier used to limit or modify the light paths from a luminaire.

Skyglow is the brightness of the night sky caused by the cumulative impact of reflected radiation (usually visible light), scattered from the constituents of the atmosphere in the direction of observation. Skyglow comprises 2 separate components: **natural skyglow** and **artificial skyglow**.

Smart controls are devices to vary the intensity or duration of operation of lighting, such as motion sensors, timers and dimmers used in concert with outdoor lighting equipment.

Spectral power curve provides a representation of the relative presence of each wavelength emitted from a light source.

Steradian (sr) is the solid angle which, having its vertex at the centre of the sphere, cuts off a spherical surface area equal to the square of the radius of the sphere.

Task lighting refers to direct light used for specific activities without illuminating the entire area or object.

Upward light ratio (ULR) or **Upwards Light Output Ratio (ULOR)** is the proportion of the light (flux) from a **luminaire** or installation that is emitted at and above the horizontal, excluding reflected light when the luminaire is mounted in its parallel position. ULR is the upward flux/total flux from the luminaire.

UV means ultraviolet. UV light represents a band of the electromagnetic spectrum with wavelengths from 10 nm to 400 nm.

Visible light transmittance (VLT) is the proportion of light transmitted by window glass. It is recorded as TVw (visible transmittance of the window) and is reported as a dimensionless value between 0 and 1, or 0 and 100%. A low TVw (<30%) indicates that little light is transmitted through the glass, while higher TVw values are associated with increasing light transmittance. While the VLT/TVw rating varies between 0 and 1, most double-glazed windows rate between 0.3 and 0.7, which means that between 30% and 70% of the available light passes through the window.

W/m^2 is a measure of the radiant intensity emitted from a unit area of a source (see **radiance**). This is an appropriate measure for understanding how animals perceive light.

Wattage is the amount of electricity needed to light a bulb. Generally, the higher the wattage, the more lumens are produced. Higher wattage and more lumens give a brighter light.

Wavelength is the distance between the peaks (or the troughs) of light waves. As light travels through space, it creates a wave with evenly spaced peaks and troughs. Ultraviolet and blue light are short-wavelength light, while red and infrared light are long-wavelength light. The energy of light is linked to the wavelength; short wavelength light has much higher energy than long wavelength light. The wavelength of optical radiation is measured in nanometres (humans can see radiation between 380 nm and 780 nm).

Zenith is an imaginary point directly above a specific location on the imaginary celestial sphere.

References

Adams, CA, Fernández-Juricic, E, Bayne, EM & St. Clair, CC 2021. Effects of artificial light on bird movement and distribution: a systematic map. *Environmental Evidence,* vol. 10(1), 37. DOI:10.1186/s13750-021-00246-8

Adden, A 2020, There and back again: the neural basis of migration in the Bogong moth, Lund University, accessed 31 May 2022. Adden, A 2020, There and back again: the neural basis of migration in the Bogong moth, Lund University, accessed 31 May 2022.

Ainley, DG, Podolsky, R, Nur, N, Deforest, L & Spencer, GA 2001, Status and population trends of the Newell's shearwater on Kauai: a model for threatened petrels on urbanized tropical oceanic islands, *Studies in Avian Biology*, vol. 22, pp. 108–123.

Alaasam, VJ, Kernbach, ME, Miller, CR & Ferguson, SM 2021. The Diversity of Photosensitivity and its Implications for Light Pollution. *Integrative and Comparative Biology*, vol. 61(3), 1170–1181. DOI:10.1093/icb/icab156

Algvere, PV, Marshall, J & Seregard, S 2006, Age-related maculopathy and the impact of blue light hazard, *Acta Ophthalmologica Scandinavica*, vol. 84(1), pp. 4–15, DOI: 10.1111/j.1600-0420.2005.00627.x.

Alkon, PU & Mitrani, DS 1988, Influence of season and moonlight on temporal-activity patterns of Indian crested porcupines (Hystrix indica), *Journal of Mammalogy*, vol. 69, pp. 71–80, DOI: 10.2307/1381749.

Allen, JA 1880, Destruction of birds by light-houses, *Bulletin of the Nuttall Ornithological Club*, vol. 5, pp. 131–138.

Amos, JN, Harrisson, KA, Radford, JQ, White, M, Newell, G, Nally, RM, Sunnucks, P, Pavlova, A 2014, Species- and sex-specific connectivity effects of habitat fragmentation in a suite of woodland birds, *Ecology,* vol. 95(6), 1556–1568. DOI:https://DOI.org/10.1890/13-1328.1

Ancillotto, L, Serangeli, MT & Russo, D 2013, Curiosity killed the bat: domestic cats as bat predators, *Mammalian Biology*, vol. 78, pp. 369–373, DOI: 10.1016/j.mambio.2013.01.003.

Androulakis, IP 2021, Circadian rhythms and the HPA axis: a systems view, *WIREs Mechanisms of Disease*, vol. 13, e1518, DOI: 10.1002/wsbm.1518.

Angers, K, Haddad, N, Selmaoui ,B & Thibault, L 2003, Effect of melatonin on total food intake and macronutrient choice in rats, *Physiology & Behavior*, vol. 80, pp. 9–18, DOI: 10.1016/s0031-9384(03)00215-4.

Angilletta Jr, MJ & Angilletta, MJ 2009, Thermal adaptation: a theoretical and empirical synthesis.

Aubrecht, TG, Weil, ZM & Nelson, RJ 2014, Dim light at night interferes with the development of the short-day phenotype and impairs cell-mediated immunity in Siberian hamsters (Phodopus sungorus), *Journal of Experimental Zoology Part A: Ecological Genetics and Physiology*, vol. 321, pp. 450–456, DOI: 10.1002/jez.1877.

Aulsebrook AE, Connelly F, Johnsson RD, Jones TM, Mulder RA, Hall ML, Vyssotski AL, Lesku JA 2020, White and Amber Light at Night Disrupt Sleep Physiology in Birds, *Current Biology,* vol. 30(18), 3657–3663.e3655, DOI: https://DOI.org/10.1016/j.cub.2020.06.085.

Aulsebrook, AE, Lesku, JA, Mulder, RA, Goymann, W, Vyssotski, AL & Jones, TM 2020, Streetlights Disrupt Night-Time Sleep in Urban Black Swans, *Frontiers in Ecology and Evolution,* vol. 8(131), DOI:10.3389/fevo.2020.00131

Australasian Bat Society 2018, ABS submission to the parliamentary inquiry into Australia's fauna extinction crisis.

Ayalon, I, de Barros Marangoni, LF, Benichou, JIC, Avisar, D & Levy, O 2019, Red Sea corals under Artificial Light Pollution at Night (ALAN) undergo oxidative stress and photosynthetic impairment, *Global Change Biology,* vol. 25(12), 4194–4207, DOI: https://DOI.org/10.1111/gcb.14795.

Ayalon I, Rosenberg Y, Benichou JI, Campos CL, Sayco SL, Nada MA, Baquiran JI, Ligson CA, Avisar D, Conaco C, Kuechly HU 2021, Coral Gametogenesis Collapse under Artificial Light Pollution, *Current Biology,* vol. 31(2), 413–419.e413, DOI: https://DOI.org/10.1016/j.cub.2020.10.039.

Azam, C, Kerbiriou, C, Vernet, A, Julien, J-F, Bas, Y, Plichard, L, Maratrat, J & Le Viol, I 2015, Is part-night lighting an effective measure to limit the impacts of artificial lighting on bats? *Global Change Biology*, vol. 21, pp. 4333–4341, DOI: 10.1111/gcb.13036.

Azam, C, Le Viol, I, Bas, Y, Zissis, G, Vernet, A, Julien, J-F & Kerbiriou, C 2018, Evidence for distance and illuminance thresholds in the effects of artificial lighting on bat activity, *Landscape and Urban Planning*, vol. 175, pp. 123–135, DOI: 10.1016/j.landurbplan.2018.02.011.

Baker, J 1990, Toad aggregations under street lamps, *British Herpetological Society Bulletin,* No. 31, pp. 26–27, Retrieved from https://www.thebhs.org/publications/the-herpetological-bulletin/issue-number-31-spring-1990/2366-hb031-04/file.

Bamford, M, Watkins, D, Bancroft, W, Tischler, G & Wahl, J 2008, *Migratory shorebirds of the East Asian–Australasian flyway: population estimates and internationally important sites*, Wetlands International – Oceania, Canberra.

Barber-Meyer, SM 2007, Photopollution impacts on the nocturnal behaviour of the sugar glider (Petaurus breviceps), *Pacific Conservation Biology*, vol. 13, pp. 171–176, DOI: 10.1071/PC070171.

Barentine, JC 2019, Methods for assessment and monitoring of light pollution around ecologically sensitive sites, *Journal of Imaging*, vol. 5(54), e5050054, DOI: 10.3390/jimaging5050054.

Bartness, T & Goldman, B 1989, Mammalian pineal melatonin: a clock for all seasons, *Experientia*, vol. 45, pp. 939–945, DOI: 10.1007/BF01953051.

Battey, NH 2000, Aspects of seasonality, *Journal of Experimental Botany,* vol. 51(352), 1769–1780, DOI: 10.1093/jexbot/51.352.1769.

Battley, PF, Warnock, N, Tibbitts, TL, Gill, RE, Piersma, T, Hassell, CJ, Douglas, DC, Mulcahy, DM, Gartrell, BD, Schuckard, R, Melville, DS & Riegen, AC 2012, Contrasting extreme long-distance migration patterns in bar-tailed godwits Limosa lapponica, *Journal of Avian Biology*, vol. 43(1), pp. 21–32, DOI: 10.1111/j.1600-048X.2011.05473.x.

Bedrosian, TA, Aubrecht, TG, Kaugars, KE, Weil, ZM & Nelson, RJ 2013a, Artificial light at night alters delayed-type hypersensitivity reaction in response to acute stress in Siberian hamsters, *Brain, Behavior, and Immunity*, vol. 34, pp. 39–42, DOI: 10.1016/j.bbi.2013.05.009.

Bedrosian, TA, Fonken, LK, Walton, JC & Nelson, RJ 2011, Chronic exposure to dim light at night suppresses immune responses in Siberian hamsters, *Biology Letters*, vol. 7, pp. 468–471, DOI: 10.1098/rsbl.2010.1108.

Bedrosian, TA, Vaughn, CA, Galan, A, Daye, G, Weil, ZM & Nelson, RJ 2013b, Nocturnal light exposure impairs affective responses in a wavelength-dependent manner, *Journal of Neuroscience*, vol. 33, pp. 13081–13087, DOI: 10.1523/JNEUROSCI.5734-12.2013.

Beier, P 2006, Effects of artificial night lighting on terrestrial mammals, in C Rich & T Longcore (eds), Ecological consequences of artificial night lighting, Island Press, Washington DC, pp. 19–42, accessed 31 May 2022.

Benenson, W, Harris, JW, Stöcker, H & Lutz, H (eds) 2006, *Handbook of physics*, Springer Science & Business Media.

Bennie, J, Davies, TW, Cruse, D, Bell, F & Gaston, KJ 2018, Artificial light at night alters grassland vegetation species composition and phenology, *Journal of Applied Ecology,* vol. 55, 442–450, DOI: 10.1111/1365-2664.12927.

Bennie, J, Davies, TW, Cruse, D & Gaston, J 2016, Ecological effects of artificial light at night on wild plants, *Journal of Ecology*, vol. 104(3), pp. 611–620, DOI: 10.1111/1365-2745.12551.

Bennie, J, Davies, TW, Cruse, D, Inger, R & Gaston, KJ 2015, Cascading effects of artificial light at night: resource-mediated control of herbivores in a grassland ecosystem, *Philosophical Transactions of the Royal Society B,* vol. 370, pp.1–9, DOI: 10.1098/rstb.2014.0131.

Benson, JF, Mahoney, PJ, Sikich, JA, Serieys, LEK, Pollinger, JP, Ernest, HB & Riley, SPD 2016, Interactions between demography, genetics, and landscape connectivity increase extinction probability for a small population of large carnivores in a major metropolitan area, *Proceedings of the Royal Society B: Biological Sciences,* vol. 283(1837), 20160957, DOI: 10.1098/rspb.2016.095.

Berg, KS, Brumfield, RT & Apanius, V 2006, Phylogenetic and ecological determinants of the neotropical dawn chorus, *Proceedings of the Royal Society B: Biological Sciences,* vol. 273(1589), pp. 999–1005, DOI: 10.1098/rspb.2005.3410.

Berg, R 1975, Myrmecochorous plants in Australia and their dispersal by ants, *Australian Journal of Botany,* vol. 23(3), pp. 475–508, DOI: https://DOI.org/10.1071/BT9750475.

Berge, J, Geoffroy, M, Daase, M, Cottier, F, Priou, P, Cohen, JH, Johnsen, G, McKee, D, Kostakis, I, Renaud, PE, Vogedes, D, Anderson, P, Last, KS, Gauthier, S, 2020, Artificial light during the polar night disrupts Arctic fish and zooplankton behaviour down to 200 m depth, *Communications Biology,* vol. 3(1), 102, DOI: 10.1038/s42003-020-0807-6.

Berson, DM 2007, Phototransduction in ganglion-cell photoreceptors, *Pflügers Archiv*, vol. 454(5), pp. 849–855. DOI: 10.1007/s00424-007-0242-2.

Bhardwaj, M, Soanes, K, Lahoz-Monfort, JJ, Lumsden, LF & van der Ree, R, 2020, Artificial lighting reduces the effectiveness of wildlife-crossing structures for insectivorous bats, *Journal of Environmental Management,* vol. 262(110313), DOI: https://DOI.org/10.1016/j.jenvman.2020.110313.

Bird, BL, Branch, LC & Miller, DL 2004, Effects of coastal lighting on foraging behaviour on beach mice, *Conservation Biology*, vol. 18, pp. 1435–1439, DOI: 10.1111/j.1523-1739.2004.00349.x.

Bishop, MJ, Mayer-Pinto, M, Airoldi, L, Firth, LB, Morris, RL, Loke, LH, Hawkins SJ, Naylor, LA, Coleman, RA, Chee, SY, Dafforn, KA 2017, Effects of ocean sprawl on ecological connectivity: impacts and solutions, *Journal of Experimental Marine Biology and Ecology,* vol. 492, pp. 7–30, DOI: https://DOI.org/10.1016/j.jembe.2017.01.021.

Black, A 2005, Light induced seabird mortality on vessels operating in the Southern Ocean: incidents and mitigation measures, *Antarctic Science*, vol. 17, pp. 67–68, DOI: 10.1017/S0954102005002439.

Blaho, M, Herczeg, T, Kriska, G, Egri, A, Szaz, D, Farkas, A, Tarjanyi, N, Czinke, L, Barta, A, Horvath, G 2014, Unexpected Attraction of Polarotactic Water-Leaving Insects to Matt Black Car Surfaces: Mattness of Paintwork Cannot Eliminate the Polarized Light Pollution of Black Cars, *PLoS ONE,* vol. 9(7), DOI: 10.1371/journal.pone.0103339

Bliss-Ketchum, LL, De Rivera, CE, Turner, BC & Weisbaum, DM 2016, The effect of artificial light on wildlife use of a passage structure, *Biological Conservation*, vol. 199, pp. 25–28, DOI: 10.1016/j.biocon.2016.04.025.

Boldogh, S, Dobrosi, D & Samu, P 2007, The effects of the illumination of buildings on house-dwelling bats and its conservation consequences, *Acta Chiropterologica*, vol. 9, pp. 527–534, DOI: 10.3161/1733-5329(2007)9[527:TEOTIO]2.0.CO;2.

Bolton, D, Mayer-Pinto, M, Clark, GF, Dafforn, KA, Brassil, WA, Becker, A & Johnston, EL 2017, Coastal urban lighting has ecological consequences for multiple trophic levels under the sea, *Science of the Total Environment*, vol. 576, pp. 1–9, DOI: 10.1016/j.scitotenv.2016.10.037.

Boom, MP, Spoelstra, K, Biere, A, Knop, E & Visser, ME, 2020 Pollination and fruit infestation under artificial light at night:light colour matters, *Scientific Reports*, vol. 10(1), https://DOI.org/10.1038/s41598-020-75471-1.

Borthwick, HA, Hendricks, SB, Parker, MW, Toole, EH & Toole, VK 1952, A Reversible Photoreaction Controlling Seed Germination, *Proceedings of the National Academy of Sciences,* vol. 38(8), 662–666, DOI: 10.1073/pnas.38.8.662.

Botha, LM, Jones, TM & Hopkins, GR 2017, Effects of lifetime exposure to artificial light at night on cricket (Teleogryllus commodus) courtship and mating behaviour, *Animal Behaviour,* vol. 129, pp. 181–188, DOI: https://DOI.org/10.1016/j.anbehav.2017.05.020.

Bourne, WRP 1979, Birds and gas flares, *Marine Pollution Bulletin*, vol. 10, pp. 124–125.

Bowmaker, JK & Martin, GR 1985, Visual pigments and oil droplets in the penguin, Spheniscus humboldti, *Journal of Comparative Physiology A*, vol. 156(1), pp. 71–77.

Bowmaker, JK 1995, The visual pigments of fish, *Progress in Retinal and Eye Research,* vol. 15(1), pp. 1–31, DOI: https://DOI.org/10.1016/1350-9462(95)00001-1

Bowmaker, JK, Heath, LA, Wilkie, SE & Hunt, DM 1997, Visual pigments and oil droplets from six classes of photoreceptor in the retinas of birds, *Vision Research*, vol. 37, pp. 2183–2194, DOI: 10.1016/S0042-6989(97)00026-6.

Boyes, DH, Evans, DM, Fox, R, Parsons, MS & Pocock, MJO 2021, Is light pollution driving moth population declines? A review of causal mechanisms across the life cycle, *Insect Conservation and Diversity*, vol. 14, pp. 167–187, DOI: 10.1111/icad.12447.

Bradford, M, Venz, M, Bell, KL, Hogan, L, Smith, GC, Eby, P, Eyre, TJ, McKeown, A, Vanderduys, E, MacDonald, S, Westcott, D 2022, The diet of a specialist nectarivore in Australia: The little red flying-fox (Pteropus scapulatus, Pteropodidae), *Austral Ecology,* vol. 47(3), pp. 619–628, DOI: https://DOI.org/10.1111/aec.13143.

Bradford, MG & Westcott, DA 2010, Consequences of southern cassowary (Casuarius casuarius, L.) gut passage and deposition pattern on the germination of rainforest seeds, *Austral Ecology,* vol. 35(3), pp. 325–333, DOI: https://DOI.org/10.1111/j.1442-9993.2009.02041.x.

Brigham, R, Gutsell, R, Geiser, F & Wiacek, R 1999, Foraging Behaviour in Relation to the Lunar Cycle by Australian Owlet-nightjars Aegotheles cristatus, *Emu, 99*, DOI: 10.1071/MU99031.

Briscoe, AD & Chittka, L 2001, The Evolution of Colour Vision in Insects, *Annual Review of Entomology,* vol. 46, pp. 471–510, DOI: 10.1146/annurev.ento.46.1.471.

Bronson, FH 1985, Mammalian reproduction: an ecological perspective, *Biology of Reproduction*, vol. 32, pp. 1–26, DOI: 10.1095/biolreprod32.1.1.

Bruni, A, Mennill, DJ & Foote, JR 2014, Dawn chorus start time variation in a temperate bird community: relationships with seasonality, weather, and ambient light, *Journal of Ornithology,* vol. 155(4), pp. 877–890, DOI: 10.1007/s10336-014-1071-7.

Brüning, A, Hölker, F, Franke, S, Kleiner, W & Kloas, W 2016, Impact of different colours of artificial light at night on melatonin rhythm and gene expression of gonadotropins in European perch, *Science of The Total Environment,* vol. 543, pp. 214–222, DOI: https://DOI.org/10.1016/j.scitotenv.2015.11.023.

Buchanan, BW 1998, Low-Illumination Prey Detection by Squirrel Treefrogs, *Journal of Herpetology,* vol. 32(2), pp. 270–274, DOI: 10.2307/1565308

Buchanan, BW 2006, Observed and potential effects of artificial night lighting on anuran amphibians, In C, Rich & T, Longcore (Eds.), *Ecological consequences of artificial night lighting*, pp. 192–220, Washington: Island Press.

Burd, M, Stayton, CT, Shrestha, M & Dyer, AG 2014, Distinctive convergence in Australian floral colours seen through the eyes of Australian birds, *Proceedings of the Royal Society B: Biological Sciences, 281*(1781), 20132862, DOI: 10.1098/rspb.2013.2862

Burgoyne, J, Crepeau, R, Jensen, J, Smith, H, Baker, G & Leavitt, SD 2021, Lampenflora in a Show Cave in the Great Basin Is Distinct from Communities on Naturally Lit Rock Surfaces in Nearby Wild Caves, *Microorganisms, 9*(6), 1188, Retrieved from https://www.mdpi.com/2076-2607/9/6/1188

Burke, CM, Davoren, GK, Montevecchi, WA & Wiese, FK 2005, 'Seasonal and spatial trends of marine birds along offshore support vessel transects and at oil platforms on the Grand Banks', in

SL Armsworthy, PJ Cranford & K Lee (eds), *Offshore oil and gas environmental effects monitoring: approaches and technologies*, Battelle Press, Columbus, Ohio, pp. 587–614.

Cabrera-Cruz, SA, Smolinsky, JA & Buler, JJ 2018, Light pollution is greatest within migration passage areas for nocturnally-migrating birds around the world, *Nature Scientific Reports*, vol. 8, e3261, DOI: 10.1038/s41598-018-21577-6.

Campbell, C 1994, 'The effects of flash photography on nesting behavior of green turtles (Chelonia mydas) at Tortuguero, Costa Rica', in *Proceedings of the Fourteenth Annual Symposium on Sea Turtle Biology and Conservation, 1–5 March 1994, Hilton Head, South Carolina*, NOAA Technical Memorandum NMFS-SEFSC, 351.

Campos, SMC 2017, The impact of artificial lighting on nature, paper presented at 6th SENAC Meeting of Integrated Knowledge, São Paulo, 18 May.

Canário, F, Hespanhol Leitão, A & Tomé, R 2012, Predation Attempts by Short-eared and Long-eared Owls on Migrating Songbirds Attracted to Artificial Lights, *Journal of Raptor Research,* vol. 46(2), pp. 232–234, Retrieved from https://DOI.org/10.3356/JRR-11-15.1.

Cannell, BL & Cullen, JM 1998, The foraging behaviour of little penguins Eudyptula minor at different light levels, *Ibis*, vol. 140(3), pp. 467–471, DOI: 10.1111/j.1474-919x.1998.tb04608.x.

Caplat, P, Edelaar, P, Dudaniec, RY, Green, A J, Okamura, B, Cote, J, Ekroos, J, Jonsson, PR, Löndahl, J, Tesson, SV, Petit, EJ 2016, Looking beyond the mountain: dispersal barriers in a changing world, *Frontiers in Ecology and the Environment,* vol. 14(5), pp. 261–268, DOI: https://DOI.org/10.1002/fee.1280.

Capuska, GEM, Huynen, L, Lambert, D & Raubenheimer, D 2011, UVS is rare in seabirds, *Vision Research*, vol. 51(12), pp. 1333–1337, DOI: 10.1016/j.visres.2011.04.008.

Carter, K & Goldizen, AW 2003, Habitat choice and vigilance behaviour of brush-tailed rock-wallabies (Petrogale penicillata) within their nocturnal foraging ranges, *Wildlife Research*, vol. 30, pp. 355–364, DOI: 10.1071/WR02095.

Cathey, HM & Campbell, LE 1975, Security lighting and its impact on the landscape, *Journal of Arboriculture,* vol. 1(10), pp. 181–187.

Chevron Australia 2018, Gorgon Gas Development and Jansz Feed Gas Pipeline Long-term Marine Turtle Management Plan, accessed 31 May 2022.

Churchill, S 2008, *Australian bats*, Allen & Unwin, Crows Nest, NSW.

Cianchetti-Benedetti, M, Becciu, P, Massa, B & Dell'Omo, G 2018, Conflicts between touristic recreational activities and breeding shearwaters: short-term effect of artificial light and sound on chick weight, *European Journal of Wildlife Research*, vol. 64, p. 19, DOI: 10.1007/s10344-018-1178-x.

Cieraad, E, Strange, E, Flink, M, Schrama, M & Spoelstra, K 2023, Artificial light at night affects plant–herbivore interactions, *Journal of Applied Ecology*, vol. 60, pp. 400–410, DOI: https://DOI.org/10.1111/1365-2664.14336.

Cisewski, B, Strass, VH, Rhein, M & Krägefsky, S 2010, Seasonal variation of diel vertical migration of zooplankton from ADCP backscatter time series data in the Lazarev Sea, Antarctica, *Deep Sea Research Part I: Oceanographic Research Papers,* vol. 57(1), pp. 78–94, DOI: https://DOI.org/10.1016/j.dsr.2009.10.005.

Cissé, YM, Russart, K & Nelson, RJ 2020, Exposure to dim light at night prior to conception attenuates offspring innate immune responses, *PloS One,* vol. 15, e0231140, DOI: 10.1371/journal.pone.0231140.

Clarke, JA 1983, Moonlight's influence on predator/prey interactions between short-eared owls (Asio flammeus) and deermice (Peromyscus maniculatus), *Behavioral Ecology and Sociobiology*, vol. 13, pp. 205–209, DOI: 10.1007/BF00299924.

Clarke, MF & Schedvin, N 1999, Removal of bell miners Manorina melanophrys from Eucalyptus radiata forest and its effect on avian diversity, psyllids and tree health, *Biological Conservation,* vol. 88, pp. 111 – 120.

Coble, AP, Autio, A, Cavaleri, MA, Binkley, D & Ryan, MG 2014, Converging patterns of vertical variability in leaf morphology and nitrogen across seven Eucalyptus plantations in Brazil and Hawaii, USA, *Trees,* vol.28, pp. 1–15, DOI: 10.1007/s00468-013-0925-6.

Cochran, WW, Mouritsen H & Wikelski, M 2004, Migrating Songbirds Recalibrate Their Magnetic Compass Daily from Twilight Cues, *Science,* vol. 304(5669), pp. 405–408, DOI: 10.1126/science.1095844.

Colwell, MA 2010, *Shorebird ecology, conservation, and management*, University of California Press, Berkeley.

Commonwealth of Australia 2010, Survey guidelines for Australia's threatened birds: guidelines for detecting birds listed as threatened under the Environment Protection and Biodiversity Conservation Act 1999, Australian Government, Canberra.

Commonwealth of Australia 2013, Matters of National Environmental Significance: Significant impact guidelines 1.1 Environment Protection and Biodiversity Conservation Act 1999, Australian Government, Canberra, accessed 31 May 2022.

Commonwealth of Australia 2015a, EPBC Act Policy Statement 3.21: Industry guidelines for avoiding, assessing and mitigating impacts on EPBC Act listed migratory shorebird species, Australian Government, Canberra, accessed 31 May 2022.

Commonwealth of Australia 2015b, Wildlife Conservation Plan for Migratory Shorebirds, Australian Government, Canberra, accessed 31 May 2022.

Commonwealth of Australia 2016a, National Recovery Plan for the Mountain Pygmy-possum Burramys parvus, prepared by the Victorian Department of Environment, Land, Water and Planning, Australian Government Department of the Environment, Canberra, accessed 31 May 2022.

Commonwealth of Australia 2016b, Conservation advice: Macroderma gigas (ghost bat), Department of the Environment, Canberra, accessed 31 May 2022.

Commonwealth of Australia 2016c, Conservation advice: Rhinonicteris aurantia (Pilbara form) Pilbara Leaf-nosed Bat, Department of the Environment, Canberra, accessed 31 May 2022.

Commonwealth of Australia 2016d, Conservation advice: Saccolaimus saccolaimus nudicluniatus (bare-rumped sheathtail bat), Department of the Environment, Canberra, accessed 31 May 2022.

Commonwealth of Australia 2017, The Recovery Plan for Marine Turtles in Australia, Department of the Environment and Energy, Canberra, accessed 31 May 2022.

Conklin, JR & Colwell, MA 2007, Diurnal and nocturnal roost site fidelity of dunlin (Calidris alpina pacifica) at Humboldt Bay, California, *The Auk*, vol. 124(2), pp. 677–689, DOI: 10.1093/auk/124.2.677.

Conole, LE & Kirkpatrick, JB 2011, Functional and spatial differentiation of urban bird assemblages at the landscape scale, *Landscape and Urban Planning,* vol. 100(1), pp. 11–23, DOI: https://DOI.org/10.1016/j.landurbplan.2010.11.007.

Cosgrove, AJ, McWhorter, TJ & Maron, M 2018, Consequences of impediments to animal movements at different scales: A conceptual framework and review, *Diversity and Distributions,* vol. 24(4), pp. 448–459, DOI: https://DOI.org/10.1111/ddi.12699.

Cresswell, W 1994, Flocking is an effective anti-predation strategy in redshanks, Tringa tetanus, *Animal Behaviour*, vol. 47(2), pp. 433–442, DOI: 10.1006/anbe.1994.1057.

Cushman, KE, Tibbitts, TW, Sharkey, TD & Wise, RR 1995, Constant-light Injury of Potato: Temporal and Spatial Patterns of Carbon Dioxide Assimilation, Starch Content, Chloroplast Integrity, and Necrotic Lesions, *Journal of the American Society for Horticultural Science,* vol. 120(6), pp. 1032–1040, DOI: 10.21273/JASHS.120.6.1032.

Czarnecka, M, Kobak, J, Grubisic, M & Kakareko, T 2021, Disruptive effect of artificial light at night on leaf litter consumption, growth and activity of freshwater shredders, *Science of The Total Environment,* vol. 786, DOI: https://DOI.org/10.1016/j.scitotenv.2021.147407.

Da Silva, A, Samplonius, JM, Schlicht, E, Valcu, M & Kempenaers, B 2014, Artificial night lighting rather than traffic noise affects the daily timing of dawn and dusk singing in common European songbirds, *Behavioral Ecology,* vol. 25(5), pp. 1037–1047, DOI: 10.1093/beheco/aru103.

Dacke, M, Nilsson, D-E, Scholtz, CH, Byrne, M & Warrant, EJ 2003, Insect orientation to polarized moonlight, *Nature,* vol. 424(6944), pp. 33–33, DOI: 10.1038/424033a.

Dadwal, N & Bhatt, D 2017, Influence of astronomical (lunar)/meteorological factors on the onset of dawn song chorus in the Pied Bush Chat (Saxicola caprata), *Current Science,* vol. 113(2), pp. 329–334, Retrieved from http://www.jstor.org/stable/26293868.

Daly, M, Behrends, PR, Wilson, MI & Jacobs, LF 1992, Behavioural modulation of predation risk: moonlight avoidance and crepuscular compensation in a nocturnal desert rodent, Dipodomys merriami, *Animal Behaviour*, vol. 44, pp. 1–9, DOI: 10.1016/S0003-3472(05)80748-1.

Dananay, KL & Benard, MF 2018, Artificial light at night decreases metamorphic duration and juvenile growth in a widespread amphibian, *Proceedings of the Royal Society B: Biological Sciences,* vol. 285(1882), DOI: 10.1098/rspb.2018.0367.

Daoud-Opit, S & Jones, DN 2016, Guided by the light: Roost choice and behaviour of urban Rainbow Lorikeets (Trichoglossus haematodus), *European Journal of Ecology,* vol. 2(1), pp. 72–80, DOI: 10.1515/eje-2016-0008.

Davies, GTO, Kirkpatrick, JB, Cameron, EZ, Carver, S & Johnson, CN 2019, Ecosystem engineering by digging mammals: effects on soil fertility and condition in Tasmanian temperate woodland, *Royal Society Open Science,* vol. 6(1), DOI: 10.1098/rsos.180621.

Davies, TW, Bennie, J, Cruse, D, Blumgart, D, Inger, R & Gaston, KJ 2017, Multiple night-time light-emitting diode lighting strategies impact grassland invertebrate assemblages, *Global Change Biology,* vol. 23, pp. 2641–2648, DOI: 10.1111/gcb.13615.

Davies, T, Bennie, J & Gaston, K 2012, Street lighting changes the composition of invertebrate communities, *Biology Letters*, vol. 8, pp. 764–767, DOI: 10.1098/rsbl.2012.0216, accessed 31 May 2022.

Davies, TW, Bennie, J, Inger, R, Hempel de Ibarra, N, Gaston, KJ 2013, Artificial light pollution: are shifting spectral signatures changing the balance of species interactions? *Global Change Biology,* vol. 19, pp. 1417–1423, DOI: 10.1111/gcb.12166.

Davies, TW, Coleman, M, Griffith, KM & Jenkins, SR 2015, Night-time lighting alters the composition of marine epifaunal communities, *Biology Letters,* vol. 11(4), DOI: 10.1098/rsbl.2015.0080.

Davies, TW, Duffy, JP, Bennie, J & Gaston, KJ 2014, The nature, extent, and ecological implications of marine light pollution, *Frontiers in Ecology and the Environment,* vol. 12(6), pp. 347–355, DOI: https://DOI.org/10.1890/130281.

Davies, TW, McKee, D, Fishwick, J, Tidau, S, Smyth, T 2020, Biologically important artificial light at night on the seafloor, *Scientific Reports,* vol. 10(1), DOI: 10.1038/s41598-020-69461-6.

Dawson, A, King, VM, Bentley, GE & Ball, GF 2001, Photoperiodic Control of Seasonality in Birds, *Journal of Biological Rhythms,* vol. 16(4), pp. 365–380, DOI: 10.1177/074873001129002079.

Deakin, JE, Waters, PD & Graves, JA 2010, *Marsupial genetics and genomics*, Springer, New York.

Deichmann, JL, Ampudia Gatty, C, Andía Navarro, JM, Alonso, A, Linares-Palomino, R, Longcore, T 2021, Reducing the blue spectrum of artificial light at night minimises insect attraction in a tropical lowland forest, *Insect Conservation and Diversity,* vol. 14(2), pp. 247–259, DOI: https://DOI.org/10.1111/icad.12479.

de Jong, M, Ouyang, JQ, Da Silva, A, van Grunsven, RHA, Kempenaers, B, Visser, ME & Spoelstra, K 2015, Effects of nocturnal illumination on life-history decisions and fitness in two wild songbird species, *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 370, 20140128, DOI: 10.1098%2Frstb.2014.0128.

Demers, DA, Doraisa, M, Wien, CH & Gosselin, A, 1998, Effects of supplemental light duration on greenhouse tomato (Lycopersicon esculentum Mill.) plants and fruit yields, *Scientia Horticulturae,* vol. 74, pp. 295–306, DOI: 10.1016/S0304-4238(98)00097-1.

de Molenaar, JG, Henkens, RJHG, ter Braak, C, van Duyne, C, Hoefsloot, G & Jonkers, DA 2003, Road illumination and nature, IV: effects of road lights on the spatial behaviour of mammals, Ministry of Transport, Public Works and Water Management of the Netherlands, Wageningen, accessed 31 May 2022.

Decoursey, PJ 1986, Light-sampling behavior in photoentrainment of a rodent circadian rhythm, *Journal of Comparative Physiology A*, vol. 159, pp. 161–169, DOI: 10.1007/BF00612299.

den Outer, P, Lolkema, D, Haaima, M, Hoff, RVD, Spoelstra, H & Schmidt, W 2011, Intercomparisons of nine sky brightness detectors, *Sensors*, vol. 11(10), 9603, DOI: 10.3390/s111009603.

Depledge, MH, Godard-Codding, CAJ & Bowen, RE 2010, Light pollution in the sea, *Marine Pollution Bulletin*, vol. 60(9), pp. 1383–1385, DOI: 10.1016/j.marpolbul.2010.08.002.

Deppe, L, Rowley, O, Rowe, LK, Shi, N, McArthur, N, Gooday, O & Goldstien, SJ 2017, Investigation of fallout events in Hutton's shearwaters (Puffinus huttoni) associated with artificial lighting, *Notornis*, vol. 64(4), pp. 181–191, accessed 31 May 2022.

Desouhant, E, Gomes, E, Mondy, N & Amat, I, 2019, Mechanistic, ecological, and evolutionary consequences of artificial light at night for insects: review and prospective, *Entomologia Experimentalis et Applicata,* vol. 167, pp. 37–58, DOI: 10.1111/eea.12754.

Diamantopoulou, C, Christoforou, E, Dominoni, DM, Kaiserli, E, Czyzewski, J, Mirzai, N & Spatharis, S 2021, Wavelength-dependent effects of artificial light at night on phytoplankton growth and community structure, *Proceedings of the Royal Society B: Biological Sciences,* vol. 288(1953), DOI: 10.1098/rspb.2021.0525.

Dias, KS, Dosso, ES, Hall, AS, Schuch, AP & Tozetti, AM, 2019, Ecological light pollution affects anuran calling season, daily calling period, and sensitivity to light in natural Brazilian wetlands, *The Science of Nature,* vol. 106(7), 46, DOI: 10.1007/s00114-019-1640-y.

Dias, MP, Granadeiro, JP, Lecoq, M, Santos, CD & Palmeirim, JM 2006, Distance to high-tide roosts constrains the use of foraging areas by dunlins: implications for the management of estuarine wetlands, *Biological Conservation*, vol. 131, pp. 446–452, DOI: 10.1016/j.biocon.2006.02.020.

Dickerson, AL, Hall, ML & Jones, TM 2020, The effect of variation in moonlight on nocturnal song of a diurnal bird species, *Behavioral Ecology and Sociobiology,* vol. 74(9), DOI: 10.1007/s00265-020-02888-z.

Dickerson, AL, Hall, ML & Jones, TM 2022, The effect of natural and artificial light at night on nocturnal song in the diurnal willie wagtail, *Science of The Total Environment,* vol. 808, DOI: https://DOI.org/10.1016/j.scitotenv.2021.151986.

Dimovski, AM & Robert, KA 2018, Artificial light pollution: shifting spectral wavelengths to mitigate physiological and health consequences in a nocturnal marsupial mammal, *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, vol. 329, pp. 497–505, DOI: 10.1002/jez.2163.

Dominoni, D, Quetting, M & Partecke, J 2013, Artificial light at night advances avian reproductive physiology, *Proceedings of the Royal Society B: Biological Sciences,* vol. 280(1756), DOI: 10.1098/rspb.2012.3017.

Dominoni, DM, Kjellberg Jensen, J, de Jong, M, Visser, ME & Spoelstra, K 2020, Artificial light at night, in interaction with spring temperature, modulates timing of reproduction in a passerine bird, *Ecological Applications,* vol. 30(3), e02062, DOI: https://DOI.org/10.1002/eap.2062.

Donners, M, van Grunsven, RHA, Groenendijk, D, van Langevelde, F, Bikker, JW, Longcore, T & Veenendaal, E 2018, Colors of attraction: Modeling insect flight to light behavior, *Journal of Experimental Zoology,* vol. 329, pp. 434–440, DOI: 10.1002/jez.2188.

Douglas, AE, 2006, Phloem-sap feeding by animals: problems and solutions, *Journal of Experimental Botany,* vol. 57(4), pp. 747–754.

Drewitt, EJA & Dixon, N 2008, Diet and prey selection of urban-dwelling peregrine falcons in southwest England, *British Birds,* vol. 101(2), pp. 58–67, Retrieved from https://britishbirds.co.uk/wp-content/uploads/article_files/V101/V101_N02/V101_N2_2_11.pdf.

Duriscoe, DM 2013, Measuring anthropogenic skyglow using a natural sky brightness model, *Publications of the Astronomical Society of the Pacific*, vol. 125, pp. 1370–1382, DOI: 10.1086/673888.

Durrant, J, Green, MP & Jones, TM 2020, Dim artificial light at night reduces the cellular immune response of the black field cricket, Teleogryllus commodus, *Insect Science,* vol. 27(3), pp. 571–582, DOI: https://DOI.org/10.1111/1744-7917.12665.

Durrant, J, Michaelides, E, B, Rupasinghe, T, Tull, D, Green, M, P & Jones, T, M, 2015, Constant illumination reduces circulating melatonin and impairs immune function in the cricket Teleogryllus commodus, *PeerJ,* vol. 3:e1075, pp. 1–23, DOI: https://DOI.org/10.7717/peerj.1075.

Dwyer, RG, Bearhop, S, Campbell, HA & Bryant, DM 2013, Shedding light on light: benefits of anthropogenic illumination to a nocturnally foraging shorebird, *Journal of Animal Ecology*, vol. 82, pp. 478–485, DOI: 10.1111/1365-2656.12012.

Eccard, JA, Scheffler, I, Franke, S & Hoffmann, J 2018, Off-grid: solar powered LED illumination impacts epigeal arthropods, *Insect Conservation and Diversity,* vol. 11, pp. 600–607, DOI: 10.1111/icad.12303.

Ecker, JL, Dumitrescu, ON, Wong, KY, Alam, NM, Chen, S, LeGates, T, Renna, JM, Prusky, GT, Berson, DM & Hattar, S 2010, Melanopsin-expressing retinal ganglion-cell photoreceptors: cellular diversity and role in pattern vision, *Neuron*, vol. 67(1), pp. 49–60, DOI: 10.1016/j.neuron.2010.05.023.

Eckert, KL, Bjorndal, KA, Abreu-Grobois, FA & Donnelly, M (eds) 1999, *Research and management techniques for the conservation of sea turtles*, IUCN/SSC Marine Turtle Specialist Group Publication No. 4, Washington, DC, p. 235.

Eisenbeis, G 2006, Artificial night lighting and insects: attraction of insects to streetlamps in a rural setting in Germany, In C, Rich & T, Longcore (Eds.), *Ecological consequences of artificial night lighting,* pp. 281–304, Washington: Island Press.

Eisenbeis, G & Hänel, A 2009, Light pollution and the impact of artificial night lighting on insects, in MJ McDonnell, AH Hahs & JH Breuste (eds), *Ecology of cities and towns: a comparative approach*, Cambridge University Press, Cambridge.

Eklöf, J 2003, *Vision in echolocating bats*, Göteborg University.

Endler, JA 1993, The Color of Light in Forests and Its Implications, *Ecological Monographs,* vol. 63(1), pp. 1–27, DOI: 10.2307/2937121.

Erb, V & Wyneken, J 2019, Nest-to-surf mortality of loggerhead sea turtle (Caretta caretta) hatchlings on Florida’s east coast, *Frontiers in Marine Science*, vol. 6(271), DOI: 10.3389/fmars.2019.00271.

Falchi, F, Cinzano, P, Duriscoe, D, Kyba, CCM, Elvidge, CD, Baugh, K, Portnov, BA, Rybnikova, NA & Furgoni, R 2016, The new world atlas of artificial night sky brightness, *Science Advances*, vol. 2(6), e1600377, DOI: 10.1126/sciadv.1600377.

Falcón, J, Migaud, H, Muñoz-Cueto, JA & Carrillo, M 2010, Current knowledge on the melatonin system in teleost fish, *General and Comparative Endocrinology,* vol. 165(3), pp. 469–482, DOI: https://DOI.org/10.1016/j.ygcen.2009.04.026.

Falkenberg, JC & Clarke, JA 1998, Microhabitat use of deer mice: effects of interspecific interaction risks, *Journal of Mammalogy*, vol. 79, pp. 558–565, DOI: 10.2307/1382986.

Farnworth, B, Innes, J, Kelly, C, Littler, R & Waas, JR 2018, Photons and foraging: Artificial light at night generates avoidance behaviour in male, but not female, New Zealand weta, *Environmental Pollution,* vol. 236, pp. 82–90, DOI: 10.1016/j.envpol.2018.01.039.

Farnworth, B, Innes, J & Waas, JR 2016, Converting predation cues into conservation tools: the effect of light on mouse foraging behaviour, *PloS One*, vol. 11, e0145432, DOI: 10.1371/journal.pone.0145432.

Farnworth, B, Meitern, R, Innes, J & Waas, JR 2019, Increasing predation risk with light reduces speed, exploration and visit duration of invasive ship rats (Rattus rattus), *Scientific Reports*, vol. 9, pp. 1–8, DOI: 10.1038/s41598-019-39711-3.

Feller, K, Lagerholm, S, Clubwala, R, Silver, M, Haughey, D, Ryan, J, Loew, E, Deutschlander, M & Kenyon, K 2009, Characterization of photoreceptor cell types in the little brown bat Myotis lucifugus (Vespertilionidae), *Comparative Biochemistry and Physiology Part B, Biochemistry & Molecular Biology*, vol. 154, pp. 412–418, DOI: 10.1016/j.cbpb.2009.08.006.

Ferreira, MT & Scheffrahn, RH 2011, Light Attraction and Subsequent Colonization Behaviors of Alates and Dealates of the West Indian Drywood Termite (Isoptera: Kalotermitidae), *Florida Entomologist,* vol. 94(2), pp. 131–136, 136, Retrieved from https://DOI.org/10.1653/024.094.0202.

Fischer, J & Lindenmayer, DB 2007, Landscape modification and habitat fragmentation: a synthesis, *Global Ecology and Biogeography,* vol. 16(3), pp. 265–280, DOI: https://DOI.org/10.1111/j.1466-8238.2007.00287.x.

Fleming, PA, Anderson, H, Prendergast, AS, Bretz, MR, Valentine, LE & Hardy, GES 2014, Is the loss of Australian digging mammals contributing to a deterioration in ecosystem function? *Mammal Review,* vol. 44(2), pp. 94–108, DOI: https://DOI.org/10.1111/mam.12014.

Fobert, EK, Burke da Silva, K & Swearer, SE 2019, Artificial light at night causes reproductive failure in clownfish, *Biology Letters*, vol. 15, e20190272, DOI: 10.1098/rsbl.2019.0272.

Fobert, EK, Schubert, KP & Burke da Silva, K 2021, The influence of spectral composition of artificial light at night on clownfish reproductive success, *Journal of Experimental Marine Biology and Ecology,* vol. 540, DOI: https://DOI.org/10.1016/j.jembe.2021.151559.

Fonken, LK, Haim, A & Nelson, RJ 2012, Dim light at night increases immune function in nile grass rats, a diurnal rodent, *Chronobiology International*, vol. 29, pp. 26–34, DOI: 10.3109/07420528.2011.635831.

Foster, JJ, Tocco, C, Smolka, J, Khaldy, L, Baird, E, Byrne, MJ, Nilsson, DE, Dacke, M 2021, Light pollution forces a change in dung beetle orientation behavior, *Current Biology,* vol. 31(17), pp. 3935–3942, DOI: 10.1016/j.cub.2021.06.038.

Frank, K 2016, Effects of artificial night lighting on moths, in T Longcore & C Rich (eds), *Artificial night lighting and protected lands: ecological effects and management approaches*, accessed 31 May 2022.

Freas, C, A, Narendra, A, Lemesle, C & Cheng, K 2017, Polarized light use in the nocturnal bull ant, Myrmecia midas, *R Soc Open Sci,* vol. 4(8), DOI: 10.1098/rsos.170598.

Fritches, KA 2012, Australian loggerhead sea turtle hatchlings do not avoid yellow, *Marine and Freshwater Behaviour and Physiology*, vol. 45(2), pp. 79–89, DOI: 10.1080/10236244.2012.690576.

Fritz, B, Horváth, G, Hünig, R, Pereszlényi, Á, Egri, Á, Guttmann, M, Schneider, M, Lemmer, U, Kriska, G, Gomard, G 2020, Bioreplicated coatings for photovoltaic solar panels nearly eliminate light pollution that harms polarotactic insects, *PLoS ONE,* vol. 15(12), DOI: 10.1371/journal.pone.0243296.

Garber, SD 1978, Opportunistic Feeding Behavior of Anolis cristatellus (Iguanidae: Reptilia) in Puerto Rico, *Transactions of the Kansas Academy of Science (1903-),* vol. 81(1), pp. 79–80, DOI: 10.2307/3627360.

Gartrell, BD 2002, Assessment of the Reproductive State in Male Swift Parrots (Lathamus discolor) by Testicular Aspiration and Cytology, *Journal of Avian Medicine and Surgery,* vol. 16(3), pp. 211–217, Retrieved from http://www.jstor.org/stable/30133223.

Gaston, KJ, Ackermann, S, Bennie, J, Cox, DTC, Phillips, BB, Sánchez de Miguel, A & Sanders, D 2021, Pervasiveness of Biological Impacts of Artificial Light at Night, *Integrative and Comparative Biology,* vol. 61(3), pp. 1098–1110, DOI: 10.1093/icb/icab145.

Gaston, KJ & Bennie, J 2014, Demographic effects of artificial nighttime lighting on animal populations, *Environmental Reviews*, vol. 22, pp. 323–330, DOI: 10.1139/er-2014-0005.

Gaston, KJ, Bennie, J, Davies, TW & Hopkins, J 2013, The ecological impacts of nighttime light pollution: a mechanistic appraisal, *Biological Reviews*, vol. 88, pp. 912–927, DOI: 10.1111/brv.12036.

Gaston, KJ, Visser, ME & Holker, F 2018, The biological impacts of artificial light at night: the research challenge, *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 370, e20140133, DOI: 10.1098/rstb.2014.0133.

Gauthreaux, SA & Belser, CG 2006, Effects of artificial night lighting on migrating birds, in C Rich & T Longcore (eds), Ecological consequences of artificial night lighting, Island Press, Washington DC, pp. 67–93, accessed 31 May 2022.

Giavi, S, Fontaine, C & Knop, E 2021, Impact of artificial light at night on diurnal plant-pollinator interactions, *Nature Communications*, vol. 12, pp. 1–5, DOI: 10.1038/s41467-021-22011-8.

Gineste, B, Souquet, M, Couzi, F-X, Giloux, Y, Philippe, J-S, Hoarau, C, Tourmetz, J, Potin, G & Le Corre, M 2016, Tropical shearwater population stability at Reunion Island, despite light pollution, *Journal of Ornithology*, vol. 158, pp. 385–394, DOI: 10.1007/s10336-016-1396-5.

Givnish, TJ 1988, Adaptation to sun and shade: A whole-plant perspective, *Australian Journal of Plant Physiology,* vol. 15, pp. 63–92.

Goldingay, RL, Carthew, SM & Whelan, RJ 1991, The Importance of Non-Flying Mammals in Pollination, *Oikos,* vol. 61(1), pp. 79–87, DOI: 10.2307/3545409.

González-Bernal, E, Brown, G & Shine, R 2014, Invasive cane toads: social facilitation depends upon an individual's personality, *PLoS ONE*, vol. 9(7), e102880, DOI: 10.1371/journal.pone.0102880.

González-Bernal, E, Greenlees, MJ, Brown, GP & Shine, R 2016, Toads in the backyard: why do invasive cane toads (Rhinella marina) prefer buildings to bushland? *Population Ecology,* vol. 58(2), pp. 293–302, DOI: https://DOI.org/10.1007/s10144-016-0539-0.

Gorresen, P, Cryan, P, Dalton, D, Wolf, S & Bonaccorso, F 2015, Ultraviolet vision may be widespread in bats, *Acta Chiropterologica*, vol. 17, pp. 193–198, DOI: 10.3161/15081109ACC2015.17.1.017.

Grenis, K & Murphy, SM 2019, Direct and indirect effects of light pollution on the performance of an herbivorous insect, *Insect Science,* vol. 26(4), pp. 770–776, DOI: https://DOI.org/10.1111/1744-7917.12574.

Griesemer, AM & Holmes, ND 2011, *Newell's shearwater population modeling for habitat conservation plan and recovery planning*, Technical Report No. 176, The Hawai`i-Pacific Islands Cooperative Ecosystem Studies Unit & Pacific Cooperative Studies Unit, University of Hawai`i, Honolulu, p. 68.

Grubisic, M, Haim, A, Bhusal, P, Dominoni, DM, Gabriel, KMA, Jechow, A, Kupprat, F, Lerner, A, Marchant, P, Riley, W, Stebelova, K, Van Grunsven, RHA, Zeman, M, Zubidat, AE & Hölker, F 2019, Light pollution, circadian photoreception, and melatonin in vertebrates, *Sustainability*, vol. 11, 6400, DOI: 10.3390/su11226400.

Grubisic, M, Singer, G, Bruno, MC, van Grunsven, RHA, Manfrin, A, Monaghan, MT & Hölker, F 2017, Artificial light at night decreases biomass and alters community composition of benthic primary producers in a sub-alpine stream, *Limnology and Oceanography,* vol. 62(6), pp. 2799–2810, DOI: https://DOI.org/10.1002/lno.10607.

Grubisic, M, van Grunsven, RHA, Manfrin, A, Monaghan, MT & Hölker, F 2018, A transition to white LED increases ecological impacts of nocturnal illumination on aquatic primary producers in a lowland agricultural drainage ditch, *Environmental Pollution,* vol. 240, pp. 630–638, DOI: https://DOI.org/10.1016/j.envpol.2018.04.146.

Haddad, NM, Brudvig, LA, Clobert, J, Davies, KF, Gonzalez, A, Holt, RD, Lovejoy TE, Sexton JO, Austin MP, Collins CD, Cook, WM, Damschen, EI, Ewers, RM, Foster, BL, Jenkins, CN, King, AJ, Laurance, WF, Levey, DJ, Margules, CR, Melbourne, BA, Nicholls, AO, Orrock, JL, Song, D & Townshend, JR 2015, Habitat fragmentation and its lasting impact on Earth's ecosystems, *Science Advances,* vol. 1(2), DOI: 10.1126/sciadv.1500052.

Haddock, JK 2018, Effects of artificial lighting on insectivorous bat communities in urban ecosystems, PhD thesis, University of Sydney, accessed 31 May 2022.

Haddock, JK, Threlfall, CG, Law, B & Hochuli, DF 2019a, Responses of insectivorous bats and nocturnal insects to local changes in street light technology, *Austral Ecology*, vol. 44(6), DOI: 10.1111?aec.12772.

Haddock, J, Threlfall, C, Law, B & Hochuli, D 2019b, Light pollution at the urban forest edge negatively impacts insectivorous bats, *Biological Conservation*, vol. 236, pp. 17–28, DOI: 10.1016/j.biocon.2019.05.016.

Hale, JD, Fairbrass, AJ, Matthews, TJ, Davies, G & Sadler, JP 2015, The ecological impact of city lighting scenarios: exploring gap crossing thresholds for urban bats, *Glob Chang Biol,* 21(7), pp. 2467–2478, DOI: 10.1111/gcb.12884.

Hänel, A, Posch, T, Ribas, SJ, Aubé, M, Duriscoe, D, Jechow, A, Kollath, Z, Lolkema, D, Moore, C, Schmidt, N, Spoelstra, H, Wuchterl, G & Kyba, CCM 2018, Measuring night sky brightness: methods and challenges, *Journal of Quantitative Spectroscopy and Radiative Transfer*, DOI: 10.1016/j.jqsrt.2017.09.008.

Harewood, A & Horrocks, J 2008, Impacts of coastal development on hawksbill hatchling survival and swimming success during the initial offshore migration, *Biological Conservation*, vol. 141, pp. 394–401, DOI: 10.1016/j.biocon.2007.10.017.

Harris, CM, Lorenz, K, Fishpool, LDC, Lascelles, B, Cooper, J, Croxall, JP, Emmerson, LM, Fraser, WR, Fijn, R, Jouventin, P, LaRue, MA, Le Maho, Y, Lynch, HJ, Naveen, R, Patterson-Fraser, DL, Peter, H-U, Poncet, S, Phillips, RA, Southwell, CJ, van Franeker, JA, Weimerskirch, H, Wienecke, B & Woehler, EJ 2015, *Important bird areas in Antarctica 2015 summary*, BirdLife International and Environmental Research & Assessment Ltd, Cambridge, p. 45.

Hart, NS 2001, The visual ecology of avian photoreceptors, *Progress in Retinal and Eye Research*, vol. 20, pp. 675–703, DOI: 10.1016/s1350-9462(01)00009-x.

Hau, M, Wikelski, M & Wingfield, JC 1998, A Neotropical Forest Bird Can Measure the Slight Changes in Tropical Photoperiod, *Proceedings: Biological Sciences,* vol. 265(1391), pp. 89–95, Retrieved from http://www.jstor.org/stable/50986.

Hays, GC 2003, A review of the adaptive significance and ecosystem consequences of zooplankton diel vertical migrations, *Hydrobiologia,* vol. 503(1), pp. 163–170, DOI: 10.1023/B:HYDR.0000008476.23617.b0.

Heard, T 2016, The Australian native bee book : keeping stingless bee hives for pets, pollination and sugarbag honey, Sugarbag Bees.

Henderson, PA & Southwood, TRE 2016, *Ecological methods*, 4th edition, Wiley-Blackwell.

Hodge, W, Limpus, CJ & Smissen, P 2007, *Queensland turtle conservation project: Hummock Hill Island nesting turtle study December 2006*, Conservation technical and data report, Environmental Protection Agency, Queensland, pp. 1–10.

Hoffmann, J, Schirmer, A & Eccard, JA 2019, Light pollution affects space use and interaction of two small mammal species irrespective of personality, *BMC Ecology*, vol. 19, pp. 1–11, DOI: 10.1186/s12898-019-0241-0.

Hoffmann, K, Illnerová, H & Vaněček, J 1981, Effect of photoperiod and of one minute light at night-time on the pineal rhythm on N-acetyltransferase activity in the Djungarian hamster Phodopus sungorus, *Biology of Reproduction*, vol. 24, pp. 551–556, DOI: 10.1095/biolreprod24.3.551.

Hölker, F, Bolliger, J, Davies, TW, Giavi, S, Jechow, A, Kalinkat, G, Longcore, T, Spoelstra, K, Tidau, S, Visser, ME & Knop, E 2021, 11 Pressing Research Questions on How Light Pollution Affects Biodiversity, *Frontiers in Ecology and Evolution,* vol. 9, DOI: 10.3389/fevo.2021.767177.

Hölker, F, Wolter, C, Perkin, EK & Tockner, K 2010, Light pollution as a biodiversity threat, *Trends in Ecology and Evolution,* 25(12), vol. pp. 681–682, DOI: 10.1016/j.tree.2010.09.007.

Hölker, F, Wurzbacher, C, Weißenborn, C, Monaghan, MT, Holzhauer, SIJ & Premke, K 2015, Microbial diversity and community respiration in freshwater sediments influenced by artificial light at night, *Philosophical Transactions of the Royal Society B: Biological Sciences,* vol. 370(1667), DOI: 10.1098/rstb.2014.0130.

Hooker, D 1911, Certain reactions to color in the young loggerhead turtle, *Papers from the Tortugas Laboratory of the Carnegie Institution of Washington*, vol. 13, pp. 71–76.

Hopkins, GR, Gaston, KJ, Visser, ME, Elgar, MA & Jones, TM 2018, Artificial light at night as a driver of evolution across urban–rural landscapes, *Frontiers in Ecology and the Environment*, vol. 16, pp. 472–479, DOI: 10.1002/fee.1828.

Horch, KW, Gocke, JP, Salmon, M & Forward, RB 2008, Visual spectral sensitivity of hatchling loggerhead (Caretta L.) and leatherback (Dermochelys coriacea L.) sea turtles, as determined by single-flash electroretinography, *Marine and Freshwater Behaviour and Physiology*, vol. 41(2), pp. 107–119, DOI: 10.1080/10236240802106556.

Hu, Z, Hu, H & Huang, Y 2018, Association between nighttime artificial light pollution and sea turtle nest density along Florida coast: a geospatial study using VIIRS remote sensing data, *Environmental Pollution*, vol. 239, pp. 30–42, DOI: 10.1016/j.envpol.2018.04.021.

Huemer, P, Kühtreiber, H & Tarmann, G 2010, Anlockwirkung moderner Leuchtmittel auf nachtaktive Insekten: Ergebnisse einer Feldstudie in Tirol (Attraction of modern lights on nocturnal insects: Results of a field study in Tyrol), Retrieved from Innsbrück, Austria: http://www.hellenot.org/fileadmin/user_upload/PDF/WeiterInfos/10_AnlockwirkungInsektenFeldstudie_TLMFundLUA.pdf.

Ikeno, T, Weil, ZM & Nelson, RJ 2014, Dim light at night disrupts the short-day response in Siberian hamsters, *General and Comparative Endocrinology*, vol. 197, pp. 56–64, DOI: 10.1016/j.ygcen.2013.12.005.

Imber, MJ 1975, Behaviour of petrels in relation to the moon and artificial lights, *Notornis*, vol. 22, pp. 302–306.

Iristech 2018, Visible spectrum, accessed 1 October 2018.

Jaeger, RG & Hailman, JP 1973, Effects of Intensity on the Phototactic Responses of Adult Anuran Amphibians: A Comparative Survey1, *Zeitschrift für Tierpsychologie,* vol. 33(3-4), pp. 352–407, DOI: https://DOI.org/10.1111/j.1439-0310.1973.tb02103.x.

James, SA & Bell, DT 2000, Influence of light availability on leaf structure and growth of two Eucalyptus globulus ssp, globulus provenances, *Tree Physiology,* vol. 20, pp. 1007–1018.

Jechow, A & Hölker, F 2019, Snowglow—The Amplification of Skyglow by Snow and Clouds Can Exceed Full Moon Illuminance in Suburban Areas, *Journal of Imaging,* vol. 5(8), pp. 69, Retrieved from https://www.mdpi.com/2313-433X/5/8/69.

Jechow, A, Kyba, CCM & Hölker, F 2019, Beyond all-sky: assessing ecological light pollution using multi-spectral full-sphere fisheye lens imaging, *Journal of Imaging*, vol. 5(46), DOI: 10.3390/jimaging5040046.

Jechow, A, Ribas, SJ, Domingo, RC, Hölker, F, Kolláth, Z & Kyba, CC 2018, Tracking the dynamics of skyglow with differential photometry using a digital camera with fisheye lens, *Journal of Quantitative Spectroscopy and Radiative Transfer*, vol. 209, pp. 212–223, DOI: 10.1016/j.jqsrt.2018.01.032.

Kamrowski, RL, Limpus, CJ, Moloney, J & Hamann, M 2012, Coastal light pollution and marine turtles: assessing the magnitude of the problem, *Endangered Species Research*, vol. 19, pp. 85–98, DOI: 10.3354/esr00462.

Kamrowski, RL, Limpus, CJ, Pendoley, K & Hamann, M 2014, Influence of industrial light pollution on the sea-finding behaviour of flatback turtle hatchlings, *Wildlife Research*, vol. 41, pp. 421–434, DOI: 10.1071/WR14155

Kasso, M & Balakrishnan, M 2013, Ecological and economic importance of bats (order Chiroptera), *ISRN Biodiversity*, 187415, DOI: 10.1155/2013/187415.

Kavanagh, KL, Pangle, R & Schotzko, AD 2007, Nocturnal transpiration causing disequilibrium between soil and stem predawn water potential in mixed conifer forests of Idaho, *Tree Physiology,* vol. 27, pp. 612–629.

Knop, E, Zoller, L, Ryser, R, Gerpe, C, Hörler, M & Fontaine, C 2017, Artificial light at night as a new threat to pollination, *Nature,* vol. 548, pp. 206–210, DOI: 10.1038/nature23288.

Kolbe, JJ, Moniz, HA, Lapiedra, O & Thawley, CJ 2021, Bright lights, big city: an experimental assessment of short-term behavioral and performance effects of artificial light at night on Anolis lizards, *Urban Ecosystems,* vol. 24(5), pp. 1035–1045, DOI: 10.1007/s11252-021-01098-3.

Kolláth, Z 2010, Measuring and modelling light pollution at the Zselic Starry Sky Park, *Journal of Physics: Conference Series*, vol. 218, e012001, DOI: 10.1088/1742-6596/218/1/012001.

Komine, H, Koike, S & Schwarzkopf, L 2020, Impacts of artificial light on food intake in invasive toads, *Sci Rep,* vol. 10(1), 6527, DOI: 10.1038/s41598-020-63503-9.

Kotler, BP, Brown, JS & Hasson, O 1991, Factors affecting gerbil foraging behavior and rates of owl predation, *Ecology*, vol. 72, pp. 2249–2260, DOI: 10.2307/1941575.

Kotler, BP, Brown, JS, Smith, RJ & Wirtz, WO 1988, The effects of morphology and body size on rates of owl predation on desert rodents, *Oikos*, vol. 53, pp. 145–152, DOI: 10.2307/3566056.

Kramer, KM & Birney, EC 2001, Effect of light intensity on activity patterns of Patagonian leaf-eared mice, Phyllotis xanthopygus, *Journal of Mammalogy*, vol. 82, pp. 535–544, DOI: 10.1644/1545-1542(2001)082<0535:EOLIOA>2.0.CO;2.

Kronfeld-Schor, N, Dominoni, D, De La Iglesia, H, Levy, O, Herzog, ED, Dayan, T & Helfrich-Forster, C 2013, Chronobiology by moonlight, *Proceedings of the Royal Society B: Biological Sciences*, vol. 280, 20123088, DOI: 10.1098/rspb.2012.3088.

Kurvers, RH & Hoelker, F 2015, Bright nights and social interactions: a neglected issue, *Behavioral Ecology*, vol. 26, pp. 334–339, DOI: 10.1093/beheco/aru223.

Kyba, CCM, Kuester, T, Sánchez de Miguel, A, Baugh, K, Jechow, A, Hölker, F, Bennie, J, Elvidge, CD, Gaston, KJ & Guanter, L 2017, Artificially lit surface of Earth at night increasing in radiance and extent, *Science Advances*, vol. 3, e1701528, DOI: 10.1126/sciadv.1701528.

Kyba, CCM, Mohar, A & Posch, T 2017, How bright is moonlight? *Astronomy and Geophysics,* vol. 58, 1.31–31.32, DOI: http://doi.org/10.1093/astrogeo/atx025.

Kyba, CCM, Ruhtz, T, Fischer, J & Hölker, F 2011, Cloud coverage acts as an amplifier for ecological light pollution in urban ecosystems, *PLoS ONE*, vol. 6, e17307, DOI: 10.1371/journal.pone.0017307.

La, VT 2012, Diurnal and Nocturnal Birds Vocalize at Night: A Review, *The Condor,* vol. *114*(2), pp. 245–257, DOI: 10.1525/cond.2012.100193.

Laforge, A, Pauwels, J, Faure, B, Bas, Y, Kerbiriou, C, Fonderflick, J & Besnard, A 2019, Reducing light pollution improves connectivity for bats in urban landscapes, *Landscape Ecology,* vol. 34(4), pp. 793–809, DOI: 10.1007/s10980-019-00803-0.

Laurance, WF 1991, Edge effects in tropical forest fragments: Application of a model for the design of nature reserves, *Biological Conservation,* vol. 57(2), pp. 205–219, DOI: https://DOI.org/10.1016/0006-3207(91)90139-Z.

Laurance, WF, Lovejoy, TE, Vasconcelos, HL, Bruna, EM, Didham, RK, Stouffer, PC, Gascon, C, Bierregaard, RO, Laurance, SG & Sampaio, E 2002, Ecosystem Decay of Amazonian Forest Fragments: a 22-Year Investigation, *Conservation Biology,* vol. 16(3), pp. 605–618, DOI: https://DOI.org/10.1046/j.1523-1739.2002.01025.x.

Lázaro-Lobo, A & Ervin, GN 2019, A global examination on the differential impacts of roadsides on native vs, exotic and weedy plant species, *Global Ecology and Conservation,* vol. 17, DOI: https://DOI.org/10.1016/j.gecco.2019.e00555.

Le Corre, M, Ollivier, A, Ribes, S & Jouventin, P 2002, Light-induced mortality of petrels: a 4-year study from Réunion Island (Indian Ocean), *Biological Conservation*, vol. 105, pp. 93–102, DOI: 10.1016/S0006-3207(01)00207-5.

Leopold, MF, Philippart, CJM & Yorio, P 2010, Nocturnal feeding under artificial light conditions by Brown-hooded Gull (Larus maculipennis) in Puerto Madryn harbour (Chubut Province, Argentina), *Hornero,* vol. 25(2), pp. 55–60, DOI: urn:nbn:nl:ui:32-443391.

Le Tallec, T, Perret, M & Théry, M 2013, Light pollution modifies the expression of daily rhythms and behavior patterns in a nocturnal primate, *PloS One*, vol. 8, e79250, DOI: 10.1371/journal.pone.0079250.

Le Tallec, T, Théry, M & Perret, M 2015, Effects of light pollution on seasonal estrus and daily rhythms in a nocturnal primate, *Journal of Mammalogy*, vol. 96, pp. 438–445, DOI: 10.1093/jmammal/gyv047.

Le Tallec, T, Théry, M & Perret, M 2016, Melatonin concentrations and timing of seasonal reproduction in male mouse lemurs (Microcebus murinus) exposed to light pollution, *Journal of Mammalogy*, vol. 97, pp. 753–760, DOI: 10.1093/jmammal/gyw003.

Levenson, DH, Eckert, SA, Crognale, MA, Deegan, JF & Jacobs, GH 2004, Photopic spectral sensitivity of green and loggerhead sea turtles, *Copeia*, vol. 2004(2), pp. 908–914, DOI: 10.1643/CP-03-217R1.

Levin, N, Kyba, CCM, Zhang, Could, Sánchez de Miguel, A, Román, MO, Li, X, Portnov, BA, Moltman, AL, Jechow, A, Miller, SD, Wang, Z, Shrestha, RM & Elvidge, COULD 2020, Remote sensing of night lights: a review and an outlook for the future, *Remote Sensing of Environment*, vol. 237, 111443, DOI: 10.1016/j.rse.2019.111443.

Levy, O, Fernandes de Barros Marangoni, LIC, Benichou, J, Rottier, C, Béraud, E, Grover, R & Ferrier-Pagès, C 2020, Artificial light at night (ALAN) alters the physiology and biochemistry of symbiotic reef building corals, *Environmental Pollution,* vol. 266, DOI: https://DOI.org/10.1016/j.envpol.2020.114987.

Lewanzik, D & Voigt, CC 2014, Artificial light puts ecosystem services of frugivorous bats at risk, *Journal of Applied Ecology*, vol. 51, pp. 388–394, DOI: 10.1111/1365-2664.12206.

Limpus, CJ & Kamrowski, RL 2013, Ocean-finding in marine turtles: the importance of low horizon elevation as an orientation cue, *Behaviour*, vol. 150, pp. 863–893.

Limpus, CJ, Miller, JD, Parmenter, CJ & Limpus, DJ 2003, The green turtle, Chelonia mydas, population of Raine Island and the Northern Great Barrier Reef: 1843–2001, *Memoirs of the Queensland Museum*, vol. 49, pp. 349–440.

Linley, GD 2017, The impact of artificial lighting on bats along native coastal vegetation, *Australian Mammalogy*, vol. 39, pp. 178–184, DOI: 10.1071/AM15047.

Linley, G, Pauligk, Y, Marneweck, C & Ritchie, E 2020, Moon phase and nocturnal activity of native Australian mammals, *Australian Mammalogy*, vol. 43, pp. 190–195, DOI: 10.1071/AM19070.

Lister, BC & Garcia, A 2018, Climate-driven declines in arthropod abundance restructure a rainforest food web, *Proceedings of the National Academy of Sciences of the United States of America,* vol. 115(44), pp. E10397–E10406, DOI: 10.1073/pnas.1722477115.

Liu, Y, Speißer, B, Knop, E & van Kleunen, M 2022, The Matthew effect: Common species become more common and rare ones become more rare in response to artificial light at night, *Global Change Biology,* vol. 28, pp. 3674–3682, DOI: https://DOI.org/10.1111/gcb.16126.

Lockett, MT, Jones, TM, Elgar, MA, Gaston, KJ, Visser, ME & Hopkins, GR 2021, Urban street lighting differentially affects community attributes of airborne and ground-dwelling invertebrate assemblages, *Journal of Applied Ecology,* vol. 58(10), pp. 2329–2339, DOI: https://DOI.org/10.1111/1365-2664.13969.

Lohmann, KJ, Witherington, B, Lohmann, CMF & Salmon, M 1997, Orientation, navigation, and natal beach homing in sea turtles, PL Lutz & JA Musick (eds), *The biology of sea turtles*, vol. I, CRC Press, Washington DC, pp. 107–135.

Longcore, T & Rich, C 2004, Ecological light pollution, *Frontiers in Ecology and the Environment*, vol. 2, pp. 191–198, DOI: 10.1890/1540-9295(2004)002[0191:ELP]2.0.CO;2.

Longcore, T & Rich, C 2006, Ecological consequences of artificial night lighting, Island Press, Washington, DC, accessed 31 May 2022.

Longcore, T, Rich, C, Mineau, P, MacDonald, B, Bert ,DG, Sullivan, LM, Mutrie, E, Gauthreaux, SA, Avery, ML, Crawford, RL, Manville, AM, Travis, ER & Drake, D 2013, Avian mortality at communication towers in the United States and Canada: which species, how many, and where?, *Biological Conservation*, vol. 158, pp. 410–419, DOI: 10.1371/journal.pone.0034025.

Longcore, T, Rodríguez, A, Witherington, B, Penniman, JF, Herf, L & Herf, M 2018, Rapid assessment of lamp spectrum to quantify ecological effects of light at night, *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, vol. 329(8–9), pp. 511–521, DOI: 10.1002/jez.2184.

Lourenço, PM, Silva, A, Santos, CD, Miranda, AC, Granadeiro, JP & Palmeirim, JM 2008, The energetic importance of night foraging for waders wintering in a temperate estuary, *Acta Oecologica*, vol. 34, pp. 122–139, DOI: 10.1016/j.actao.2008.04.005.

Luarte, T, Bonta, CC, Silva-Rodriguez, EA, Quijón, PA, Miranda, C, Farias, AA & Duarte, C 2016, Light pollution reduces activity, food consumption and growth rates in a sandy beach invertebrate, *Environmental Pollution,* vol. 218, pp. 1147–1153, DOI: 10.1016/j.envpol.2016.08.068.

Macgregor, CJ, Evans, DM, Fox, R & Pocock, MJO 2017, The dark side of street lighting: impacts on moths and evidence for the disruption of nocturnal pollen transport.

Maisey, AC, Haslem, A, Leonard, SWJ & Bennett, AF 2021, Foraging by an avian ecosystem engineer extensively modifies the litter and soil layer in forest ecosystems, *Ecological Applications,* vol. 31(1), DOI: https://DOI.org/10.1002/eap.2219.

Manfrin, A, Singer, G, Larsen, S, Weiß, N, Grunsven, RHAv, Weiß, N-S, Wohlfahrt, S, Monaghan, MT & Hölker, F 2017, Artificial Light at Night Affects Organism Flux across Ecosystem Boundaries and Drives Community Structure in the Recipient Ecosystem, *Frontiers in Environmental Science*, DOI: 10.3389/fenvs.2017.00061.

Marchesan, M, Spoto, M, Verginella, L & Ferrero, EA 2005, Behavioural effects of artificial light on fish species of commercial interest, *Fisheries Research,* vol. 73(1), pp. 171–185, DOI: https://DOI.org/10.1016/j.fishres.2004.12.009.

Marshall, NJ, Cortesi, F, de Busserolles, F, Siebeck, UE & Cheney, KL 2019, Colours and colour vision in reef fishes: Past, present and future research directions, *Journal of Fish Biology,* vol. 95(1), pp. 5–38, DOI: https://DOI.org/10.1111/jfb.13849.

Matzke, EB 1936, The Effect of Street Lights in Delaying Leaf-Fall in Certain Trees, *American Journal of Botany,* vol. 23(6), pp. 446–452, Retrieved from https://www.jstor.org/stable/2436035.

May, D, Shidemantle, G, Melnick-Kelley, Q, Crane, K & Hua, J 2019, The effect of intensified illuminance and artificial light at night on fitness and susceptibility to abiotic and biotic stressors, *Environmental Pollution,* vol. 251, pp. 600–608, DOI: https://DOI.org/10.1016/j.envpol.2019.05.016.

McAlary, FA & McFarland, WN 1993, The effect of light and darkness on hatching in the pomacentrid Abudefduf saxatilis, *Environmental Biology of Fishes,* vol. 37(3), pp. 237–244, DOI: 10.1007/BF00004631.

McAllan, BM, Westman, W & Joss, JMP 2002, The seasonal reproductive cycle of a marsupial, Antechinus stuartii: effects of oral administration of melatonin, *General and Comparative Endocrinology*, vol. 128, pp. 82–90, DOI: 10.1016/S0016-6480(02)00067-9.

McLaren, JD, Buler, JJ, Schreckengost, T, Smolinsky, JA, Boone, M, van Loon, E, Dawson, DK & Walters, EL 2018, Artificial light at night confounds broad-scale habitat use by migrating birds, *Ecology Letters*, vol. 21(3), pp. 356–364, DOI: 10.1111/ele.12902.

McLay, LK, Green, MP & Jones, TM 2017, Chronic exposure to dim artificial light at night decreases fecundity and adult survival in Drosophila melanogaster, *Journal of Insect Physiology,* vol. 100, pp. 15–20, DOI: 10.1016/j.jinsphys.2017.04.009.

McLay, LK, Nagarajan-Radha, V, Green, MP & Jones, TM 2018, Dim artificial light at night affects mating, reproductive output and reactive oxygen species in Drosophila melanogaster, *Journal of Experimental Zoology - Part A,* vol. 329, pp. 419–428, DOI: 10.1002/jez.2164.

McNeil, R, Drapeau, P & Pierotti, R 1993, Nocturnality in colonial waterbirds: occurrence, special adaptations, and suspected benefits, in DM Power (ed), *Current ornithology*, vol. 10, Springer US, Boston MA, pp. 187–246, DOI: 10.1007/978-1-4615-9582-3_4.

Mehner, T 2012, Diel vertical migration of freshwater fishes – proximate triggers, ultimate causes and research perspectives, *Freshwater Biology,* vol. 57(7), pp. 1342–1359, DOI: https://DOI.org/10.1111/j.1365-2427.2012.02811.x.

Menkhorst, P, Rogers, D, Clarke, R, Davies, J, Marsack, P & Franklin, K 2017, *The Australian bird guide*, CSIRO Publishing, Clayton South, Victoria.

Merkel, FR & Johansen, KL 2011, Light-induced bird strikes on vessels in southwest Greenland, *Marine Pollution Bulletin*, vol. 62, pp. 2330–2336, DOI: 10.1016/j.marpolbul.2011.08.040.

Meyer, LA, Mažeika, S & Sullivan, P 2013, Bright lights, big city: influences of ecological light pollution on reciprocal stream–riparian invertebrate fluxes, *Ecological Applications,* vol. 23(6), pp. 1322–1330.

Mitkus, M, Nevitt, GA, Danielsen, J & Kelber, A 2016, Vision on the high seas: spatial resolution and optical sensitivity in two procellariform seabirds with different foraging strategies, *Journal of Experimental Biology*, vol. 219, pp. 3329–3338, DOI: 10.1242/jeb.140905.

Montevecchi, WA 2006, Influences of artificial light on marine birds, in C Rich & T Longcore (eds), Ecological consequences of artificial night lighting, Island Press, Washington DC, accessed 31 May 2022.

Moro, D, van de Merwe, J, Thomas, M, Smith, A & Lagdon R, 2018, Integrating resource development with island conservation: Barrow Island as a model for conservation and development, in D Moro, D Ball & S Bryant (eds) *Australian island arks: conservation, management and opportunities*, CSIRO Publishing, Melbourne, pp. 131–146, accessed 31 May 2022.

Mougeot, F & Bretagnolle, V 2000, Predation risk and moonlight avoidance in nocturnal seabirds, *Journal of Avian Biology,* vol. 31(3), pp. 376–386, DOI: https://DOI.org/10.1034/j.1600-048X.2000.310314.x.

Mrosovsky, N & Shettleworth, SJ 1968, Wavelength preferences and brightness cues in the water finding behaviour of sea turtles, *Behaviour*, vol. 32, pp. 211–257, DOI: 10.1163/156853968X00216.

Mrosovsky, N 1968, Nocturnal emergence of hatchling sea turtles: control by thermal inhibition of activity, *Nature*, vol. 220, pp. 1338–1339, DOI: 10.1038/2201338a0.

Mrosovsky, N 1972, The water finding ability of sea turtles, *Brain Behaviour and Evolution*, vol. 5, pp. 202–225, DOI: 10.1159/000123748.

Müller, B, Goodman, S & Peichl, L 2007, Cone photoreceptor diversity in the retinas of fruit bats (Megachiroptera), *Brain, Behavior and Evolution*, vol. 70, pp. 90–104, DOI: 10.1159/000102971

Murphy, RC 1936, *Oceanic birds of South America*, Macmillan, New York.

Murphy, SM, Vyas, DK, Hoffman, JL, Jenck, CS, Washburn, BA, Hunnicutt, KE, Davidson, A, Andersen, JM, Bennet, RK, Gifford, A, Herrera, M, Lawler, B, Lorman, S, Peacock, V, Walker, L, Watkins, E, Wilkinson, L, Williams, Z & Tinghitella, RM 2021, Streetlights positively affect the presence of an invasive grass species, *Ecology and Evolution,* vol. 11(15), pp. 10320–10326, DOI: https://DOI.org/10.1002/ece3.7835.

Murphy, SM, Vyas, DK, Sher, AA & Grenis, K 2022, Light pollution affects invasive and native plant traits important to plant competition and herbivorous insects, *Biological Invasions,* vol. 24(3), pp. 599–602, DOI: https://DOI.org/10.1007/s10530-021-02670-w.

Narango, DL, Tallamy, DW & Marra, PP 2018, Nonnative plants reduce population growth of an insectivorous bird, *Proceedings of the National Academy of Sciences,* vol. 115(45), pp. 11549–11554, DOI: 10.1073/pnas.1809259115.

Navarro-Barranco, C & Hughes, LE 2015, Effects of light pollution on the emergent fauna of shallow marine ecosystems: Amphipods as a case study, *Marine Pollution Bulletin,* vol. 94(1), pp. 235–240, DOI: https://DOI.org/10.1016/j.marpolbul.2015.02.023.

Naylor, E 2001, Marine Animal Behaviour in Relation to Lunar Phase, Dordrecht.

Nelson, DE & Takahashi, JS 1991, Comparison of visual sensitivity for suppression of pineal melatonin and circadian phase-shifting in the golden hamster, *Brain Research*, vol. 554, pp. 272–277, DOI: 10.1016/0006-8993(91)90200-F.

Nelson, RJ, Demas, GE, Klein, SL & Kriegsfeld, LJ 1995, The influence of season, photoperiod, and pineal melatonin on immune function, *Journal of Pineal Research*, vol. 19, pp. 149–165, DOI: 10.1111/j.1600-079X.1995.tb00184.x.

Newman, EA & Hartline, PH 1981, Integration of visual and infrared information to biomodal neurons in the rattlesnake optic tectum, *Science*, vol. 213(4509), pp. 789–791, DOI: 10.1126/science.7256281.

Nightingale, B, Longcore, T & Simenstad, CA 2006, Artificial night lighting and Fishes, In C, Rich & T, Longcore (Eds.), *Ecological consequences of artificial night* lighting, pp. 257–276, Washington: Island Press.

Nordberg, EJ & Schwarzkopf, L 2022, Afraid of the Dark? The Influence of Natural and Artificial Light at Night on the Behavioral Activity of a Nocturnal Gecko, *Frontiers in Ecology and Evolution,* vol. 10, DOI: 10.3389/fevo.2022.821335.

Nuñez, JD, Bas, CC, Pérez García, M, Ocampo, EH, Ribeiro, PD & Luppi, TA 2021, Artificial light at night may increase the predation pressure in a salt marsh keystone species, *Marine Environmental Research,* vol. 167, DOI: https://DOI.org/10.1016/j.marenvres.2021.105285.

Omand, MM, Steinberg, DK & Stamieszkin, K 2021, Cloud shadows drive vertical migrations of deep-dwelling marine life, *Proceedings of the National Academy of Sciences,* vol. 118(32), DOI: 10.1073/pnas.2022977118.

O'Rourke, RL, Anson, JR, Saul, AM & Banks, PB 2020, Limits to alien black rats (Rattus rattus) acting as equivalent pollinators to extinct native small mammals: the influence of stem width on mammal activity at native Banksia ericifolia inflorescences, *Biological Invasions,* vol. 22(2), pp. 329–338, DOI: 10.1007/s10530-019-02090-x.

Ouyang, JQ, Davies, S & Dominoni, D 2018, Hormonally mediated effects of artificial light at night on behavior and fitness: linking endocrine mechanisms with function, *The Journal of Experimental Biology*, vol. 221, jeb156893, DOI: 10.1242/jeb.156893.

Ouyang, JQ, de Jong, M, Hau, M, Visser, ME, van Grusven, RHA & Spoelstra, K 2015, Stressful colours: corticosterone concentrations in a free-living songbird vary with the spectral composition of experimental illumination, *Biology Letters*, vol. 11, e20150517, DOI: 10.1098/rsbl.2015.0517.

Owens, ACS, Cochard, P, Durrant, J, Farnworth, B, Perkin, EK & Seymoure, B 2020, Light pollution is a driver of insect declines, *Biological Conservation*, vol. 241, 108259, DOI: 10.1016/j.biocon.2019.108259.

Owens, ACS & Lewis, SM 2018, The impact of artificial light at night on nocturnal insects: a review and synthesis, *Ecology and Evolution*, vol. 8, pp. 11337–11358, DOI: 10.1002/ece3.4557.

Palmer, M, Gibbons, RB, Bhagavathula, R, Holshouser, D & Davidson, D 2017, Roadway lighting's impact on altering soybean growth, vol. 1, Retrieved from https://rosap.ntl.bts.gov/view/dot/32411.

Pandi-Perumal, SR, Srinivasan, V, Maestroni, G, Cardinali, D, Poeggeler, B & Hardeland, R 2006, Melatonin: nature's most versatile biological signal?, *The FEBS Journal*, vol. 273, pp. 2813–2838, DOI: 10.1111/j.1742-4658.2006.05322.x.

Park, J, Lee, HB, An, SK, Lee, JH & Kim, KS 2020, Increasing duration and intensity of nighttime supplemental lighting promotes growth and photosynthesis in young Cymbidium plants, *Horticulture, Environment, and Biotechnology*, DOI: DOI.org/10.1007/s13580-021-00352-z.

Paton, DC & Ford, HA 1977, Pollination by Birds of Native Plants in South Australia, *Emu - Austral Ornithology,* vol. 77(2), pp. 73–85, DOI: 10.1071/MU9770073.

Patriarca, E & Debernardi, P 2010, Bats and light pollution, accessed 31 May 2022.

Pawson, SM & Bader, MK-F 2014, LED lighting increases the ecological impact of light pollution irrespective of color temperature, *Ecological Applications,* vol. 24(7), pp. 1561–1568, DOI: 10.1890/14-0468.1.

Pendoley, K & Kamrowski, RL 2015a, Influence of horizon elevation on the sea-finding behaviour of hatchling flatback turtles exposed to artificial light glow, *Marine Ecology Progress Series*, vol. 529, pp. 279–288, DOI: 10.3354/meps11305.

Pendoley, K & Kamrowski, RL 2015b, Sea-finding in marine turtle hatchlings: what is an appropriate exclusion zone to limit disruptive impacts of industrial light at night?, *Journal for Nature Conservation*, vol. 30, pp. 1–11, DOI: 10.1016/j.jnc.2015.12.005.

Pendoley, K 2000, The influence of gas flares on the orientation of green turtle hatchlings at Thevenard Island, Western Australia, in NJ Pilcher & G Ismail (eds), *Second ASEAN Symposium and Workshop on Sea Turtle Biology and Conservation*, ASEAN Academic Press, Kota Kinabalu, Borneo, pp. 130–142.

Pendoley, KL 2005, Sea turtles and the environmental management of industrial activities in north west Western Australia, PhD thesis, Murdoch University, accessed 31 May 2022.

Pendoley, KL, Whittock, PA, Vitenbergs, A & Bell, CD 2016, Twenty years of turtle tracks: marine turtle nesting activity at remote locations in the Pilbara, Western Australia, *Australian Journal of Zoology*, vol. 64, pp. 217–226, DOI: 10.1071/ZO16021.

Pennell, JP 2000, *The effect of filtered roadway lighting on nesting by loggerhead sea turtles (Caretta caretta) and green turtle (Chelonia mydas) hatchlings*, Florida Atlantic University, Boca Raton.

Pérez-Granados, C & López-Iborra, GM 2020, Dupont's Lark males start to sing earlier but reduce song rate on full moon dawns, *Journal of Ornithology,* vol. 161(2), pp. 421–428, DOI: 10.1007/s10336-019-01731-1.

Perkin, EK, Hölker, F, Richardson, JS, Sadler, JP, Wolter, C & Tockner, K 2011, The influence of artificial light on stream and riparian ecosystems: questions, challenges, and perspectives, *Ecosphere,* vol. 2(11), DOI: https://DOI.org/10.1890/ES11-00241.1.

Perkin, EK, Hölker, F & Tockner, K 2014, The effects of artificial lighting on adult aquatic and terrestrial insects, *Freshwater Biology,* vol. *59*, pp. 368–377, DOI: 10.1111/fwb.12270.

Perry, G & Fisher, RN 2006, Night lights and reptiles: Observed and potential effects, In C, Rich & T, Longcore (Eds.), *Ecological consequences of artificial night lighting*, pp. 169–191, Washington: Island Press.

Pettersen, R, I, Torre, S & Gislerød, H, R, 2010, Effects of leaf aging and light duration on photosynthetic characteristics in a cucumber canopy, *Scientia Horticulturae,* vol. 125, pp. 82–87, DOI: 10.1016/j.scienta.2010.02.016.

Phillips, NG, Lewis, JD, Logan, BA & Tissue, DT 2010, Inter- and intra-specific variation in nocturnal water transport in Eucalyptus, *Tree Physiology,* vol. 30, pp. 586–596, DOI: 10.1093/treephys/tpq009.

Phillips, RD, Bohman, B & Peakall, R 2021, Pollination by nectar-foraging pompilid wasps: a new specialized pollination strategy for the Australian flora, *Plant Biology,* vol. 23(5), pp. 702–710, DOI: https://DOI.org/10.1111/plb.13286.

Phillips RD, Peakall R, Retter BA, Montgomery K, Menz MH, Davis BJ, Hayes C, Brown GR, Swarts ND & Dixon KW 2015, Pollinator rarity as a threat to a plant with a specialized pollination system, *Botanical Journal of the Linnean Society,* vol. 179(3), pp. 511–525, DOI: https://DOI.org/10.1111/boj.12336.

Piersma, T & Baker, AJ 2000, Life history characteristics and the conservation of migratory shorebirds, in LM Gosling & WJ Sutherland (eds), *Behaviour and conservation*, Cambridge University Press, Cambridge, pp. 105–124.

Podolsky, R, Ainley, D, Spencer, G, Deforest, L & Nur, N 1998, Mortality of Newell's shearwaters caused by collisions with urban structures on Kauai, *Colonial Waterbirds*, vol. 21, pp. 20–34, DOI: 10.2307/1521727.

Polak, T, Korine, C, Yair, S & Holderied, MW 2011, Differential effects of artificial lighting on flight and foraging behaviour of two sympatric bat species in a desert, *Journal of Zoology*, vol. 285, pp. 21–27, DOI: 10.1111/j.1469-7998.2011.00808.x.

Poot, H, Ens, B, Vries, H, Donners, MAH, Wernand, MR & Marquenie, JM 2008, Green light for nocturnally migrating birds, *Ecology and Society*, vol. 13(2), pp. 47, DOI: 10.5751/ES-02720-130247.

Post, E & Forchhammer, MC 2008, Climate change reduces reproductive success of an Arctic herbivore through trophic mismatch, *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 363, pp. 2367–2373, DOI: 10.1098/rstb.2007.2207.

Price, JT, Drye, B, Domangue, RJ & Paladino, FV 2018, Exploring the role of artificial light in loggerhead turtle (Caretta caretta) nest-site selection and hatchling disorientation, *Herpetological Conservation and Biology*, vol. 13(2), pp. 415–422.

Poulin, C, Bruyant, F, Laprise, M-H, Cockshutt, AM, Marie-Rose Vandenhecke, J & Huot, Y 2013, The impact of light pollution on diel changes in the photophysiology of Microcystis aeruginosa, *Journal of Plankton Research,* vol. 36(1), pp. 286–291, DOI: 10.1093/plankt/fbt088.

Prihartato, PK, Irigoien, X, Genton, MG & Kaartvedt, S 2016, Global effects of moon phase on nocturnal acoustic scattering layers, *Marine Ecology Progress Series,* vol. 544, pp. 65–75, Retrieved from https://www.jstor.org/stable/24896790.

Rahman, SA, Kollara, A, Brown, TJ & Casper, RF 2008, Selectively filtering short wavelengths attenuates the disruptive effects of nocturnal light on endocrine and molecular circadian phase markers in rats, *Endocrinology*, vol. 149, pp. 6125–6135, DOI: 10.1210/en.2007-1742.

Raine, H, Borg, JJ, Raine, A, Bariner, S & Cardona, MB 2007, Light pollution and its effect on yelkouan shearwaters in Malta: causes and solutions, BirdLife Malta, Malta: Life Project Yelkouan Shearwater, pp. 1–54, accessed 31 May 2022.

Rand, AS, Bridarolli, ME, Dries, L & Ryan, MJ 1997, Light Levels Influence Female Choice in Túngara Frogs: Predation Risk Assessment? *Copeia,* vol. 1997(2), pp. 447–450, DOI: 10.2307/1447770.

Rasmussen, G & Macdonald, D 2012, Masking of the zeitgeber: African wild dogs mitigate persecution by balancing time, *Journal of Zoology*, vol. 286, pp. 232–242, DOI: 10.1111/j.1469-7998.2011.00874.x.

Rawsthorne, J, Watson, DM & Roshier, DA 2012, The restricted seed rain of a mistletoe specialist, *Journal of Avian Biology,* vol. 43(1), pp. 9–14, DOI: https://DOI.org/10.1111/j.1600-048X.2011.05515.x.

Reed, DF & Woodard, TN 1981, Effectiveness of highway lighting in reducing deer-vehicle accidents, *The Journal of Wildlife Management*, vol. 45, pp. 721–726, DOI: 10.2307/3808706.

Reed, JR 1986, 'Seabird vision: spectral sensitivity and light-attraction behavior', PhD thesis, University of Wisconsin, Madison.

Reed, JR, Sincock, JL & Hailman, JP 1985, Light attraction in endangered procellariform birds: reduction by shielding upward radiation, *The Auk*, vol. 102, pp. 377–383, DOI: 10.2307/4086782.

Rich, C & Longcore, T (eds) 2006, Ecological consequences of artificial night lighting, Island Press, Washington DC, accessed 31 May 2022.

Ries, L, Fletcher, RJ, Battin, J & Sisk, TD 2004, Ecological Responses to Habitat Edges: Mechanisms, Models, and Variability Explained, *Annual Review of Ecology, Evolution, and Systematics,* vol. 35, pp. 491–522, Retrieved from http://www.jstor.org/stable/30034125.

Rodríguez, A, Orozco-Valor, PM & Sarasola, JH 2021, Artificial light at night as a driver of urban colonization by an avian predator, *Landscape Ecology,* vol. 36(1), pp. 17–27, DOI: 10.1007/s10980-020-01132-3.

Robert, KA, Lesku, JA, Partecke, J & Chambers, B 2015, Artificial light at night desynchronizes strictly seasonal reproduction in a wild mammal, *Proceedings of the Royal Society B: Biological Sciences*, vol. 282, 20151745, DOI: 10.1098/rspb.2015.1745.

Roberts, BJ, Catterall, CP, Eby, P & Kanowski, J 2012, Long-distance and frequent movements of the Flying-fox Pteropus poliocephalus: implications for management, *PLoS One*, vol. 7, e42532, DOI: 10.1371/journal.pone.0042532.

Robertson, K, Booth, DT & Limpus, CJ 2016, An assessment of 'turtle-friendly' lights on the sea-finding behaviour of loggerhead turtle hatchlings (Caretta caretta), *Wildlife Research*, vol. 43, pp. 27–37, DOI: 10.1071/WR15138.

Rodríguez, A, Burgan, G, Dann, P, Jessop, R, Negro, JJ & Chiaradia, A 2014, Fatal attraction of short-tailed shearwaters to artificial lights, *PLoS ONE*, vol. 9(10), e110114, DOI: 10.1016/j.jnc.2017.07.001.

Rodríguez, A, Dann, P & Chiaradia, A 2017, Reducing light-induced mortality of seabirds: high pressure sodium lights decrease the fatal attraction of shearwaters, *Journal for Nature Conservation*, vol. 39, pp. 68–72, DOI: 10.1016/j.jnc.2017.07.001.

Rodríguez, A, García, D, Rodríguez, B, Cardona, E, Parpal, L & Pons, P 2015, Artificial lights and seabirds: is light pollution a threat for the threatened Balearic petrels?, *Journal of Ornithology*, vol. 156, pp. 893–902, DOI: 10.1007/s10336-015-1232-3.

Rodríguez, A, Holmberg, R, Dann, P & Chiaradia, A 2018, Penguin colony attendance under artificial lights for ecotourism, *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, vol. 329(8–9), pp. 457–464, DOI: 10.1002/jez.2155.

Rodríguez, A, Holmes, ND, Ryan, PG, Wilson, K-J, Faulquier, L, Murillo, Y, Raine, AF, Penniman, J, Neves, V, Rodríguez, B, Negro, JJ, Chiaradia, A, Dann, P, Anderson, T, Metzger, B, Shirai, M, Deppe L, Wheeler J, Hodum P, Gouveia C, Carmo V, Carreira GP, Delgado-Alburqueque L, Guerra-Correa C, Couzi F-X, Travers M & Le Corre M 2017a, A global review of seabird mortality caused by land-based artificial lights, *Conservation Biology*, vol. 31, pp. 986–1001, DOI: 10.1111/cobi.12900.

Rodríguez, A, Moffet, J, Revoltós, A, Wasiak, P, McIntosh, RR, Sutherland, DR, Renwick, L, Dann, P & Chiaradia, A 2017b, Light pollution and seabird fledglings: targeting efforts in rescue programs, *Journal of Wildlife Management*, vol. 81, pp. 734–741, DOI: 10.1002/jwmg.21237.

Rodríguez, A, Rodríguez, B & Lucas, MP 2012, Trends in numbers of petrels attracted to artificial lights suggest population declines in Tenerife, Canary Islands, *Ibis*, vol. 154, pp. 167–172, DOI: 10.1111/j.1474-919X.2011.01175.x.

Rodríguez, A, Rodríguez, B & Negro, JJ 2015, GPS tracking for mapping seabird mortality induced by light pollution, *Scientific Reports*, vol. 5, 10670, DOI: 10.1038/srep10670.

Rogers, DI, Battley, PF, Piersma, T, Van Gils, JA & Rogers, KG 2006, High-tide habitat choice: insights from modelling roost selection by shorebirds around a tropical bay, *Animal Behaviour*, vol. 72(3), pp. 563–575, DOI: 10.1016/j.anbehav.2005.10.029.

Rogers, DI, Piersma, T & Hassell, CJ 2006, Roost availability may constrain shorebird distribution: exploring the energetic costs of roosting and disturbance around a tropical bay, *Biological Conservation*, vol. 133(2), pp. 225–235, DOI: 10.1016/j.biocon.2006.06.007.

Rojas, LM, McNeil, R, Cabana, T & Lachapelle, P 1999, Diurnal and nocturnal visual capabilities in shorebirds as a function of their feeding strategies, *Brain Behavior and Evolution*, vol. 53(1), pp. 29–43, DOI: 10.1159/000006580.

Ronconi, RA, Allard, KA & Taylor, PD 2015, Bird interactions with offshore oil and gas platforms: review of impacts and monitoring techniques, *Journal of Environmental Management*, vol. 147, pp. 34–45, DOI: 10.1016/j.jenvman.2014.07.031.

Rosas-Guerrero, V, Aguilar, R, Martén-Rodríguez, S, Ashworth, L, Lopezaraiza-Mikel, M, Bastida, JM & Quesada, M 2014, A quantitative review of pollination syndromes: do floral traits predict effective pollinators? *Ecology Letters,* vol. 17(3), pp. 388–400, DOI: https://DOI.org/10.1111/ele.12224.

Ross, GJB, Burbidge, AA, Canty, P, Dann, P, Fuller, PJ, Kerry, KR, Norman, FI, Menkhorst, PW, Shaughnessy, G, Shaughnessy, PD & Smith, GC 1996, Status of Australia's seabirds, in *State of the Environment Report*, CSIRO Sustainable Ecosystems, Perth, pp. 167–182.

Rotics, S, Dayan, T & Kronfeld-Schor, N 2011, Effect of artificial night lighting on temporally partitioned spiny mice, *Journal of Mammalogy*, vol. 92, pp. 159–168, DOI: 10.1644/10-MAMM-A-112.1.

Rowse, EG, Lewanzik, D, Stone, EL, Harris, S & Jones, G 2016, Dark matters: the effects of artificial lighting on bats, in CC Voigt & T Kingston (eds) *Bats in the anthropocene: conservation of bats in a changing world*, Springer International Publishing, Cham, accessed 31 May 2022.

Ruckle, ME, DeMarco, SM & Larkin, RM 2007, Plastid Signals Remodel Light Signaling Networks and Are Essential for Efficient Chloroplast Biogenesis in Arabidopsis, *The Plant Cell,* vol. 19, pp. 3944–3960, DOI: 10.1105/tpc.107.054312.

Russ, A, Rüger, A & Klenke, R 2015, Seize the night: European Blackbirds (Turdus merula) extend their foraging activity under artificial illumination, *Journal of Ornithology,* vol. 156, pp. 123–131.

Russart, KLG & Nelson, RJ 2018a, Artificial light at night alters behavior in laboratory and wild animals, *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, vol. 329(8–9), pp. 401–408, DOI: 10.1002/jez.2173.

Russart, KLG & Nelson, RJ 2018b, Light at night as an environmental endocrine disruptor, *Physiology & behavior*, vol. 190, pp. 82–89, DOI: 10.1016/j.physbeh.2017.08.029.

Rydell, J 1992, Exploitation of insects around streetlamps by bats in Sweden, *Functional Ecology*, vol. 6, pp. 744–750, DOI: 10.2307/2389972.

Rydell, J 2005, Bats and their insect prey at streetlights, in T Longcore & C Rich (eds), Ecological consequences of artificial night lighting, accessed 31 May 2022.

Sameoto, D, Cochrane, NA & Herman, AW 1985, Response of Biological Acoustic Backscattering to Ships' Lights, *Canadian Journal of Fisheries and Aquatic Sciences,* vol. 42(9), pp. 1535–1543, DOI: 10.1139/f85-192.

Salmon, M & Wyneken, J 1990, Do swimming loggerhead turtles (Caretta L.) use light cues for offshore orientation? *Marine Behavioural Physiology*, vol. 17, pp. 233–246, DOI: 10.1080/10236249009378774.

Salmon, M 2003, Artificial night lighting and sea turtles, *Biologist*, vol. 50, pp. 163–168, accessed 31 May 2022.

Salmon, M 2006, Protecting sea turtles from artificial night lighting at Florida's oceanic beaches, in C Rich & T Longcore (eds), *Ecological consequences of artificial night lighting*, Island Press, Washington DC, pp. 141–168, accessed 31 May 2022.

Salmon, M, Reiners, R, Lavin, C & Wyneken, J 1995, Behavior of loggerhead sea turtles on an urban beach. I: Correlates of nest placement, *Journal of Herpetology*, vol. 29(4), pp. 560–567, DOI: 10.2307/1564739.

Salmon, M, Wyneken, J, Fritz, E & Lucas, M 1992, Sea finding by hatchling sea turtles: role of brightness, silhouette and beach slope as orientation cues, *Behaviour*, vol. 122, pp. 56–77, accessed 31 May 2022.

Sánchez-Bayo, F & Wyckhuys, KaG 2019, Worldwide decline of the entomofauna: a review of its drivers, *Biological Conservation*, vol. 232, pp. 8–27, DOI: 10.1016/j.biocon.2019.01.020.

Sánchez de Miguel, A, Bennie, J, Rosenfeld, E, Dzurjak, S, Gaston, KJ 2021, First Estimation of Global Trends in Nocturnal Power Emissions Reveals Acceleration of Light Pollution, *Remote Sensing*, vol. 13(16), 3311, DOI: 10.3390/rs13163311.

Sanders, D, Frago, E, Kehoe, R, Patterson, C & Gaston, KJ 2021, A meta-analysis of biological impacts of artificial light at night, *Nature Ecology & Evolution*, vol. 5, pp. 74–81, DOI: 10.1038/s41559-020-01322-x.

Sanders, D & Gaston, KJ 2018, How ecological communities respond to artificial light at night, *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, vol. 329(8–9), pp. 394–400, DOI: 10.1002/jez.2157.

Santiago-Quesada, F, Estrella, SM, Sanchez-Guzman, JM & Masero, JA 2014, Why water birds forage at night: a test using black-tailed godwits Limosa limosa during migratory periods, *Journal of Avian Biology*, vol. 45(4), pp. 406–409, DOI: 10.1111/jav.00420.

Santos, CD, Miranda, AC, Granadeiro, JP, Lourenço, PM, Saraiva, S & Palmeirim, JM 2010, Effects of artificial illumination on the nocturnal foraging of waders, *Acta Oecologica*, vol. 36, pp. 166–172, DOI: 10.1016/j.actao.2009.11.008.

Schoenle, LA, Zimmer, C & Vitousek, MN 2018, Understanding context dependence in glucocorticoid–fitness relationships: the role of the nature of the challenge, the intensity and frequency of stressors, and life history, *Integrative and Comparative Biology*, vol. 58, pp. 777–789, DOI: 10.1093/icb/icy046.

Schroer, S & Hölker, F 2016, Impact of lighting on flora and fauna, in R Karlicek, CC Sun, G Zissis & R Ma (eds), *Handbook of advanced lighting technology*, Springer International Publishing, pp. 1–33.

Scudder, GGE 2017, The Importance of Insects, In RG Foottit & PH Adler (Eds.), *Insect Biodiversity : Science and Society - Volume 1*, Hoboken, UNITED KINGDOM: John Wiley & Sons, Incorporated.

Segrestin J, Mondy N, Boisselet C, Guigard L, Lengagne T, Poussineau S, Secondi J & Puijalon S 2021, Effects of artificial light at night on the leaf functional traits of freshwater plants, *Freshwater Biology,* vol. 66(12), pp. 2264–2271, DOI: https://DOI.org/10.1111/fwb.13830.

Serventy, DL, Serventy, VN & Warham, J 1971, *The handbook of Australian sea-birds*, Sydney.

Shier, DM, Bird, AK & Wang, TB 2020, Effects of artificial light at night on the foraging behavior of an endangered nocturnal mammal, *Environmental Pollution*, vol. 263, 114566, DOI: 10.1016/j.envpol.2020.114566.

Silva, AD, Diez-Méndez, D & Kempenaers, B 2017, Effects of experimental night lighting on the daily timing of winter foraging in common European songbirds, *Journal of Avian Biology,* vol. *48*, pp. 862–871.

Simões, BF, Foley, NM, Hughes, GM, Zhao, H, Zhang, S, Rossiter, SJ & Teeling, EC 2018, As blind as a bat? Opsin phylogenetics illuminates the evolution of color vision in bats, *Molecular Biology and Evolution*, vol. 36, pp. 54–68, DOI: 10.1093/molbev/msy192.

Singhal, RK, Kmar, M & Bose, B 2019, Eco-physiological responses of artificial night light pollution in plants, *Russian Journal of Plant Physiology,* vol. 66(2), pp. 109–202, DOI: 10.1134/S1021443719020134.

Škvareninová J, Tuhárska M, Škvarenina J, Babálová D, Slobodníková L, Slobodník B, Středová H & Minďaš J 2017, Effects of light pollution on tree phenology in the urban environment, *Moravian Geographical Reports,* vol. 25(4), pp. 282–290, DOI: 10.1515/mgr-2017-0024.

Smith, TM, Hindell, JS, Jenkins, GP, Connolly, RM & Keough, MJ 2011, Edge effects in patchy seagrass landscapes: The role of predation in determining fish distribution, *Journal of*

Experimental Marine Biology and Ecology, vol. 399(1), pp. 8–16, DOI: https://DOI.org/10.1016/j.jembe.2011.01.010.

Smyth TJ, Wright AE, Mckee D, Tidau S, Tamir R, Dubinsky Z, Iluz D, Davies TW 2021, A global atlas of artificial light at night under the sea, *Elementa: Science of the Anthropocene,* vol. 9(1), DOI: 10.1525/elementa.2021.00049.

Soanes, K, Taylor, AC, Sunnucks, P, Vesk, PA, Cesarini, S & van der Ree, R 2018, Evaluating the success of wildlife crossing structures using genetic approaches and an experimental design: Lessons from a gliding mammal, *Journal of Applied Ecology,* vol. 55(1), pp. 129–138, DOI: https://DOI.org/10.1111/1365-2664.12966.

Sordello, R, Busson, S, Cornuau, JH, Deverchère P, Faure, B, Guetté, A, Hölker, F, Kerbiriou, C, Lengagne, T, Le Viol, I & Longcore, T 2022, A plea for a worldwide development of dark infrastructure for biodiversity – Practical examples and ways to go forward, *Landscape and Urban Planning,* vol. 219, DOI: https://DOI.org/10.1016/j.landurbplan.2021.104332.

Spoelstra, K, Van Grunsven, RHA, Ramakers, JJC, Ferguson, KB, Raap, T, Donners, MaH, Veenendaal, EM & Visser, ME 2017, Response of bats to light with different spectra: light-shy and agile bat presence is affected by white and green, but not red light. *Proceedings of the Royal Society B*, vol. 284, 20170075, DOI: 10.1098/rspb.2017.0075.

Staicer, CA, Spector, DA & Horn, AG 2019, The Dawn Chorus and Other Diel Patterns in Acoustic Signaling, In E, K, Donald & H, M, Edward (Eds.), *Ecology and Evolution of Acoustic Communication in Birds*, pp. 426–453, Cornell University Press.

State of Queensland 2020, Flying-fox roost management guideline, Department of Environment and Science, accessed 31 May 2022.

Stone, EL, Harris, S & Jones, G 2015, Impacts of artificial lighting on bats: a review of challenges and solutions, *Mammalian Biology*, vol. 80, pp. 213–219, DOI: 10.1016/j.mambio.2015.02.004.

Surman, CA & Nicholson, LW 2014a, *Monitoring of annual variation in seabird breeding colonies throughout the Lowendal Group of islands: 2014 annual report*, Lowendal Island Seabird Monitoring Program (LISMP), unpublished report prepared for Apache Energy Ltd by Halfmoon Biosciences.

Surman, CA & Nicholson, LW 2014b, *The Integrated Shearwater Monitoring Project (ISMP): annual report for the 2013/14 season*, unpublished report prepared for Apache Energy Ltd by Halfmoon Biosciences.

Syposz, M, Goncalves, F, Carty, M, Hoppitt, W & Manco, F 2018, Factors influencing Manx shearwater grounding on the west coast of Scotland, *Ibis*, vol. 160, pp. 846–854, DOI: 10.1111/ibi.12594.

Sysoeva, MI, Markovskaya, EF & Shibaeva, TG 2010, Plants under Continuous Light: A Review, *Plant Stress,* vol. 4(1), pp. 5–17.

Szaz D, Horvath G, Barta A, Robertson BA, Farkas A, Egri A, Tarjanyi N, Racz G & Kriska G 2015, Lamp-lit bridges as dual light-traps for the night-swarming mayfly, Ephoron virgo: interaction of polarized and unpolarized light pollution, *PLoS ONE,* vol. 10(3), e0121194–e0121194, DOI: 10.1371/journal.pone.0121194.

Tanner, JE 2005, Edge effects on fauna in fragmented seagrass meadows, *Austral Ecology,* vol. 30(2), pp. 210–218, DOI: https://DOI.org/10.1111/j.1442-9993.2005.01438.x.

Telfer, TC, Sincock, JL, Byrd, GV & Reed, JR 1987, Attraction of Hawaiian seabirds to lights: conservation efforts and effects of moon phase, *Wildlife Society Bulletin*, vol. 15, pp. 406–413, accessed 31 May 2022.

Thapan, K, Arendt, J & Skene, DJ 2001, An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans, *The Journal of Physiology*, vol. 535, pp. 261–267, DOI: 10.1111/j.1469-7793.2001.t01-1-00261.x.

Thébault, E & Fontaine, C 2010, Stability of Ecological Communities and the Architecture of Mutualistic and Trophic Networks, *Science,* vol. 329(5993), pp. 853–856, Retrieved from http://www.jstor.org/stable/40799748.

Theimer, TC 2001, Seed scatterhoarding by white-tailed rats: consequences for seedling recruitment by an Australian rain forest tree, *Journal of Tropical Ecology,* vol. 17(2), pp. 177–189, DOI: 10.1017/S0266467401001122.

Thomas, RJ, Székely, T, Cuthill, IC, Harper, DG, Newson, SE, Frayling, TD & Wallis, PD 2002, Eye size in birds and the timing of song at dawn, *Proc Biol Sci,* vol. 269(1493), pp. 831–837, DOI: 10.1098/rspb.2001.1941.

Threlfall, CG, Law, B & Banks, PB 2013, The urban matrix and artificial light restricts the nightly ranging behaviour of Gould's long-eared bat (Nyctophilus gouldi), *Austral Ecology,* vol. 38(8), pp. 921–930, DOI: https://DOI.org/10.1111/aec.12034.

Thums, M, Whiting, SD, Reisser, JW, Pendoley, KL, Pattiaratchi, CB, Proietti, M, Hetzel, Y, Fisher, R & Meekan, M 2016, Artificial light on water attracts turtle hatchlings during their near shore transit, *Royal Society Open Science*, vol. 3, e160142, DOI: 10.1098/rsos.160142.

Tidau S, Smyth T, McKee D, Wiedenmann J, D'Angelo C, Wilcockson D, Ellison A, Grimmer AJ, Jenkins SR, Widdicombe S & Queirós AM 2021, Marine artificial light at night: An empirical and technical guide, *Methods in Ecology and Evolution,* vol. 12(9), pp. 1588–1601, DOI: https://DOI.org/10.1111/2041-210X.13653.

Tosini, G, Ferguson, I & Tsubota, K 2016, Effects of blue light on the circadian system and eye physiology, *Molecular Vision*, vol. 22, pp. 61–72, accessed 31 May 2022.

Touzot M, Lefebure T, Lengagne T, Secondi J, Dumet A, Konecny-Dupre L, Veber P, Navratil V, Duchamp C & Mondy N 2022, Transcriptome-wide deregulation of gene expression by artificial light at night in tadpoles of common toads, *Science of The Total Environment,* vol. 818, DOI: https://DOI.org/10.1016/j.scitotenv.2021.151734.

Touzot M, Lengagne T, Secondi J, Desouhant E, Théry M, Dumet A, Duchamp C & Mondy N 2020, Artificial light at night alters the sexual behaviour and fertilisation success of the common toad, *Environmental Pollution,* vol. *259*, DOI: https://DOI.org/10.1016/j.envpol.2019.113883.

Troy, J, Holmes, N, Veech, J & Green, M 2013, Using observed seabird fallout records to infer patterns of attraction to artificial light, *Endangered Species Research*, vol. 22, pp. 225–234, DOI: 10.3354/esr00547.

Truscott, Z, Booth, DT & Limpus, CJ 2017, The effect of on-shore light pollution on sea-turtle hatchlings commencing their off-shore swim, *Wildlife Research* 3(5), pp. 127–134, DOI: 10.1071/WR16143.

Ulrich J, Bucher SF, Eisenhauer N, Schmidt A, Türke M, Gebler A, Barry K, Lange M & Römermann C 2020, Invertebrate Decline Leads to Shifts in Plant Species Abundance and Phenology, *Frontiers in Plant Science,* vol. *11*, DOI: 10.3389/fpls.2020.542125.

van de Kam, J, Ens, B, Piersma, T & Zwarts, L 2004, *Shorebirds: an illustrated behavioural ecology*, KNNV Publishers, Utrecht, p. 368.

Van Dyck, S & Strahan, R 2008, *The mammals of Australia*, Reed New Holland, Sydney.

Van Gestel NC, Nesbit AD, Gordon EP, Green C, Paré PW, Thompson L, Peffley EB & Tissue DT 2005, Continuous light may induce photosynthetic downregulation in onion - consequences for growth and biomass partitioning, *Physiologia plantarum,* vol. 125(2), pp. 235–246, Retrieved from http://explore.bl.uk/primo_library/libweb/action/display.do?tabs=detailsTab&gathStatTab=true&ct=display&fn=search&doc=ETOCRN174142037&indx=1&recIds=ETOCRN174142037.

van Grunsven, RHA, Becker, J, Peter, S, Heller, S & Hölker, F 2019, Long-Term Comparison of Attraction of Flying Insects to Streetlights after the Transition from Traditional Light Sources to Light-Emitting Diodes in Urban and Peri-Urban Settings, *Sustainability,* vol. 11, pp. 1–9, DOI: 10.3390/su11226198.

van Grunsven, RHA, Creemers, R, Joosten, K, Donners, M & Veenendaal, EM 2017, Behaviour of migrating toads under artificial lights differs from other phases of their life cycle, *Amphibia-Reptilia,* vol. 38(1), pp. 49–55, DOI: https://DOI.org/10.1163/15685381-00003081.

van Grunsven RH, Donners M, Boekee K, Tichelaar I, Van Geffen KG, Groenendijk D, Berendse F, Veenendaal EM 2014, Spectral composition of light sources and insect phototaxis, with an evaluation of existing spectral response models, *Journal of Insect Conservation*, pp. 1–7, DOI: 10.1007/s10841-014-9633-9.

Vásquez, RA 1994, Assessment of predation risk via illumination level: facultative central place foraging in the cricetid rodent Phyllotis darwini, *Behavioral Ecology and Sociobiology*, vol. 34, pp. 375–381, DOI: 10.1007/BF00197008.

Velez-Ramirez, AI, van Ieperen, W, Vreugdenhil, D & Millenaar, FF 2011, Plants under continuous light, *Trends in Plant Science,* vol. 16(6), pp. 310–318, DOI: 10.1016/j.tplants.2011.02.003.

Verheijen, FJ 1985, Photopollution: artificial light optic spatial control systems fail to cope with incidents, causations, remedies. *Experimental Biology*, vol. 44(1), pp. 1–18, accessed 31 May 2022.

Voigt, C, Azam, C, Dekker, J, Ferguson, J, Fritze, M, Gazaryan, S, Hölker, F, Jones, G, Leader, N, Lewanzik, D, Limpens, H, Mathews, F, Rydell, J, Schofield, H, Spoelstra, K & Zagmajster, M 2018, Guidelines for consideration of bats in lighting projects, UNEP/EUROBATS Secretariat, Bonn, accessed 31 May 2022.

Voigt, C & Kingston, T 2016, Bats in the Anthropocene, in C Voigt & T Kingston (eds), *Bats in the Anthropocene: conservation of bats in a changing world*, Springer International Publishing, Cham, accessed 31 May 2022.

Vorobyev, M 2003, Coloured oil droplets enhance colour discrimination, *Proceedings of the Royal Society B: Biological Sciences*, vol. 270, pp. 1255–1261, DOI: 10.1098/rspb.2003.2381.

Wakefield, A, Broyles, M, Stone, EL, Harris, S & Jones, G 2018, Quantifying the attractiveness of broad-spectrum street lights to aerial nocturnal insects, *Journal of Applied Ecology,* vol. 55, pp. 714–722, DOI: 10.1111/1365-2664.13004.

Warham, J 1990, *The behaviour, population biology and physiology of the petrels*, Academic Press, London.

Warrant, EJ, Frost, B, Green, K, Mouritsen, H, Dreyer, D, Adden, A, Brauburger, K & Heinze, S 2016, The Australian Bogong moth Agrotis infusa: a long-distance nocturnal navigator, *Frontiers in Behavioural Neuroscience*, DOI: 10.3389/fnbeh.2016.00077.

Watanuki, Y 1986, Moonlight avoidance behavior in leach’s storm-petrels as a defense against slaty-backed gulls, *The Auk*, vol. 103(1), pp. 14–22, DOI: 10.1093/auk/103.1.14.

Weil, ZM, Borniger, JC, Cisse, YM, Abi Salloum, BA & Nelson, RJ 2015, Neuroendocrine control of photoperiodic changes in immune function, *Frontiers in Neuroendocrinology*, vol. 37, pp. 108–118, DOI: 10.1016/j.yfrne.2014.10.001.

West, KE, Jablonski, MR, Warfield, B, Cecil, KS, James, M, Ayers, MA, Maida, J, Bowen, C, Sliney, DH, Rollag, MD & Hanifin, JP 2010, Blue light from light-emitting diodes elicits a dose-dependent suppression of melatonin in humans, *Journal of Applied Physiology*, vol. 110(3), pp. 619–626, DOI: 10.1152/japplphysiol.01413.2009.

Whiles MR, Lips KR, Pringle CM, Kilham SS, Bixby RJ, Brenes R, Connelly S, Colon-Gaud JC, Hunte-Brown M, Huryn AD & Montgomery C 2006, The effects of amphibian population declines on the structure and function of Neotropical stream ecosystems, *Frontiers in Ecology and the Environment,* vol. 4(1), pp. 27–34, DOI: https://DOI.org/10.1890/1540-9295(2006)004[0027:TEOAPD]2.0.CO;2.

White, D & Gill, J 2007, A “lost years” flatback turtle Natator depressus (Garman, 1858) found, *Northern Territory Naturalist*, vol. 19, pp. 51–53.

Willmott, N, J, Henneken, J, Selleck, CJ & Jones, TM 2018, Artificial light at night alters life history in a nocturnal orb-web spider, *PeerJ,* vol. 6, DOI: 10.7717/peerj.5599.

Wilson, AL & Downs, CT 2015, Light interference and melatonin affects digestion and glucocorticoid metabolites in striped mouse, *Biological Rhythm Research*, vol. 46, pp. 929–939, DOI: 10.1080/09291016.2015.1066546.

Wilson, DE & Mittermeier, RA 2009, *Handbook of the mammals of the world*, Lynx Edicions.

Wilson, P, Thums, M, Pattiaratchi, CB, Meekan, M, Pendoley, K, Fisher, R & Whiting, S 2018, Artificial light disrupts the nearshore dispersal of neonate flatback turtles Natator depressus, *Marine Ecology Progress Series*, vol. 600, pp. 179–192, DOI: 10.3354/meps12649.

Wilson, P, Thums, M, Pattiaratchi, CB, Whiting, S, Pendoley, K, Ferreira, L & Meekan, M 2019, High predation of marine turtle hatchlings near a coastal jetty, *Biological Conservation*, vol. 236, pp. 571–579, DOI: 10.1016/j.biocon.2019.04.015.

Wiltschko, W & Wiltschko, R 1999, The effect of yellow and blue light on magnetic compass orientation in European robins, Erithacus rubecula, *Journal of Comparative Physiology A*, vol. 184, pp. 295–299, DOI: 10.1007/s003590050327.

Winter, Y, López, J & Helversen, O 2003, Ultraviolet vision in a bat, *Nature*, vol. 425, pp. 612–614, DOI: 10.1038/nature01971.

Witherington, B & Martin, RE 2003, *Understanding, assessing, and resolving light-pollution problems on sea turtle nesting beaches*, Florida Fish and Wildlife Conservation Commission FMRI Technical Report TR-2, Jensen Beach, Florida.

Witherington, B 1997, The problem of photopollution for sea turtles and other nocturnal animals, in JR Clemmons & R Buchholz (eds), *Behavioral approaches to conservation in the wild*, Cambridge University Press, Cambridge, pp. 303–328.

Witherington, BE & Bjorndal, KA 1991, Influences of artificial lighting on the seaward orientation of hatchling loggerhead turtles Caretta, *Biological Conservation*, vol. 55(2), pp. 139–149, accessed 31 May 2022.

Witherington, BE 1992, Behavioural response of nesting sea turtles to artificial lighting, *Herpetologica*, vol. 48, pp. 31–39, accessed 31 May 2022.

Wolfe, JL & Summerlin, CT 1989, The influence of lunar light on nocturnal activity of the old-field mouse, *Animal Behaviour*, vol. 37, pp. 410–414, DOI 10.1016/0003-3472(89)90088-2.

Woolley, P 1966, ‘Reproduction in Antechinus spp. and other dasyurid marsupials’, paper presented at Symposia of the Zoological Society of London, London, 10–11 November.

Xiang, S, Dauchy, RT, Hauch, A, Mao, L, Yuan, L, Wren, MA, Belancio, VP, Mondal, D, Frasch, T & Blask, DE 2015, Doxorubicin resistance in breast cancer is driven by light at night-induced disruption of the circadian melatonin signal, *Journal of Pineal Research*, vol. 59, pp. 60–69, DOI: 10.1111/jpi.12239.

Yao, XC, Tu, HQ, Wang, XL & Wang, J 2021, The effect of supplemental LED night lighting on the growth and physiology of the Para rubber tree, *Journal of Rubber Research*, DOI: DOI.org/10.1007/s42464-021-00095-7.

Zeale, MRK, Bennitt, E, Newson, SE, Packman, C, Browne, WJ, Harris, S, Jones, G & Stone, E 2016, Mitigating the impact of bats in historic churches: the response of Natterer’s Bats Myotis nattereri to artificial roosts and deterrence, *PLoS One*, vol. 11, e0146782, DOI: 10.1371/journal.pone.0152531.

Zozaya, SM, Alford, RA & Schwarzkopf, L 2015, Invasive house geckos are more willing to use artificial lights than are native geckos. *Austral Ecology*, vol. 40(8), pp. 982–987. DOI: https://doi.org/10.1111/aec.12287