



Australian Government

Department of Climate Change, Energy,
the Environment and Water

National Light Pollution Guidelines for Wildlife – Ecological Communities

Consultation draft

Department of Climate Change, Energy, the Environment and Water



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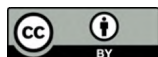
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Ecological Communities

Key takeaways

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 disrupt ecological communities indirectly by fragmenting habitat, reducing habitat connectivity, affecting key ecological processes such as pollination, seed transport, nutrient cycling and food webs, and by assisting the survival and spread of invasive species.

The effects of light pollution on an ecological community depends 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 methods

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. As always, the best strategy will usually involve 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 (e.g. fragmentation) as well as experiencing a multitude of ongoing threats.

1 Introduction: 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).

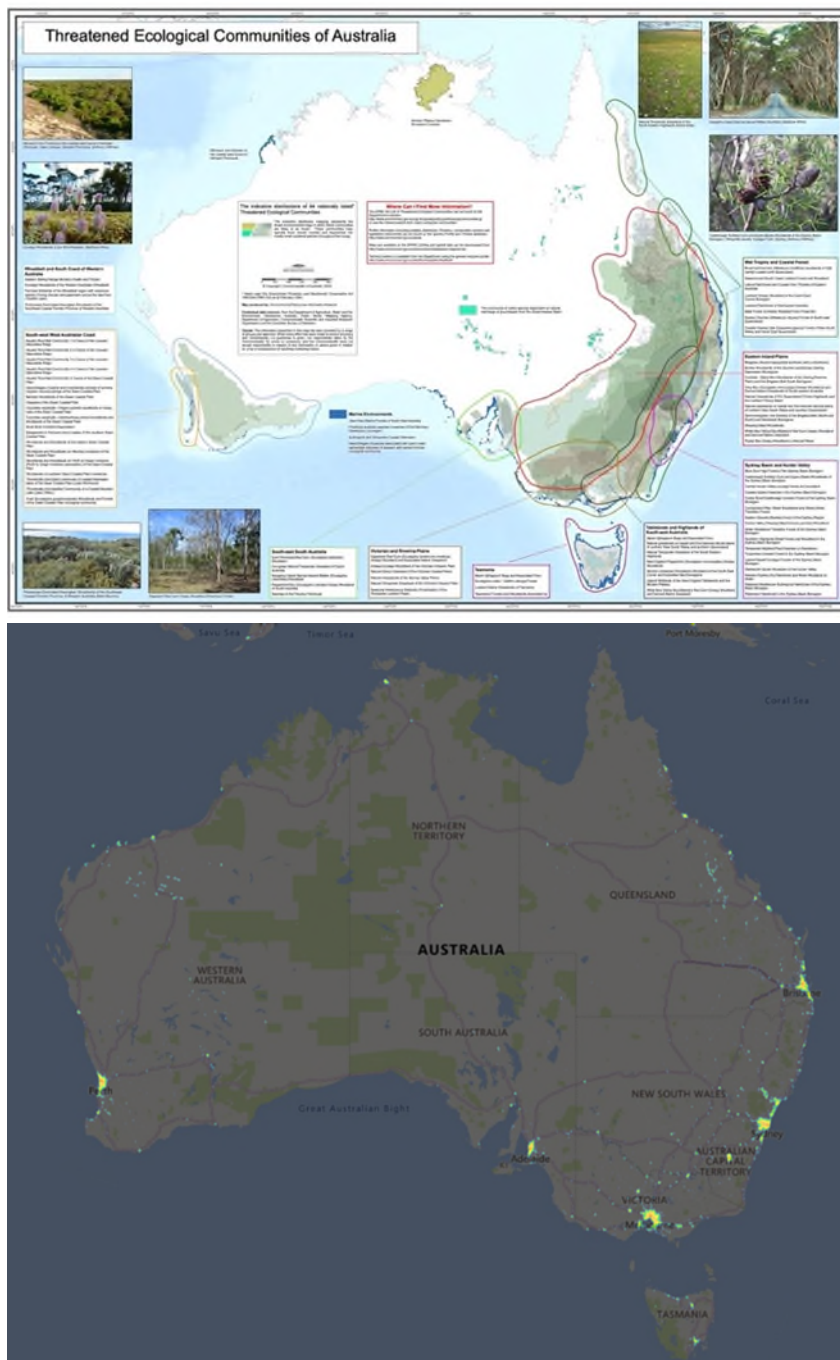
Ecological communities have strong cultural significance for both First Nations and non-indigenous Australians, and support important values including native biodiversity and distinctive landscapes and seascapes. ECs also provide vital ecosystem services to both humans and wildlife, including the management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

), 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 dceew.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).

2 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 thus find resources, navigate, avoid predators and provides plants and other primary producers with the energy for photosynthesis.

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 (sky glow) – 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 Appendixes F to J).

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, 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 interactions within the 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 upon particular attributes of a community, and of the lighting in question, including:

- **Proximity to artificial light sources** – ecological communities in close proximity to sources of artificial light such as towns, transport corridors or mine sites may be affected by direct light spill, intermittent vehicle lights and sky glow. In contrast, ecological communities in remote areas may only be affected by sky glow and, perhaps, occasional vehicular light pollution. Different parts of a single 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 lighting 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 lighting 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. Sky glow, 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, Soanes, Lahoz-Monfort, Lumsden, & van der Ree, 2020; Eisenbeis, 2006; Sanders & Gaston, 2018). As a consequence, 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. Further, artificial lighting in or through the middle of a patch, such as along a walking path, can be a barrier to movement within the patch, effectively fragmenting it into smaller patches for many nocturnal species.
- **Water bodies** – the effects of light pollution on marine and freshwater communities are likely to be at least 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 & fire regime** – the effect of light pollution within a given landscape or habitat patch can vary over time. Canopy, understorey 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 can penetrate 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 the 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 F, G & H, and relevant sections below). For a given ecological community, the effects of artificial lighting 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 known effects of light pollution on some groups such as turtles, seabirds, migratory shorebirds, bats and terrestrial mammals, are addressed in appendices F to J. 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 light pollution can have acute effects on organisms adapted to very low light (Berge et al., 2020) and reduce biodiversity through colonisation by more light-adapted species (Burgoyne et al., 2021). Artificial light pollution 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.

3 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, Autio, Cavaleri, Binkley, & Ryan, 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, van Ieperen, Vreugdenhil, & Millenaar, 2011) – see Figure 1. Even brief pulses of light at night can be enough to cause mistimed seasonal responses (Borthwick, Hendricks, Parker, Toole, & Toole, 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 1: Artificial light masks natural daylength signal & disrupts seasonal changes in plants

Street lighting beside 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, Davies, Cruse, Inger, & Gaston, 2015) and biomass (Bennie, Davies, Cruse, Bell, & Gaston, 2018), and shifts in the timing of flowering (Bennie et al., 2018; Cathey & Campbell, 1975), vegetative growth (Cathey & Campbell, 1975; Palmer, Gibbons, Bhagavathula, Holshouser, & Davidson, 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 timings 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, Davies, Cruse, & Gaston, 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. Further, 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

In addition to its role as a signal, light also provides plants with energy and carbon via photosynthesis. Plants in close proximity to 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, Doraisa, Wien, & Gosselin, 1998; Park, Lee, An, Lee, & Kim, 2020; Yao, Tu, Wang, & Wang, 2021), but can also promote responses that reduce a plant's capacity to assimilate carbon. These 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, Tibbitts, Sharkey, & Wise, 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 (N. G. Phillips, Lewis, Logan, & Tissue, 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 (Narango, Tallamy, & Marra, 2018), and any other fauna that rely on plants – for example, at nesting sites (see ‘Artificial light disrupts food webs’ below). Additionally, there is some evidence that common invasive plants are more likely to tolerate or benefit from light pollution than native plants (Liu, Speißer, Knop, & van Kleunen, 2022; Murphy et al., 2021). This is particularly a concern along roadways, which are frequently lit at night, and are already common vectors for plant invasions (Lázaro-Lobo & Ervin, 2019). Artificial light may thus assist the establishment and spread of invasive weeds.

4 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, Bennie, Inger, Hempel de Ibarra, & Gaston, 2013; Donners et al., 2018) – see Figure 5

. 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; Roy H. A. van Grunsven et al., 2014; Wakefield, Broyles, Stone, Harris, & Jones, 2018).

However, replacing artificial lighting 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; Roy H. A. van Grunsven, Becker, Peter, Heller, & Hölker, 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 the water where they would normally lay their eggs. Artificial light can affect invertebrate reproduction, first by attracting invertebrates away from suitable habitat and then 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, Nilsson, Scholtz, Byrne, & Warrant, 2003) and native bull ants (*Myrmecia midas*) (Freas, Narendra, Lemesle, & Cheng, 2017). As polarized moonlight cues are exceptionally subtle, they are easily disrupted by light pollution, including dim sky glow, 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, Evans, Fox, Parsons, & Pocock, 2020; Hölker, Wolter, Perkin, & Tockner, 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 Appendix I – Bats under ‘Insects’), and similar effects occur in ground-dwelling invertebrates (Eccard, Scheffler, Franke, & Hoffmann, 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, Evans, Fox, & Pocock, 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 Durrant, Green, & Jones, 2020; J. Durrant et al., 2015; McLay, Nagarajan-Radha, Green, & Jones, 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, Henneken, Selleck, & Jones, 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, Gomes, Mondy, & Amat, 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 (R. D. Phillips, Bohman, & Peakall, 2021) or even by a limited cohort within a single species of wasp (Ryan D. 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.

5 Artificial light and terrestrial birds

Note: the effects of light pollution on seabirds and migratory shorebirds are addressed in Appendix G and Appendix H, 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, King, Bentley, & Ball, 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 (D. Dominoni, Quetting, & Partecke, 2013; D. M. Dominoni, Kjellberg Jensen, de Jong, Visser, & Spoelstra, 2020). Such changes have been observed in birds exposed to very low levels of artificial light (0.3 lux) (D. 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) 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), 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, Samplonius, Schlicht, Valcu, & Kempenaers, 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, Greenlees, Brown, & Shine, 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, Connelly, et al., 2020; Aulsebrook, Lesku, 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 owl-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, Gutsell, Geiser, & Wiacek, 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 (K. S. 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 (e.g. streetlight) or sky glow (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, Stayton, Shrestha, & Dyer, 2014), seed transport (M. G. Bradford & Westcott, 2010; Rawsthorne, Watson, & Roshier, 2012), controlling invertebrates (Clarke & Schedvin, 1999), nutrient cycling and fuel load reduction (Maisey, Haslem, Leonard, & Bennett, 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, Fernández-Juricic, Bayne, & St. Clair, 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.

6 Artificial light, reptiles and amphibians

Artificial light is known to have severe impacts on marine turtles (see Appendix F), 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, 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 (Roy H.A. van Grunsven, Creemers, Joosten, Donners, & Veenendaal, 2017). These restrictions on movement can impact entire populations, by restricting mate-choice (Rand, Bridarolli, Dries, & Ryan, 1997) and/or preventing the dispersal of juveniles across the landscape (Roy H.A. van Grunsven et al., 2017). Attraction to street and path lighting also exposes anurans to novel risks including vehicles and pedestrians (Baker, 1990; Roy H.A. 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, Dosso, Hall, Schuch, & Tozetti, 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, Shidemantle, Melnick-Kelley, Crane, & Hua, 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, van Grunsven, Manfrin, Monaghan, & Hölker, 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 squamate (scaly) reptiles that are usually diurnal, may extend their hours of activity under artificial light (Garber, 1978; Perry & Fisher, 2006), but may suffer impaired sleep as a consequence (Kolbe, Moniz, Lapiedra, & Thawley, 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 as prey for birds, fish and small mammals, as 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). Further, since artificial light appears to facilitate prey capture by cane toads, it may be one (of many) factors contributing to the spread and persistence of this species in northern Australia, and the consequential loss of native fauna.

7 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, McKee, Fishwick, Tidau, & Smyth, 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, Cortesi, de Busserolles, Siebeck, & Cheney, 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 on-shore and offshore sources now affects around 2 million km² 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 life-cycle events and related movement in response to moonlight cues. These include reproductive events, juvenile migration and moulting (Ayalon, de Barros Marangoni, Benichou, Avisar, & Levy, 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, Strass, Rhein, & Krägefsky, 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, Irigoien, Genton, & Kaartvedt, 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 so on up the food chain (Figure 2).

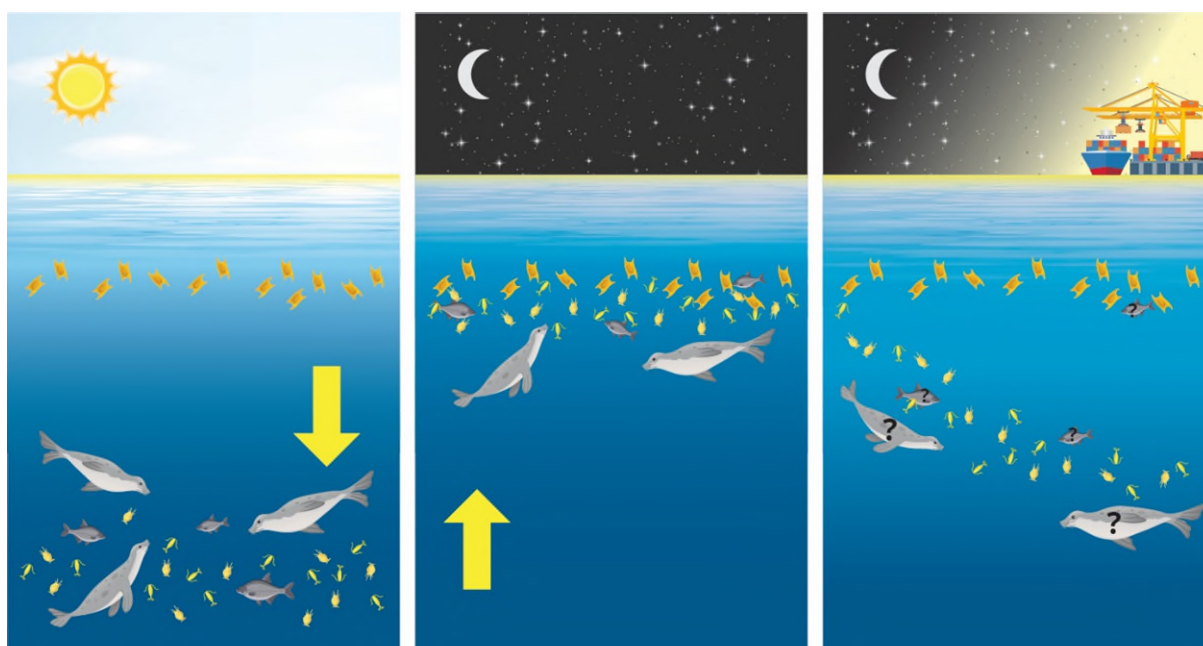


Figure 2: Effects of artificial light on vertical migration in aquatic systems

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.

To complicate matters, 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). As a consequence, 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, Duffy, Bennie, & Gaston, 2014). Some of these changes reflect innate attraction to or repulsion by lighting, which may be highly spectrum-dependent (Marchesan, Spoto, Verginella, & Ferrero, 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, many species of diurnal fish congregate at unlit wharves, which are used as habitat at nighttime, when these fish are largely sedentary. The addition of LED lighting to such wharves reduces fish numbers, with many presumably moving in to deeper waters to avoid the light. However, those 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 to more closely resemble diurnal communities (Bolton et al., 2017; Davies, Coleman, Griffith, & Jenkins, 2015).

Effects of artificial light on flying invertebrate recruitment

Freshwater, saltmarsh and estuary systems provide key habitat for many 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 south east 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 caused 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:nitrogen ratio, consistent with resources being directed to photosynthetic organs rather than structural growth (Segrestin et al., 2021). Since such shifts appear to be a response to perceived shading, they 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 increased the presence of photoautotrophic (photosynthesizing or similar) microbes, but reduced heterotrophic microbes (those that consume organic matter), and reduced overall respiration (CO₂ production) (Hölker et al., 2015). This suggests that long-wavelength lighting may increase carbon sequestration, but reduce 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, Kobak, Grubisic, & Kakareko, 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 (6000-10,000 K) light than under long wavelength (2000 K) lights (Ayalon et al., 2019). Moreover, changes including bleaching as a result of artificial light were 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 through cumulative stressors.

Effects of artificial light on reproduction and fitness of aquatic animals

There has been less research into the effects of artificial light on aquatic animals compared to terrestrial species, however studies to date suggest that the impacts may be just as severe. As with terrestrial fauna, the daily and seasonal rhythms of aquatic species are closely tied to natural light cycles (Falcón, Migaud, Muñoz-Cueto, & Carrillo, 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, Hölker, Franke, Kleiner, & Kloas, 2016); the nocturnal hatching of marine fish, timed to avoid diurnal predators (McAlary & McFarland, 1993) and the production of coral sperm and egg cells, 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 most aspects of aquatic ecosystems, including animal behaviour, plant and algal growth, predator-prey interactions, daily and seasonal movement, reproduction, development, and decomposition. As in terrestrial systems, in ecological communities with an aquatic component, these effects are likely to have cascading impacts on 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 thus the physical structures on which reef communities depend. However, the potential for both direct and indirect impacts of light pollution in freshwater and marine communities represents a significant knowledge gap that requires further investigation.

8 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, Fletcher, Battin, & Sisk, 2004). Edge effects are common in both terrestrial and aquatic systems, including at the boundary between sandy seafloor and seagrass patches (Smith, Hindell, Jenkins, Connolly, & Keough, 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 thus 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 3)—thereby reducing the size of intact habitat, and reducing connectivity between the remnant patches.

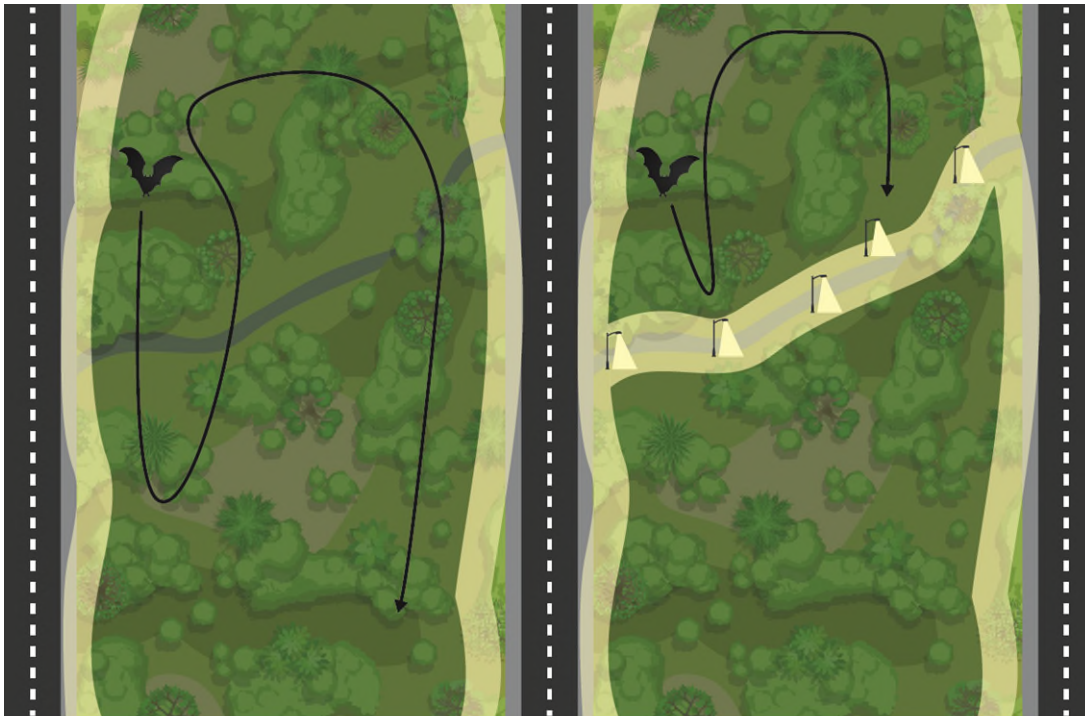


Figure 3: Effects of artificial light on habitat fragmentation and edge effects

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 suffer 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 many 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). Such 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 refuse to cross artificially illuminated areas (Bhardwaj et al., 2020; Farnworth, Innes, Kelly, Littler, & Waas, 2018; Hale, Fairbrass, Matthews, Davies, & Sadler, 2015; Threlfall, Law, & Banks, 2013; Roy H.A. 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’ above).

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).

9 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 of 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 nectivorous fauna—including birds, bats, arboreal mammals and insects—and subsequent transport from one flower to another (M. 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*) (M. G. Bradford & Westcott, 2010; Rawsthorne et al., 2012); the deliberate collection and transport of seeds by ants (myrmecochory) in order to provision nests with ant-attractive food rewards (elaiosomes), which is a common reproductive strategy in Australian desert plants (R. 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 all of the 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, Anson, Saul, & Banks, 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 (G. T. O. Davies, Kirkpatrick, Cameron, Carver, & Johnson, 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 Appendices F, G, H, I and J).

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 4). 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).

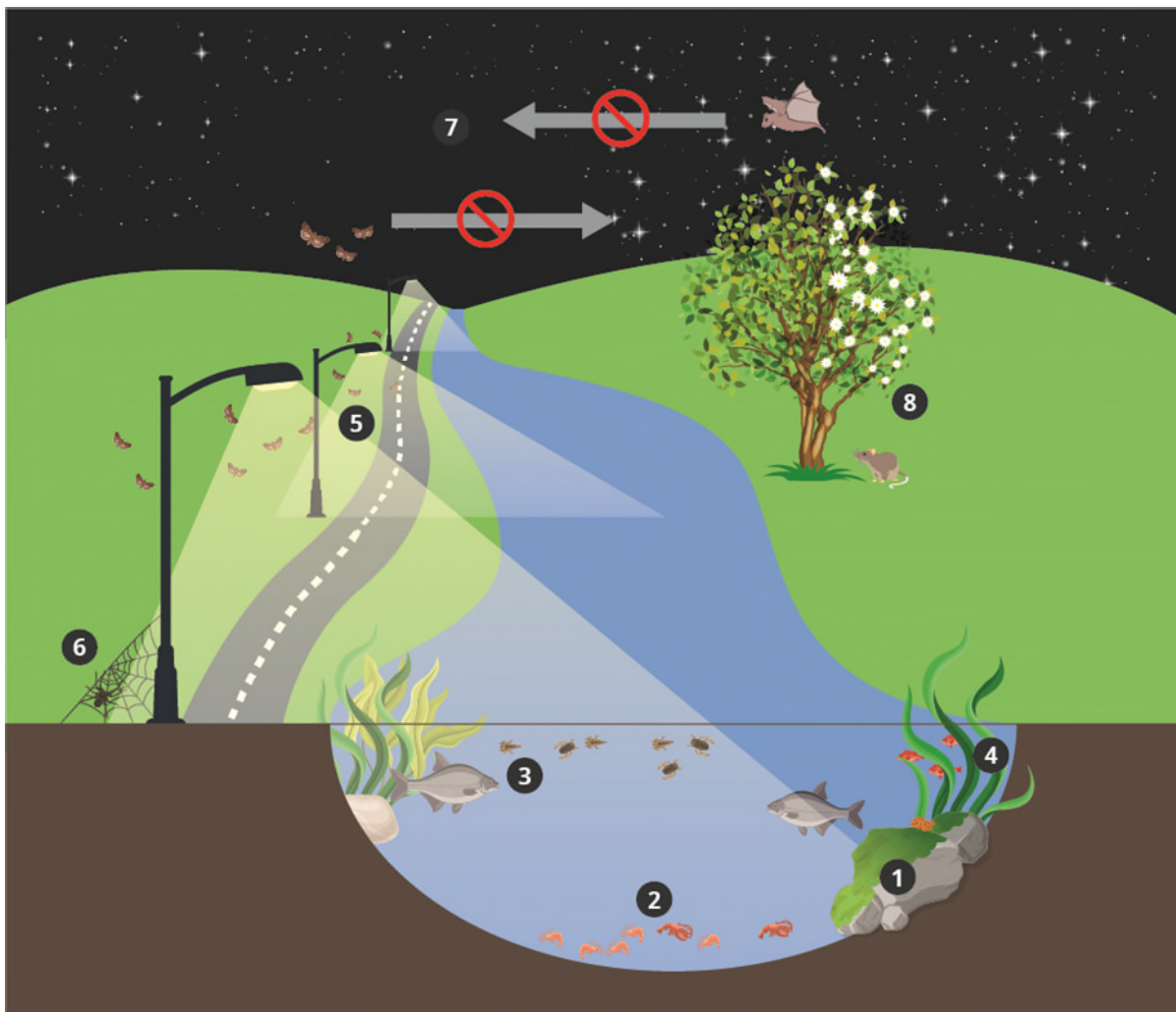


Figure 4: Effects of artificial light on food webs, pollination and seed dispersal

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, as a result 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 a number of EPBC Act listed species, including small terrestrial mammals and reptiles.

Cane toads, along with invasive common house geckos (*Hemidactylus frenatus*), are able to 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 taken into account 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.

10 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; Environmental Impact Assessment for 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 principles here are also worth considering with a view to minimising the ecological effects of artificial lighting. This includes considering whether the project lighting is likely to reduce connectivity in the landscape—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 kilometers from its source. This is not just because light from some sources can deeply penetrate a habitat patch, but also because the effects of artificial light on habitat fragmentation and ecological processes can threaten the integrity and quality of ecological communities at the landscape scale. In addition, artificial light is often only one of a matrix of human-generated impacts that may arise from a given project, 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 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 always 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 to the National Light Pollution Guidelines: Appendix F – Marine Turtles; Appendix G – Seabirds; Appendix H – Migratory Shorebirds; Appendix I – Terrestrial Mammals; and Appendix J – Bats
- 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 an artificial lighting management plan, 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.

- Describe 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 sky glow
- 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, but is likely to include surveys or monitoring of at least some of: 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 **Error! Reference source not found.**)
 - 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 help describe the light. Quantitative data on existing sky glow 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) 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 at 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 at 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 mean that artificial light is:
 - more or less likely to impact the community?
 - likely to have different impacts at different times?

Table 1 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 1: Community attributes and corresponding direct and indirect vulnerabilities to the effects of artificial light

Light pollution attributes		
Community includes:	Direct effects	Indirect effects
LANDSCAPE ATTRIBUTES		

Grassland	<ul style="list-style-type: none"> • Generally flat or undulating landscape with few topographical impediments to light spill. • Little or no shade or filtering by canopy trees; sky glow is likely to affect entire landscape • Filtering/shade effects of vegetation may change dramatically following drought/fire/storm/grazing 	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Light penetration will be greater at edges than in centre of patch (edge effects) • Lighting intensity of sky glow may be relatively high at canopy level but much lower in understorey 	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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) 	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Reflective properties of snow and ice will increase spread of light during winter 	<ul style="list-style-type: none"> • Effects of artificial light on invertebrate migration (Bogong moths) in other regions can disrupt food webs in alpine areas,

	<ul style="list-style-type: none"> Lighting on high points (hilltops) can spread over large distances; lighting in valleys will have only limited spatial effect 	and flow of nutrients from non-alpine to alpine regions
Caves	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> Artificial light effects on plant investment and morphology may reduce root growth (with consequences for root mat communities)
Linear patches	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Edge effects of lighting are likely to substantially reduce the effective patch size for light-sensitive organisms 	
SPECIES ATTRIBUTES		
Terrestrial plants	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> 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 break down of detritus and the cycling of carbon in aquatic systems
Aquatic fauna	<ul style="list-style-type: none"> Artificial light may suppress diel vertical migration reducing 	<ul style="list-style-type: none"> White lighting may reduce the biomass of algae and periphyton

(see also: Corals)	<p>opportunities for zooplankton to feed at the surface</p> <ul style="list-style-type: none"> 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 	<p>available as food resources for aquatic predators</p> <ul style="list-style-type: none"> Loss of juvenile crabs and other invertebrates can reduce oxygenation of mudflats, sediment decomposition and plant productivity
Corals	<ul style="list-style-type: none"> Artificial light can lead to mistimed breeding that fails to synchronize with appropriate conditions Longer-wavelength (amber) lighting that helps some marine species (e.g. turtles – Appendix F) does not appear to prevent breeding failure in corals (but does reduce light-induced bleaching) 	<ul style="list-style-type: none"> 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 (e.g. artificial light plus heat stress)
Insects and other invertebrates	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Lights may cause smaller nocturnal birds (for example, owl 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 	<ul style="list-style-type: none"> Artificial light may reduce invertebrate abundance with impacts on food resource of nocturnal birds including nightjars, owls and frogmouths
Diurnal birds	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> Artificial light may reduce invertebrate abundance with impacts on birds' food resource
Seabirds	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Artificial light may delay nightly departure from roost, and disrupt foraging and commuting behaviour Rows of lighting may present a barrier to landscape connectivity 	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> • Most native mammals are active in low light to avoid predators. Artificial lighting can restrict 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 	<ul style="list-style-type: none"> • Artificial light may reduce invertebrate abundance with impacts on insectivorous mammals' food resource
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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:

- 1) the threatened status of any taxa identified at step 2
- 2) 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

- 3) the synchronicity of high artificial light periods (long nights, lack of dense growth) with light-sensitive developmental stages of key taxa (flowering, migration, reproduction)
- 4) 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
- 5) 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
- 6) 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), biological and abiotic community information (Step 2) and attributes that make the EC or its key species vulnerable to light pollution effects (Step 3), 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 '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.

11 Ecological communities light mitigation toolbox

Appropriate artificial lighting design, controls and mitigation will be site, project, community and often species specific. Table 2 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 5

), 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:

- use of narrow spectrum, long wavelength amber or red lighting; this is likely to benefit most invertebrates and some algae, but its effects on other animals groups (fish, birds, amphibians, mammals) is highly variable (Alaasam, Kernbach, Miller, & Ferguson, 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
- the use of motion sensor lighting or dimmers may reduce the overall amount of light emitted.

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

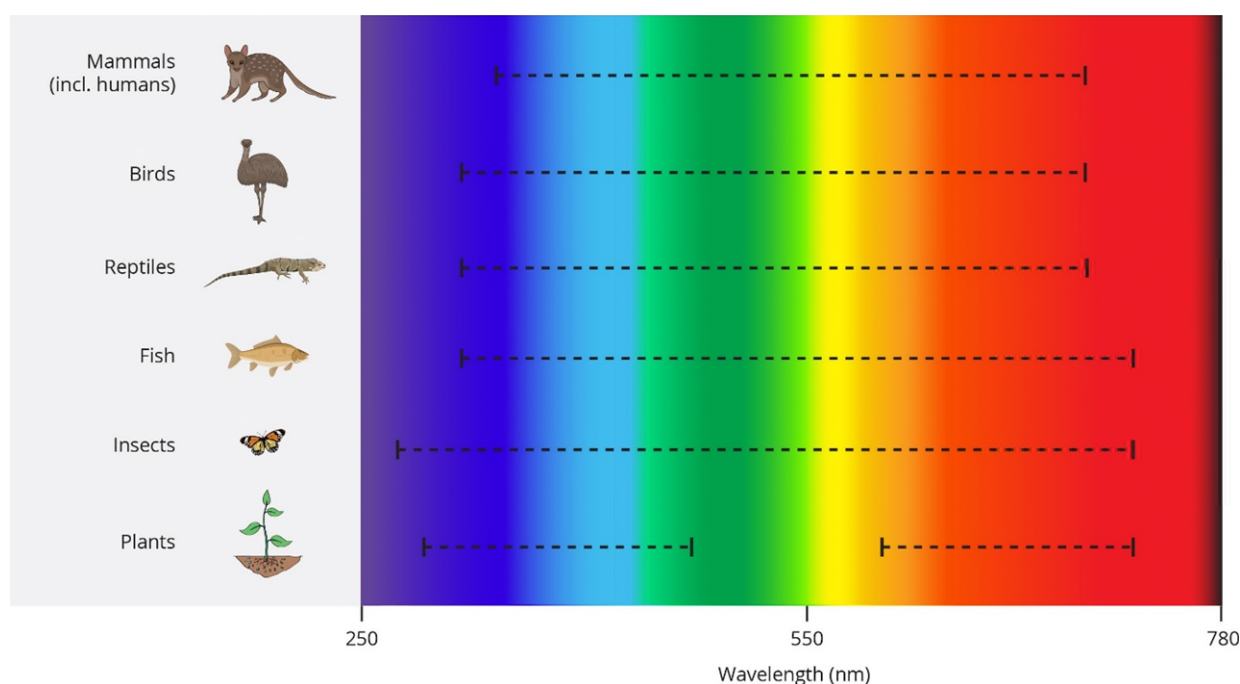
Table 2: Artificial light management options for ecological communities

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 lights 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
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 enables increases in 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, plus flying invertebrates and their predators, and plants pollinated by flying invertebrates

Management action	Detail	Groups likely to benefit
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 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.	Most species, but especially insects and other invertebrates, 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 or may not be an effective mitigation measure for some 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 this 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	Migratory birds, dispersing frogs, spawning corals and fish, nesting and hatching marine turtles and

Management action	Detail	Groups likely to benefit
	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.	potentially most species (although it will not be practical to help all taxa without removing lighting altogether)
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 (such as bats, birds, arboreal fauna, flying invertebrates)

Figure 5: Indicative light spectral range to which major groups of organisms found in ecological communities can respond to or detect.



Arrows indicate the range of spectra that can be detected by at least some taxa within each group. 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 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, within a given species, sensitivity is not equal across all parts of the spectrum: humans can (just) see in violet or red light, but our spectral sensitivity peaks toward the centre of the spectrum.

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