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UPDATE TO AUSTRALIA’S NATIONAL LIGHT POLLUTION GUIDELINES FOR WILDLIFE TO INCLUDE APPENDICES FOR NON-MIGRATORY TAXA/ECOSYSTEMS: BATS, TERRESTRIAL MAMMALS AND ECOLOGICAL COMMUNITIES

(Submitted by the Government of Australia)

Summary:

The Australian Government has continued to develop additional evidence-based guidance on the impacts of light pollution on wildlife and has updated its National Light Pollution Guidelines to include appendices for non-migratory taxa/ecosystems — bats, terrestrial mammals and ecological communities, which are reproduced in this document.

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.

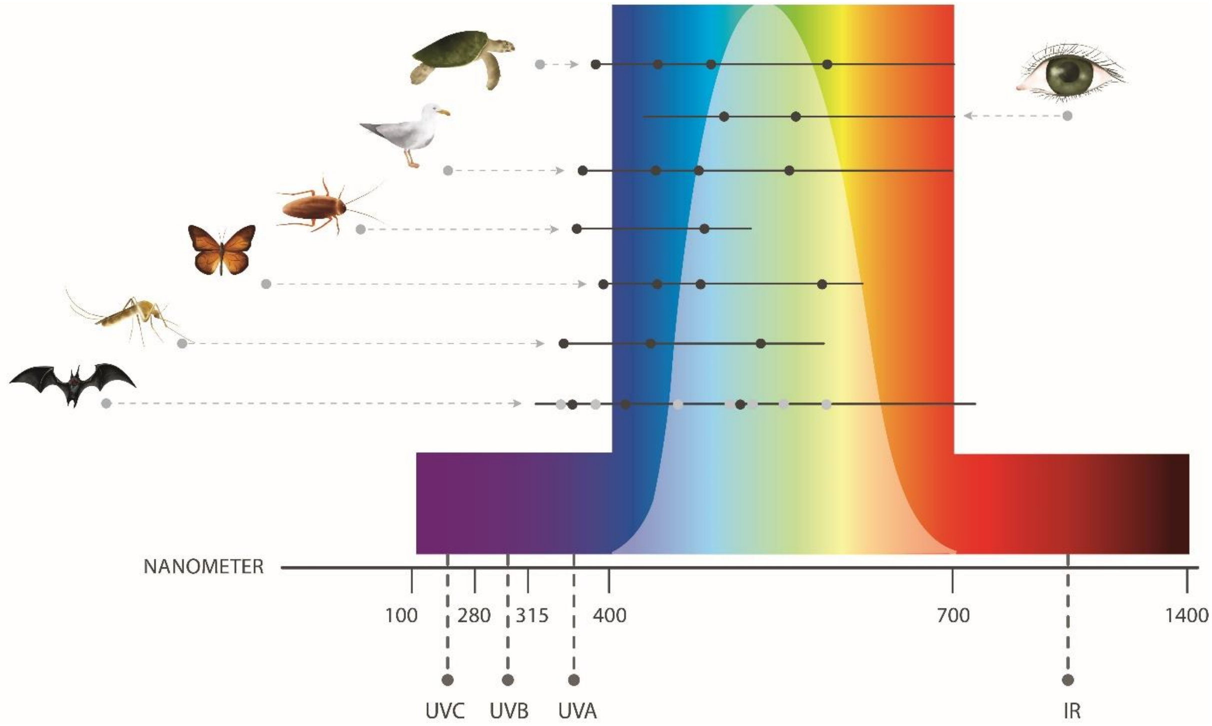
Frugivores and nectarivores

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.

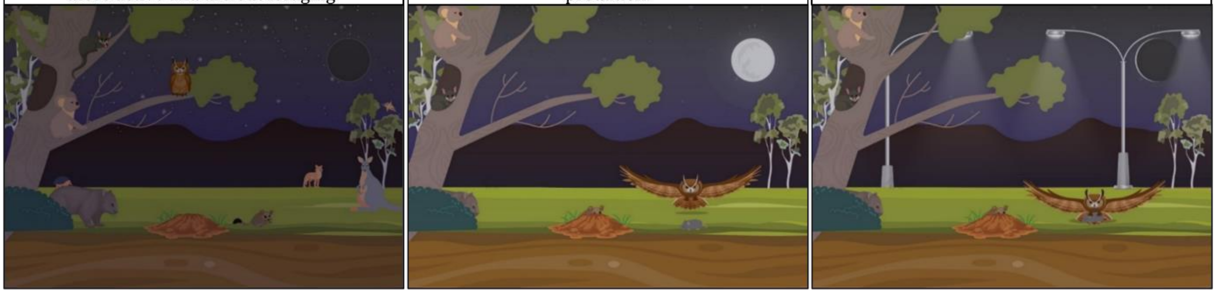
Landscapes fragmented by artificial light can lead to isolated habitat patches and consequently limit access to and between foraging and refuge sites (Bliss-Ketchum et al. 2016; Gaston & Bennie 2014). Fragmentation by artificial light can isolate individuals or populations, limiting breeding opportunities 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).

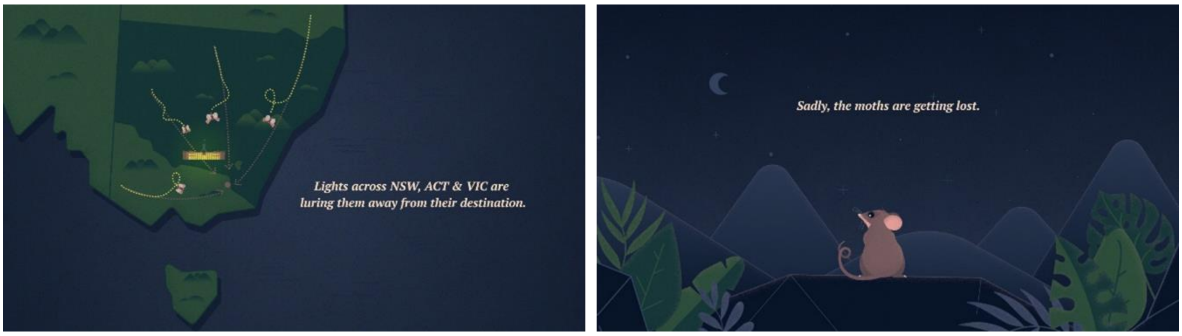
Box 1 Indirect impacts on Mountain Pygmy-possum occurring over large distances

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.

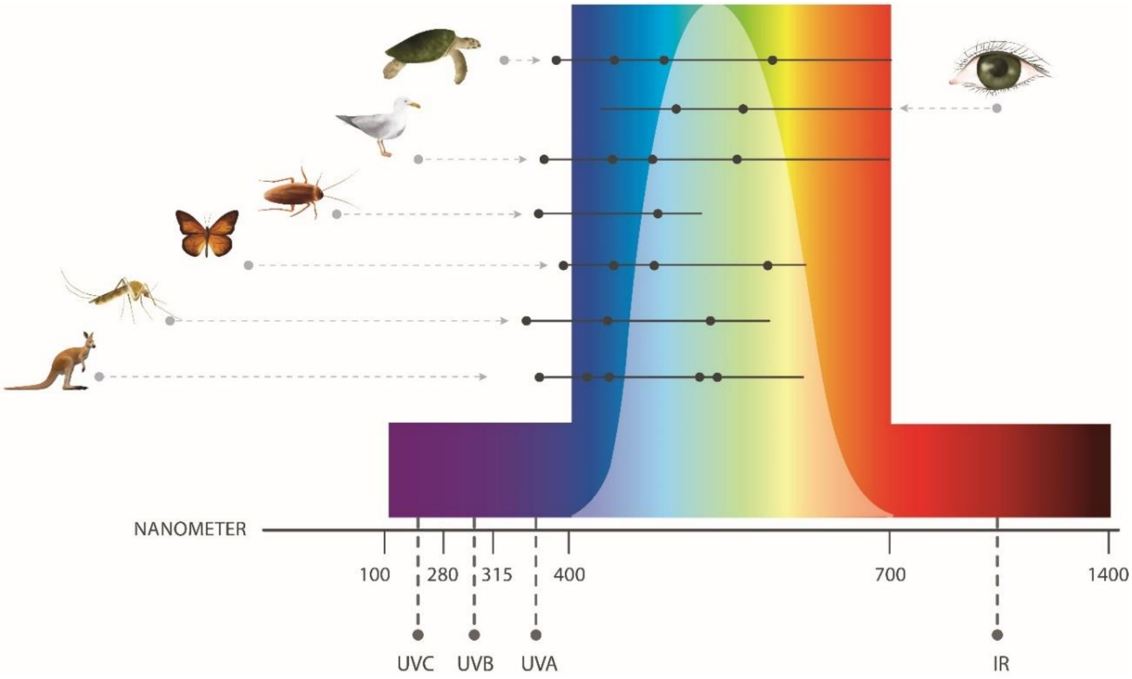
Mitigation of indirect impacts of artificial light

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).

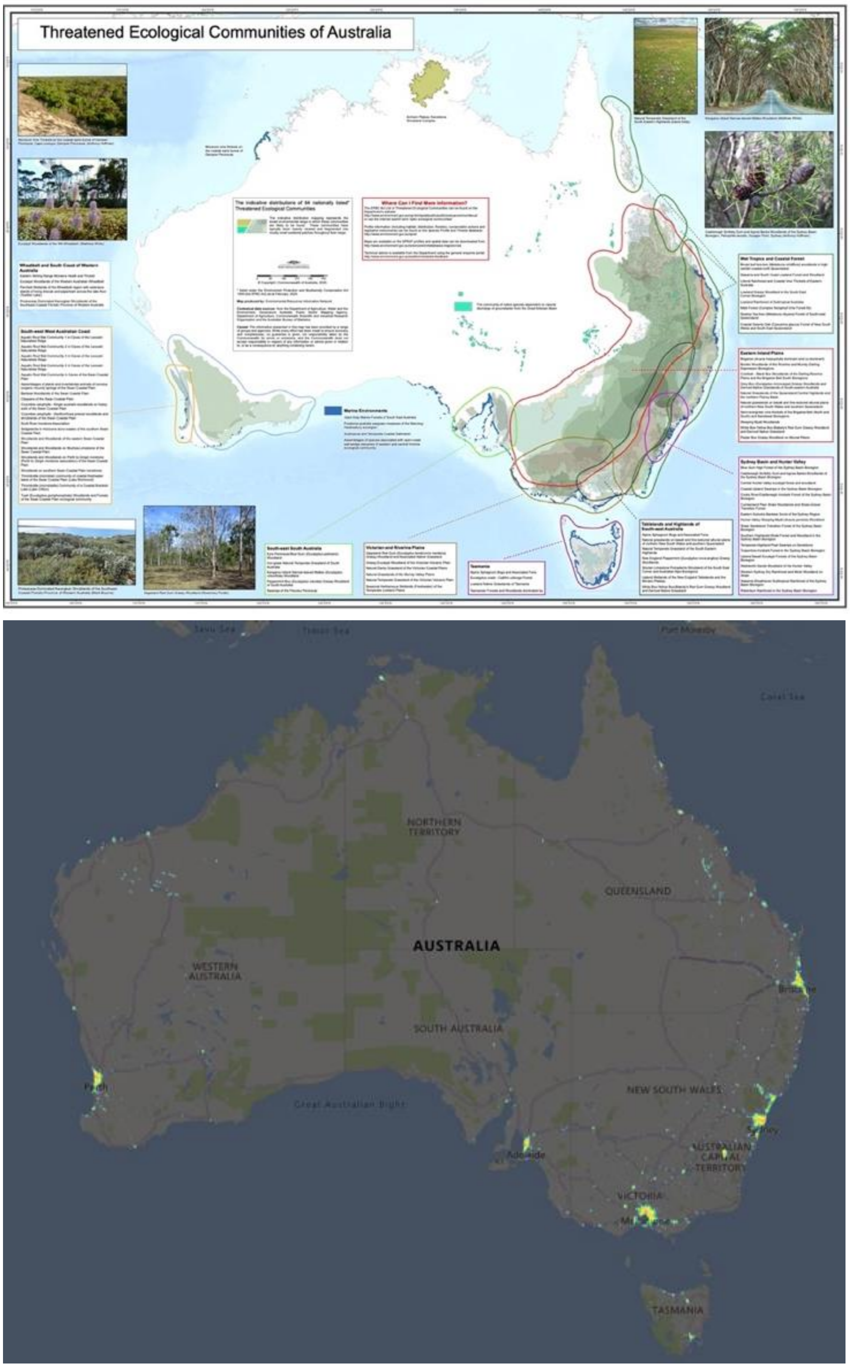
Ecological communities have strong cultural significance for both First Nations and non-indigenous Australians and support important values including native biodiversity and distinctive landscapes and seascapes. ECs also provide vital ecosystem services to both humans and wildlife, including the management 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).

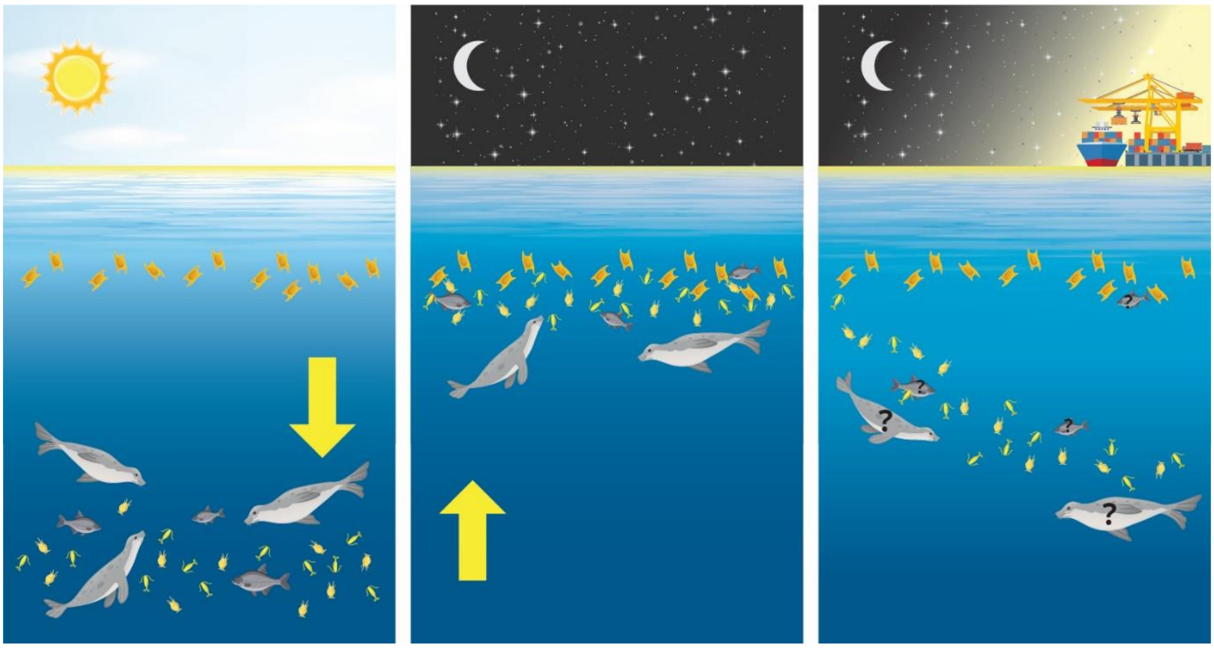


Figure 39: Effects of artificial light on vertical migration in aquatic systems

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.

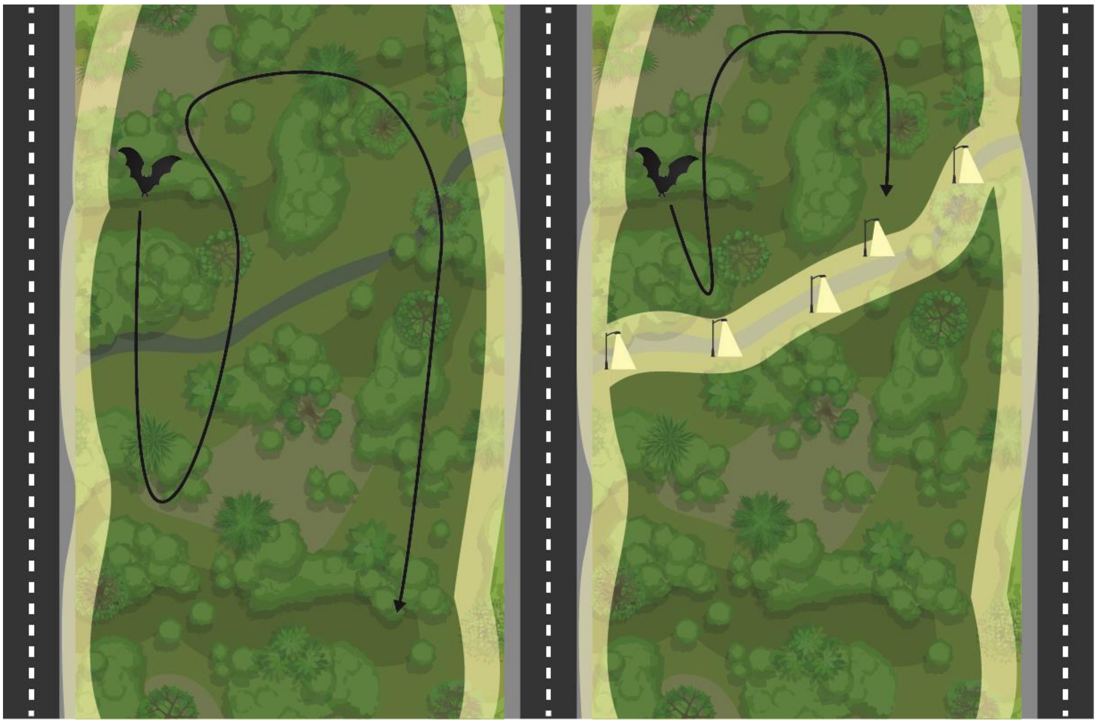


Figure 40: Effects of artificial light on habitat fragmentation and edge effects

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).

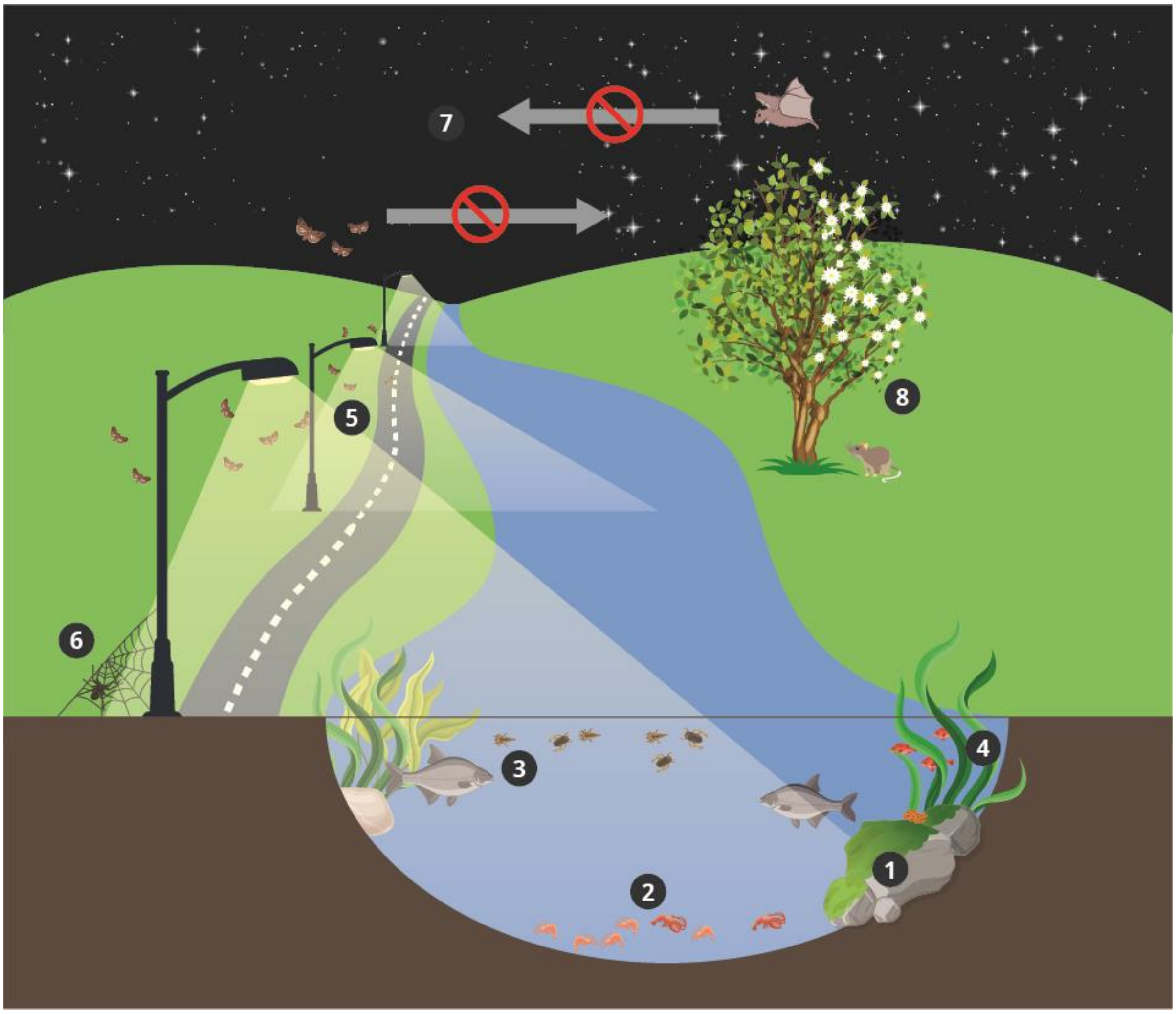


Figure 41: Effects of artificial light on food webs, pollination and seed dispersal

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.

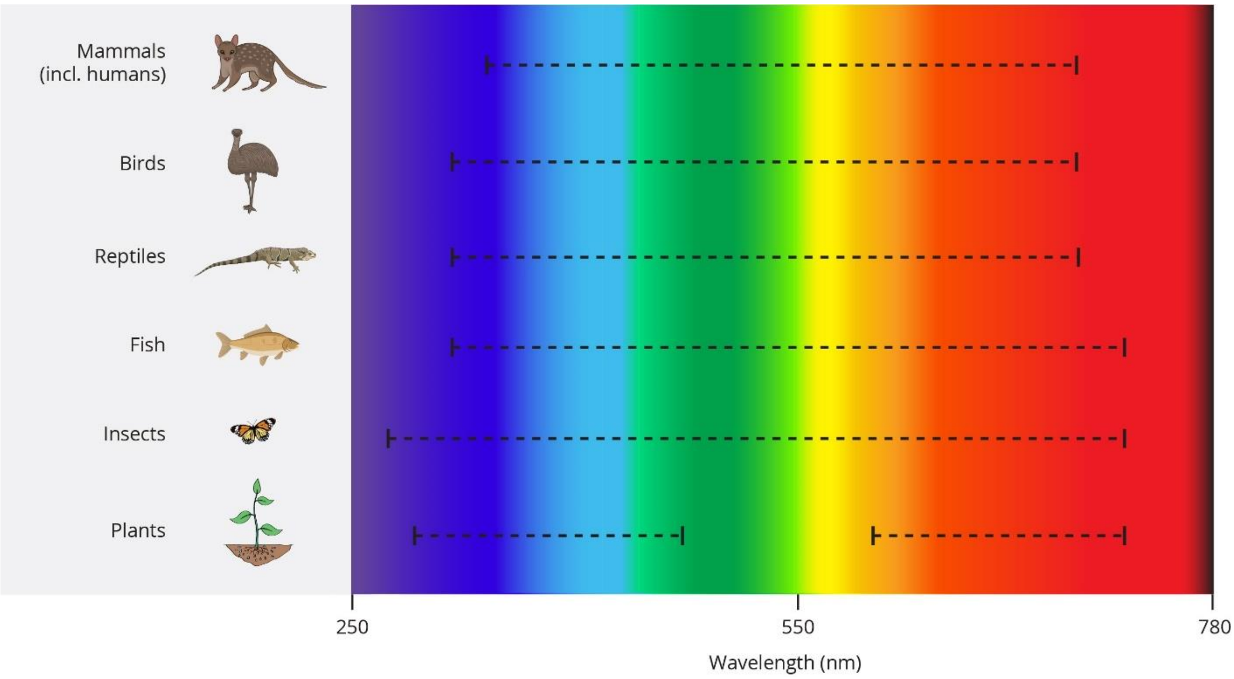
Table 18: Artificial light management options for ecological communities

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.

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