



Australian Government

Department of Climate Change, Energy,
the Environment and Water

National Light Pollution Guidelines for Wildlife – Terrestrial Mammals

Consultation draft

Department of Climate Change, Energy, the Environment and Water



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Acknowledgement of Country

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

Contents

Introduction.....	1
Conservation status of threatened terrestrial mammals.....	3
Habitat use.....	4
Habitats in which species may be susceptible to light pollution	4
Effects of artificial light on terrestrial mammals	6
Behaviour and activity.....	6
Physiology.....	10
Reproduction.....	12
Indirect impacts	13
Vision in terrestrial mammals.....	16
Environmental impact assessment of artificial light on terrestrial mammals.....	18
Associated guidance	18
Qualified personnel.....	18
Step 1: Describe the project lighting.....	19
Step 2: Describe the terrestrial mammal population and behaviour.....	19
Step 3: Risk assessment	21
Step 4: Light management plan	21
Step 5: Biological and light monitoring and auditing	21
Review	22
Terrestrial mammal light mitigation toolbox	23
References	26

Tables

Table 1 Light management options specific to terrestrial mammals.....	23
Table 2 Commercial luminaire types that are considered generally less disruptive for use near important terrestrial mammal habitat, and those to avoid.....	25

Figures

Figure 1 Southern Brown Bandicoot	1
Figure 2 Effects of lunar illumination and artificial light at night on activity and predation risk for nocturnal animals	6
Figure 3 Day length and environmental conditions, by season.....	8
Figure 4 Disruption of seasonal lighting cues by artificial light at night	9
Figure 5 Stills from ‘Lights Off for Moths’ campaign, Zoos Victoria.....	14

Figure 6 Comparative light perception among different species groups 16

Boxes

Box 1 Indirect impacts on Mountain Pygmy-possum occurring over large distances 14

Introduction

Key points

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

Key management actions

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

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

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

Figure 1 Southern Brown Bandicoot



Photo: © Susan Flashman.

Artificial light has been shown to disrupt behaviour and physiology in terrestrial mammals. Potential negative impacts of artificial light include reduced time spent foraging (Shier, Bird & Wang 2020; Bird et al. 2004), increased predation (Clarke 1983; Kotler et al. 1988; Kotler, Brown & Hasson 1991) and altered timing of reproduction (Le Tallec, Théry & Perret 2015; Le Tallec, Théry & Perret 2016; Robert et al. 2015).

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

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

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

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

Conservation status of threatened terrestrial mammals

At May 2021, over 100 terrestrial mammal species were listed as threatened under the EPBC Act. Of these EPBC Act listed terrestrial mammal species, all except the Numbat are nocturnal or crepuscular.

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

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

- [Australian Capital Territory – Threatened species of the ACT](#)
- New South Wales – Threatened biodiversity profile search
- Northern Territory – Threatened animals
- Queensland – Threatened species
- South Australia – Threatened species in South Australia
- Tasmania – List of threatened species
- Victoria – Framework for conserving threatened species
- Western Australia – Threatened species and communities.

Habitat use

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

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

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

Habitats in which species may be susceptible to light pollution

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

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

The introduction of artificial light into these areas can degrade terrestrial mammals' habitat and reduce their area of occupancy or disrupt critical behaviours, which may affect recovery of the species. In habitats in which species may be susceptible to light pollution, artificial light should be managed to ensure critical behaviours continue to occur.

Refuge sites

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

Foraging areas

Terrestrial mammals require foraging areas to meet energy demands for survival. Foraging areas are species and population specific and may be seasonally driven and/or dependent on resource availability. Artificial light spilling onto foraging sites can increase the visibility of terrestrial mammals to predators (Clarke 1983). As a result of the perceived predation risk, nocturnal mammals may use these foraging sites less (Bird et al. 2004) or not at all, resulting in a loss of habitat (Rotics, Dayan & Kronfeld-Schor 2011).

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

Commuting routes

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

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

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

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

Effects of artificial light on terrestrial mammals

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

Figure 2 Effects of lunar illumination and artificial light at night on activity and predation risk for nocturnal animals



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

Both point source artificial lighting directly illuminating habitat, and sky glow that increases ambient light levels have the potential to impact terrestrial mammals. While research has predominantly focused on direct lighting of habitat (point source lighting), the impact of sky glow on terrestrial mammals is less well known. However, changes in behaviour under moonlight conditions (Linley et al. 2020) (see Figure 2) suggests sky glow is likely to disrupt some terrestrial mammal species where it masks natural lunar cycles. Further research on the effects of sky glow is required.

Behaviour and activity

Terrestrial mammals rely on daily and seasonal light cues (Figure 3) to anticipate favourable and unfavourable conditions for survival and reproduction and adjust their behaviour accordingly (Russart & Nelson 2018a; Le Tallec, Perret & Théry 2013). The introduction of artificial light into the night-time environment can mask these cues, leading to a shift in the timing of critical behaviours (Figure 4) and reducing the fitness of an animal (Russart & Nelson 2018b).

Exposure to artificial light at night can alter movement patterns (Rotics, Dayan & Kronfeld-Schor 2011), reduce home range (Hoffmann, Schirmer & Eccard 2019) and change individual (Hoffmann, Schirmer & Eccard 2019) or species interactions (Rotics, Dayan & Kronfeld-Schor 2011). Nocturnal mammals have been shown to reduce the total duration of activity under

artificial light (Barber-Meyer 2007; Bedrosian et al. 2013b; Rotics, Dayan & Kronfeld-Schor 2011; Sanders et al. 2021). Nocturnal rodents have been shown to decrease the amount of time spent foraging and reduce the amount of food collected (Bird et al. 2004; Farnworth, Innes & Waas 2016; Rotics, Dayan & Kronfeld-Schor 2011; Shier, Bird & Wang 2020). These shifts in behaviour and activity are suggested to be in response to an increased predation risk under artificial light (Kotler, Brown & Hasson 1991; Russart & Nelson 2018a). If artificial light is continuous throughout the night and the environment then terrestrial mammals must risk predation and forage under artificial light (Alkon & Mitrani 1988) or continue to minimise predation risk at the cost of body condition (Vásquez 1994). That is, they must either risk being easily seen and eaten by predators or avoid exposing themselves by minimising foraging activities and risk becoming malnourished.

Figure 3 shows natural changes in day length across the year that provide important cues for mammals to anticipate environmental conditions. Changes in day length across the year allow animals to predict favourable (for example, high food availability in spring after winter rain, and high insect abundance in summer) and unfavourable (cold, challenging winter) conditions for survival.

Figure 4 shows artificial light at night masking seasonal day length and interfering with seasonal lighting cues, disrupting important behaviours such as breeding, migration, feeding and hibernation.

Figure 3 Day length and environmental conditions, by season

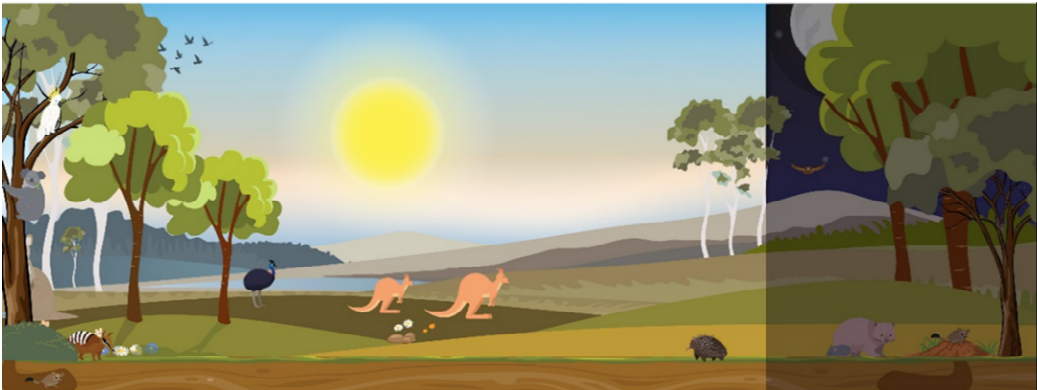



	<p><i>Summer</i></p> <p>Characterised by long days and short nights with warm weather, high food availability and active animals.</p>
	<p><i>Autumn</i></p> <p>Approximately equal day and night length (shorter daylength than summer). Animals put on weight before winter.</p>
	<p><i>Winter</i></p> <p>Short days and long nights accompanied by cold weather causing animals to hide in refuge.</p>
	<p><i>Spring</i></p> <p>Approximately equal day and night length (longer daylength than winter). Green vegetation following winter rain, with increases in animal activity.</p>

Figure 4 Disruption of seasonal lighting cues by artificial light at night

Light avoidance behaviour occurs even under relatively low light intensity (Kramer & Birney 2001; Vásquez 1994). Terrestrial mammals reduce their activity (Falkenberg & Clarke 1998; Shier, Bird & Wang 2020; Wolfe & Summerlin 1989) and stay closer to refuge sites under full moon (Daly et al. 1992) (Figure 2). Terrestrial mammal species like the Rufous Bettong (*Aepyprymnus rufescens*) and EPBC Act listed Southern Brown Bandicoot (*Isododon obesulus*) and Eastern Quoll (*Dasyurus viverrinus*) show higher activity at half-moon than full moon (Linley et al. 2020). In some species such as wallabies and rodents, this reduction in activity at full moon also leads to increased vigilance (Vásquez 1994) and decreased foraging (Carter & Goldizen 2003), resulting in less food consumed per trip and an increased number of trips between refuge and foraging areas (Vásquez 1994). Consequently, the introduction of artificial light which masks these natural changes in lunar illumination or results in a light intensity equivalent to a permanent full moon is likely to disrupt the behaviour and activity of terrestrial mammals.

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

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

To minimise predation while foraging and commuting under natural illumination, terrestrial mammals use parts of their habitat (for example, under grass or between rocks) that lower the risk of detection by predators. Maintaining suitable vegetation cover, including canopy cover for arboreal species, and ensuring artificial light does not spill into the habitat can reduce the

impacts of artificial light on activity and behaviour of terrestrial mammals. However, the suitability of the environment to mitigate light levels will likely depend on habitat type. For example, species living in dense bushland are likely to experience more protection from artificial light and predation than those living in open desert or grasslands.

Mitigation of behavioural impacts of artificial light

Direct artificial light on refuges or the entrances and exits of refuge sites and foraging areas and along commuting routes should be avoided to mitigate impacts on the activity and behaviour of terrestrial mammals. Consideration should be given to whether the species of interest are considered ground dwelling or arboreal. Light shielding should be used to prevent artificial light spilling upward, contributing to sky glow and directly entering the habitat of arboreal species. Downward light should be directed or shielded away from habitat of ground-dwelling species. See the Terrestrial mammal light mitigation toolbox in this document and 'Best practice lighting design' in the National Light Pollution Guidelines for Wildlife Including Marine Turtles, Seabirds and Migratory Shorebirds for further details.

Physiology

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

Natural changes in light and dark cycles across the year allow mammals to anticipate environmental conditions and adjust their behaviour accordingly to improve their chance of survival (Ouyang, Davies & Dominoni 2018) (see Figure 3). These natural day length changes are also responsible for synchronising the physiology of animals with seasonal environmental conditions. The introduction of artificial light at night into the habitat of terrestrial mammals can mask these natural light/dark cycles, provide misleading cues and ultimately disrupt the predictability of environmental conditions. To date most research into these effects has been conducted on only select species; however, impacts are likely to be similar across nocturnal terrestrial mammals.

Melatonin

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

The duration of melatonin production reflects the length of the night (Ouyang, Davies & Dominoni 2018) (Figure 3). In this way melatonin conveys information about time of day as well as time of year. For mammals that breed at a certain time of year (seasonal breeders), production of melatonin can drive changes in reproductive hormones to ensure that births occur at the time of year that is most favourable for survival (for example, suitable temperature, high food availability, reduced predation) (Weil et al. 2015).

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

Glucocorticoids

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

Artificial light may act as a novel stressor for terrestrial mammals, resulting in an increase in glucocorticoid production. If this elevation in glucocorticoids is sustained it will result in a trade-off between reproduction and immune function in favour of survival. This means that prolonged high levels of glucocorticoids can disrupt reproduction and increase the vulnerability of the animal to disease (Schoenle, Zimmer & Vitousek 2018).

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

Immune function

Melatonin and glucocorticoids play a key role in modulating immune function in mammals (Weil et al. 2015). Maintaining adequate immune function is critical for survival through challenging winter conditions (Nelson et al. 1995) and can be considered a proxy for survival. Exposure to artificial light at night has been shown to reduce the production and activation of white blood cells (Aubrecht et al. 2014), and there is some evidence that exposure to artificial light may lead to intergenerational decline in innate immunity (that is, immunity that is present at birth) (Cissé, Russart & Nelson 2020). Exposure to direct artificial light at night can also inhibit winter adaptation (Ikeno, Weil & Nelson 2014) and compromise immune function, with negative consequences for individual fitness (Bedrosian et al. 2011).

While the impact of artificial light on mammalian immune systems has been described in laboratory studies, it has not been explored in wild mammals. It is possible that where direct artificial lighting reaches a sufficient intensity and duration it could cause similar disruptions to immune function in wild animals, resulting in reduced survival.

Mitigation of physiological impacts of artificial light

Artificial light consisting of short, blue wavelengths (for example, white LEDs) is known to cause the greatest disruption to the physiology of terrestrial mammals (Nelson & Takahashi 1991; Thapan, Arendt & Skene 2001). Therefore, the colour as well as the intensity of light should be considered near terrestrial mammal habitat. To reduce the impacts on the physiology of terrestrial mammals, artificial lighting should be used only where required, the use of blue

wavelengths (400 nm to 500 nm) should be limited, and lighting should be at the lowest intensity suitable. See the Terrestrial mammal light mitigation toolbox and the guidelines on best practice lighting design for further details.

Reproduction

Some mammals are able to breed at all times of the year in response to food availability or rainfall (for example, Eastern Pygmy-possum, *Cercartetus nanus*). Other mammals restrict reproduction to certain times of year (for example, Western Ringtail Possum, *Pseudocheirus occidentalis* – noting that some populations can breed year round) to synchronise births with predictable environmental conditions including suitable temperature, increased food availability and decreased predation rates (Schroer and Hölker 2016). These species are termed seasonal breeders. The timing of seasonal reproduction can be cued by changing light levels (see Figure 3 and Physiology) that indicate time of year, to ensure that sufficient food is available to compensate for the increased energetic demands associated with the provisioning of young (Bronson 1985). The introduction of artificial light which masks day length changes has the potential to provide misleading light cues and disrupt the timing of reproduction in seasonally reproductive terrestrial mammals.

Artificial light has been shown to mask natural day length changes and delay reproduction in wild Tammar Wallabies (Robert et al. 2015). This shift in birth dates can result in a mismatch between the timing of births and food availability, reducing offspring survival and consequently threatening the recovery and persistence of threatened terrestrial mammal populations (Post and Forchhammer 2008).

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

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

Mitigation of reproductive impacts of artificial light

The population-scale effects of artificial light on reproduction in terrestrial mammals represents a knowledge gap. However, based on current evidence, artificial light that is sufficient to mask natural day length changes and disrupt physiology is likely to disrupt reproduction in seasonally reproductive terrestrial mammals. The installation or upgrade of artificial lighting should consider the wavelengths and intensity of light used near terrestrial mammal habitat. Consideration should be given to avoiding blue (400 nm to 500 nm) wavelength light as well as

installing low intensity lighting. Consideration should also be given to the areas of habitat and food resources that are critical for reproduction, as well as the time of year for seasonal breeders, to avoid disturbing species during a critical reproductive period. See the Terrestrial mammal light mitigation toolbox and the guidelines on best practice lighting design for further details.

Indirect impacts

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

Predation

Artificial light can make it easier for nocturnal predators to locate terrestrial mammals (see Figure 2). Even low levels of light at full moon can increase rates of predation and capture by owls (Clarke 1983; Kotler et al. 1988; Kotler, Brown & Hasson 1991). Owls predate on many listed terrestrial mammals. If artificial light illuminates the habitat of these mammals through direct lighting or sky glow it could increase the rate of predation by owls.

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

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

Prey availability

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

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

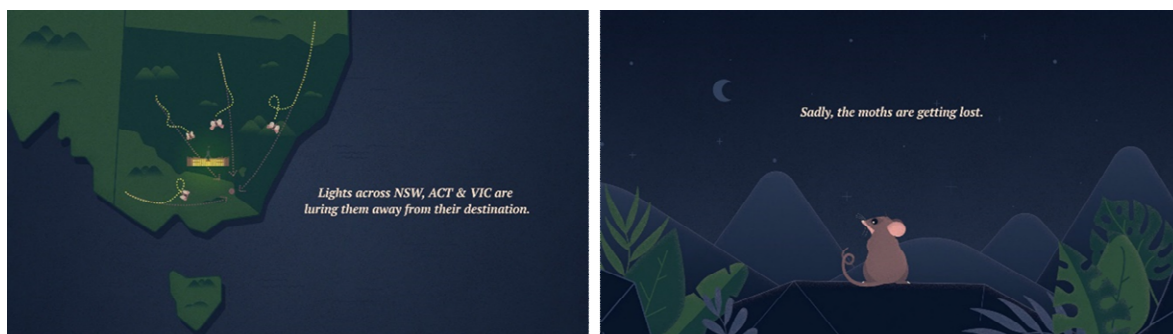
Box 1 Indirect impacts on Mountain Pygmy-possum occurring over large distances

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

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

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

Figure 5 Stills from 'Lights Off for Moths' campaign, Zoos Victoria



Video stills: © Samuel Van Ingen.

Competition with invasive species

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

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

Ecological communities

The introduction of artificial light can alter species interactions and could disrupt ecological communities (Longcore & Rich 2004). For example, artificial light that disrupts the activity of insects has been shown to reduce pollination rates for some plant species (Giavi, Fontaine &

Knop 2021). Further studies are required to understand the impact of artificial light on complex ecosystem dynamics and ecological communities.

Terrestrial mammals provide critical ecosystem functions in ecological communities including pollination and seed dispersal. If artificial light disrupts the activity and habitat use of terrestrial mammals it could disrupt the critical ecosystem roles they serve and ultimately disrupt the function of EPBC Act listed ecological communities.

Road mortality

Artificial light can make it more difficult for nocturnal mammals to avoid collisions with vehicles, especially where the animal experiences a rapid shift in illumination (that is, emerging from dark bushland into bright artificial lighting) (Beier 2006). The low-light-adapted vision of nocturnal terrestrial mammals can quickly become saturated by artificial light, leaving them temporarily blinded (Beier 2006). This results in mammals becoming disoriented and unable to see the dark areas across the road. This disadvantage can remain for 10 to 40 minutes after returning to darkness (Beier 2006). As such, the use of highway illumination has not been shown to be an effective strategy to reduce mammal vehicle strikes (Reed and Woodard 1981) and may increase strike-related mortality.

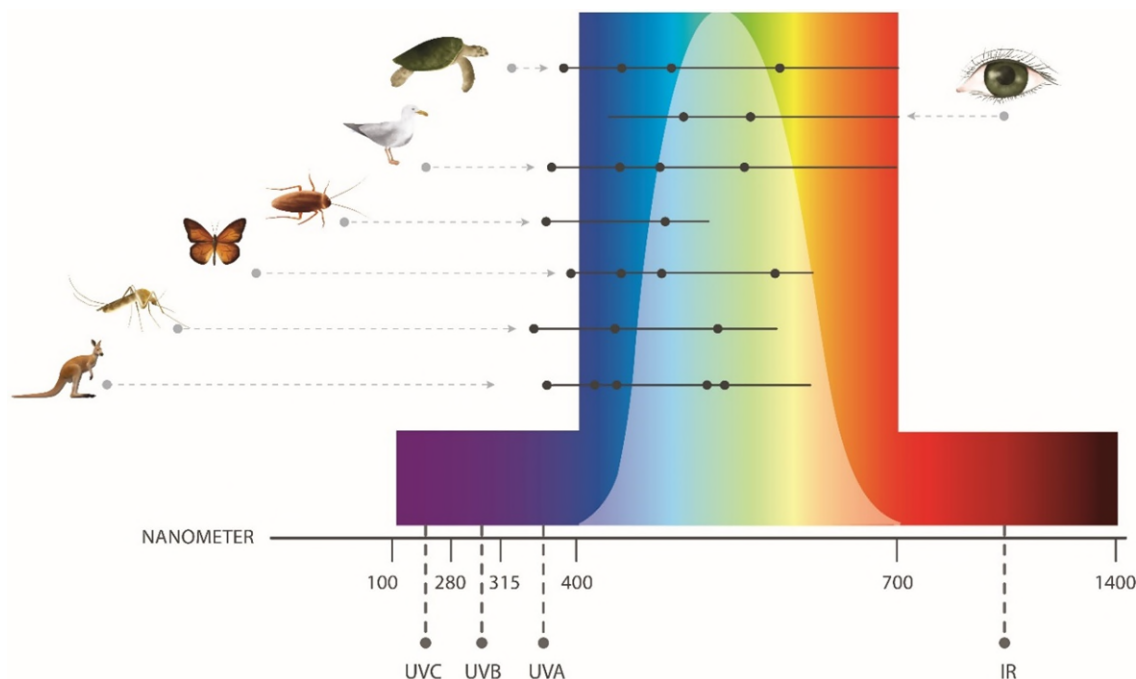
Mitigation of indirect impacts of artificial light

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

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

Vision in terrestrial mammals

Figure 6 Comparative light perception among different species groups



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

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

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

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

If artificial light must be used in terrestrial mammal habitat it is appropriate to consider and evaluate the use of luminaires that have a spectral content outside the visual range of these animals. Further research is required to better understand light perception and sensitivities in

Australian terrestrial mammals. In general, low-intensity light in the orange to red (590 nm to 740 nm) spectrum is likely to be less disruptive to terrestrial mammals.

Environmental impact assessment of artificial light on terrestrial mammals

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

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

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

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

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

Associated guidance

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

Qualified personnel

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

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

Step 1: Describe the project lighting

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

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

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

Step 2: Describe the terrestrial mammal population and behaviour

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

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

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

Biological monitoring of terrestrial mammals

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

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

- understand the size and importance of the terrestrial mammal population(s)

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

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

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

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

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

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

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

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

As a minimum, qualitative descriptive data on visible light types, location and directivity should also be collected at the same time as the biological data. Handheld camera images can help describe the light. Quantitative data on existing 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’ in the National Light Pollution Guidelines for Wildlife for a review.

Step 3: Risk assessment

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

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

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

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

Step 4: Light management plan

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

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

Step 5: Biological and light monitoring and auditing

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

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

given to monitoring control sites. Monitoring should be undertaken both before and after artificial light upgrades or installations at both the affected and control sites.

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

Review

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

Terrestrial mammal light mitigation toolbox

Appropriate artificial lighting design, controls and impact mitigation will be site, project and species specific. Table 1 provides a toolbox of management options relevant to terrestrial mammals. These options should be implemented in addition to the 6 best practice lighting design principles outlined in the National Light Pollution Guidelines for Wildlife. Not all mitigation options will be relevant for every project. Table 2 Commercial luminaire types that are considered generally less disruptive for use near important terrestrial mammal habitat, and those to avoid provides a suggested list of light types appropriate for use near terrestrial mammal habitat and those to avoid.

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

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

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

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

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

Table 1 Light management options specific to terrestrial mammals

Management action	Detail
Avoid adding artificial light to previously unlit areas.	Introduction of artificial light to dark areas is likely to have a greater impact than alterations or additions to areas where artificial lighting already exists.
Avoid artificial light directly onto refuge sites.	Avoid installing and directing luminaires near refuge sites as this can change terrestrial mammal refuge behaviour and use of refuge sites. Artificial light spilling onto terrestrial mammal habitat can reduce the available area for refuge.
Avoid artificial light directly onto foraging areas and commuting routes.	Avoid installing and directing luminaires near foraging areas and commuting routes. Artificial light can lead to fragmentation, degradation and loss of habitat for foraging and commuting. Artificial light in terrestrial mammal habitat can permanently reduce the available area for foraging and commuting or provide an advantage for predators.
Shield light sources to prevent artificial light spilling onto habitat for ground-dwelling species.	Where ground-dwelling terrestrial mammal species are present, artificial light should be directed onto the exact surface area requiring illumination. Use shielding on lights to prevent light spill outside the target area.
Shield light sources to prevent upward artificial	Where arboreal terrestrial mammal species are present, vertical light should be shielded such that it is not visible from the tree canopy above the luminaire installations. Any pole lighting should be at a height lower than arboreal

Management action	Detail
light spill for arboreal species.	mammal refuge, foraging and commuting habitat without compromising human safety.
Avoid using high intensity light.	Keep artificial light intensity as low as possible near terrestrial mammal refuge sites and known foraging areas and commuting routes. Artificial light spill into terrestrial mammal habitat should be kept at as low an intensity as practicable. For arboreal species this includes keeping the intensity of vertical artificial light spill onto vegetation as low as possible. Behaviour of terrestrial mammals can be disrupted by artificial light intensities above natural levels of darkness. Isolated artificial light sources will likely have less effect than large arrays of high-intensity artificial lighting, except in areas where single artificial light sources are newly introduced.
Prevent indoor lighting reaching the outdoor environment.	Use fixed window screens, blinds or tinting on windows and skylights to contain artificial light inside buildings.
Use luminaires with spectral content appropriate for the species present.	Give consideration 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 terrestrial mammals. Terrestrial mammals also show a strong physiological response to blue-wavelength light. Longer wavelength artificial light (such as red light) may have less impact on terrestrial mammal species, though this may not be the case for all species. Where this option is progressed, careful post-installation monitoring should be undertaken to assess the success of mitigation.
Implement part-night lighting schemes to reduce the amount of artificial light present throughout the night.	Part-night lighting may not be an effective mitigation measure for some species. Terrestrial mammals may benefit from part-night lighting, particularly if artificial lights are turned off at times appropriate for the species in question. Where this option is progressed, careful post-installation monitoring should be undertaken to assess the success of mitigation.
Implement motion sensor lighting.	Installing motion sensor lighting may or may not be an effective mitigation measure for some species. Terrestrial mammals may benefit from motion sensor lighting, particularly if it reduces the amount of artificial light present throughout the night. Note, however, that this may cause a startle response in some species. Where this option is progressed, careful post-installation monitoring should be undertaken to assess the success of mitigation.

If all other mitigation options have been exhausted and there is still a need for artificial light, see Table 2 Commercial luminaire types that are considered generally less disruptive for use near important terrestrial mammal habitat, and those to avoid Table 2 for guidance on types of commercial luminaires that are more suitable for use near terrestrial mammal habitat. The effectiveness of these luminaires will depend on which species are being considered. Careful post-installation monitoring should be undertaken to assess the success of mitigation.

Table 2 Commercial luminaire types that are considered generally less disruptive for use near important terrestrial mammal habitat, and those to avoid

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

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

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