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The effects of light and noise from urban development on biodiversity: Implications for protected areas in Australia

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Summary Global population growth and associated urban development are having profound effects on biodiversity. Two major outcomes of expanding development that affect wildlife are light and noise pollution. In this paper, we review literature reporting the effects of light and noise on biodiversity, and assess implications for conservation planning in Australia. Our results clearly indicate that light and noise pollution have the potential to affect the physiology, behaviour and reproduction of a range of animal taxa. Types of effects include changes in foraging and reproductive behaviours, reduction in animal fitness, increased risk of predation and reduced reproductive success. These could have flow-on consequences at the population and ecosystem levels. We found a significant gap in knowledge of the impact of these pollutants on Australian fauna. To reduce the effect of light and noise pollution, there needs to be careful planning of urban areas in relation to protected areas, and for biodiversity more generally. Potential measures include strategically planning the types of development and associated human activities adjacent to protected areas, and the use of shields and barriers, such as covers for lights or the use of dense native vegetation screens, while still allowing movement of animals. Changes in government standards and regulations could also help to reduce the impacts of light and noise pollution.

Key words: *biodiversity, light, noise, pollution, protected areas, urban development.*

Introduction

More than half of the world's human population live in urban areas, and this proportion is expected to increase over the next 20 years (McDonald 2008). Urbanisation has not been spatially even, and much of Europe and North America is already heavily urbanised, with other parts of the globe rapidly catching up. Australia is particularly urbanised, with 88% of its population living in major cities (McDonald *et al.* 2009). Biodiversity in urban and peri-urban environments is significantly affected by the development associated with expanding cities (Chace & Walsh 2006), and the negative effects are expected to intensify with increasing urban development (Soule 1991; Luck *et al.* 2004).

More than 12% of the world's land surface has varying degrees of conservation protection (Chape *et al.* 2005; Pyke 2007; UNEP-WCMC 2008; Leverington *et al.* 2010), an increase from 0.5% in the 1950s (McDonald *et al.* 2009). As cities expand into surrounding non-urban land, the proximity of urban land to protected areas will decrease (McDonald *et al.* 2009) with potential spillover effects on 'protected' natural values.

In this paper, we focus on the effects of light and noise pollution (see Box 1 and 2) on biodiversity wherever it occurs, but in particular 'protected areas' as these are the parts of the landscape where society concentrates on conservation efforts. We define protected areas as national parks, nature reserves and other places set aside primarily for nature conservation. Two key effects of urban areas on biodiversity are light and noise pollution (Longcore & Rich 2004; Barber *et al.* 2010). While there has been some research on the ecological impact of these pollutants in the international literature, mainly Europe and North America, the subject has received less attention in Australia. It is not clear that findings from the northern hemisphere are applicable in Australasia. With expected growth of the Australian human population, and associated urban spread, understanding and mitigating the effects of light and noise pollution on biodiversity, particularly in protected areas, will assume growing importance. Australia provides an excellent case study, because the human population is highly urbanised, with further rapid and ongoing development, but the climate and ecology are very different from much of Europe and North America. Studies on effects of urbanisation in Australia may therefore provide better information on what might be expected in other parts of Australasia.

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Box 1. Definitions of artificial light pollution

Longcore and Rich (2004) describe any artificial light that alters the natural patterns of light and dark in ecosystems as 'ecological light pollution'. This includes chronic or periodical increases in illumination (e.g. floodlights and expanding urban areas), unexpected changes in illumination (e.g. car headlights and floodlights) and direct glare (e.g. from reflective surfaces, such as buildings and billboards). The brightening of the night sky caused by both natural and artificial sources is known as the sky glow (Teikari 2007). Sky glow has been observed from distances of between 8 and 67 km in a study looking at five cities in the southwest United States (Duriscoe *et al.* 2014). There are two key sources of artificial light that should be considered in urban areas:

1 **Street, house and public area lighting.** This lighting is usually on all night and every night, giving a mix of constant illumination and varying intensity depending on usage patterns. Street and public area lighting increases the mean level of night illumination and adds to the level of sky glow.

2 **Floodlights**. This sort of lighting is typically used for sports grounds and security and industrial purposes. In Australia, according to Australian Standards and government regulations, sports ground floodlights vary in amount of illumination depending on the sport and usage practices (training, games) (Table 1). This type of floodlight is usually turned on at twilight for several hours while the fields are being used and then turned off, and thus will create intense illumination for shorter periods. A recent study looking at the light pollution sources in Flagstaff, Arizona, found that 33% of the total uplight came from sport lighting. When this was turned off, then security and industrial lighting accounted for 66% of the total (Luginbuhl *et al.* 2009).

Table 1. Lighting minimum performance criteria (service illuminance lux)

Level of play	Outdoor tennis	Outdoor netball, basketball	Outdoor hockey	Football (all codes) professional	Football (all codes) Semi-professional	Football (all codes) amateur
International	1000	–	500	500	–	–
Competition	350	200	250	500	200	100
Training	250	100	250	100	50	50

(Australian Standards 2007; The Government of Western Australia Department of Sport & Recreation 2010). –, No data.

The aims of this review were to quantify the amount of research in this area. To do this, we did the following:

1 Reviewed the effects of light and noise on biodiversity, particularly within Australia;

2 Identified the likely effects of light and noise pollution associated with urban areas;

3 Assessed implications for Australian urban development and planning.

By identifying the extent of research on the effects of light and noise pollution in Australia, and the knowledge gaps, we hope to provide the basis for a research agenda that will better inform conservation and urban planning.

Methods

Literature search

Broad definitions of light and noise pollution can be found in Box 1 and Box 2. Relevant literature was identified using four databases or citation lists: ISI Web of Science (http://apps.isiknowledge.com/), Scopus (http://www.scopus.com/), Google (http://www.google.com.au/) and Google Scholar (http://scholar.google.com.au/) (12 June 2014). We used the following search terms in different combinations: ('light pollut*' OR 'light*' OR 'noise pollut*' OR 'noise' OR 'urban development' OR 'moon*' OR 'circadian') AND ('species*' OR 'animal*' OR 'bird*' OR 'frog*' OR 'insect*' OR 'fauna*' OR 'biodiversity*' OR 'Australia' OR 'marsupial'). The search terms were used in limited combinations depending on the requirements of the database used. We also searched the cited literature. Marine animals, fresh water fish and migration studies were not included in the results because terrestrial environments were our focus.

Each paper was evaluated for the type of response (physiological or behavioural), effects on the organism (positive, negative or neutral), type of noise or light (artificial or natural) and the experimental conditions (laboratory or field based).

Results

Artificial light

We found 93 research papers and twelve review articles looking at the effects of moonlight and artificial light on animals (Fig. 1 and Appendix S1). Of these, 28 studies documented the responses of individual laboratory and wild animals to moonlight. We reviewed only those reports relevant to artificial light pollution and so excluded these studies.

There were 81 studies examining animal responses to artificial light, although some did not specify exact levels. Field conditions can be expected to provide a better understanding of how wild populations react to artificial light. We found 45 studies were carried out in the field and 30 were conducted under laboratory or captive conditions.

Box 2. Definitions of noise pollution

Noise pollution is any human-made sound that alters the behaviour of animals or interferes with their functioning (known as 'masking'; Barber *et al.* 2010). This includes altering reproduction, communications (courtship, begging, distress and alarm calls), survivorship, habitat use, distribution, abundance or genetic composition (Bowles 1995; Radle 1997; Warren *et al.* 2006; Barber *et al.* 2010).

Urban noise, especially traffic noise, is ubiquitous and louder than most natural sources of noise and is stronger at low frequencies (Rheindt 2003; Brumm & Slabbekoorn 2005; Warren *et al.* 2006; Hu & Cardoso 2009). There are three key sources of artificial noise that should be considered in urban areas (Table 2):

1. **Traffic** noise from passing vehicles that can extend for more than 4 km from a road depending on the volume and speed of traffic and the prevailing weather conditions (Department of Transport Welsh Office 1988).
2. **Human voices** from the surrounding houses, bushwalkers and sports grounds.
3. **Game sirens** from sports grounds sounding during and at the end of games. These can emit a very loud sound that can last for a few seconds and can be assumed to be similar to a stationary ambulance siren.

Table 2. Sound pressure levels of various familar sounds in air from Bowles 1995; Center for Hearing & Communication 2010 and Pepper *et al.* 2003

Example source	Sound pressure level in air (dB)	Effects on humans
Sound just audible to nocturnal carnivore	−20	
Breathing	0–10	Barely audible
Quiet desert	20	
Rustling of leaves		
Night-time home	40	
Quiet residential area		
Bird calls (44 dB)		
Normal speech	60	Half as loud as 70 dB, fairly quiet
Safe limit continuous noise	70	Arbitrary base of comparison
Freeway traffic		
Power lawn mower	65–96	80 dB possible damage; 2 times as loud as 70 dB
Heavy traffic		
Propeller plane flying overhead at 305 m		
Truck	90	Likely damage in 8 hours exposure; 4 times as loud as 70 dB
Shouted conversation		
Boeing 737 at 1.8 km before landing		
Motorcycle	95–110	
Jackhammer	100	Serious damage in 8 hours exposure; 8 times as loud as 70 dB
Jet flyover at 305 m		
Helicopter at 30 m		
Leaf blower	110	Average human pain threshold; 16 times as loud as 70 dB
Car horn		
Live rock music (108-114 dB)		
Football game (stadium)	117	
Thunder storm	120	Painfully loud; 32 times as loud as 70 dB
Ambulance siren		
Chain saw		
Rock concert		
Aeroplane taking off	140	
Jet taking off (at 25 m)	150	Eardrum rupture

There has been little research conducted in Australia on the effects of light pollution on fauna (seven research papers: one under captive conditions and six under field conditions). We found no Australian research on the effects of artificial light on the physiology, circadian cycles or reproduction of terrestrial Australian animals.

Noise pollution

There were 68 studies examining animal responses to noise, although Australian

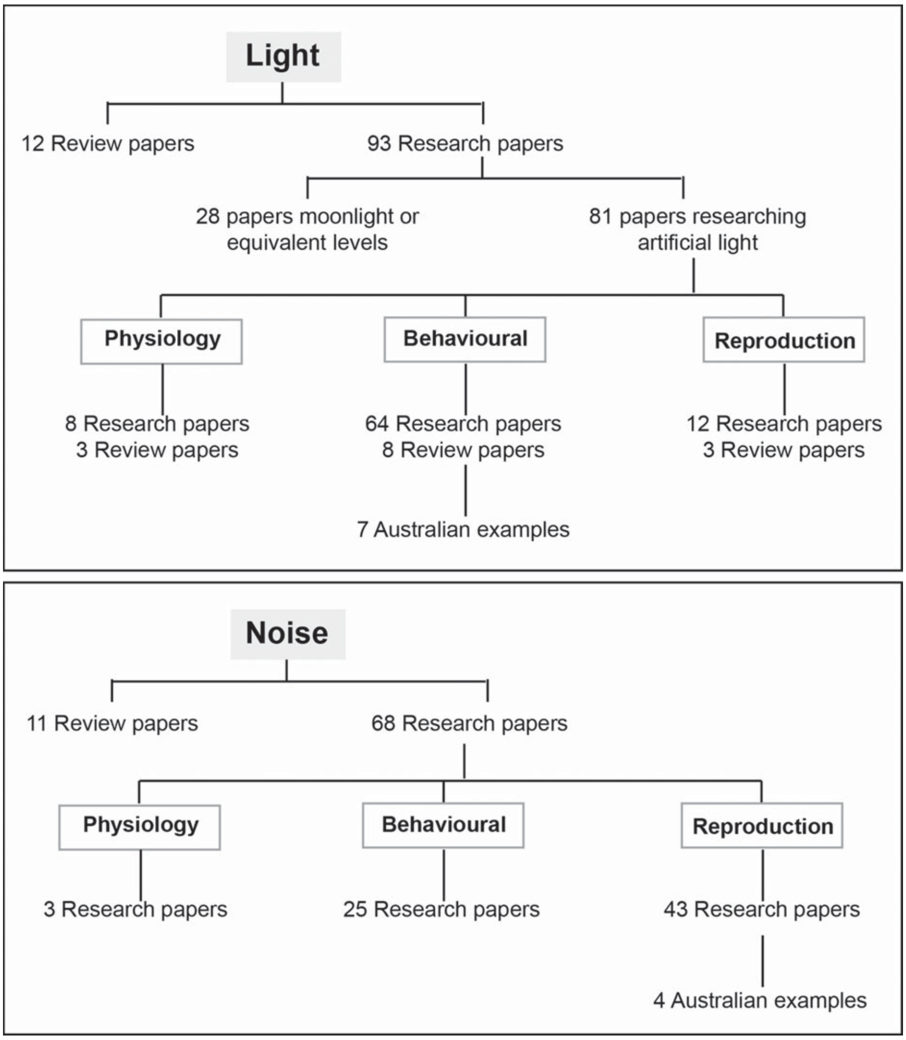

Figure 1. Summary of literature research.

research in this area was sparse (three research papers, under field conditions) (Fig. 1 and Appendix S2). The majority of the research has examined the effects of noise on bird species (Appendix S2), probably due to birds' high visibility and the relative ease with which they can be studied. Other groups studied included frogs (four studies), invertebrates (three studies) and mammals (eight studies) (Appendix S2).

Discussion

Our review showed that research on the effects of light and noise on biodiversity in Australia is sparse when compared with the international literature. Nevertheless, with the research gathered, we found that effects fell into three key categories: (i) physiology; (ii) behaviour; and (iii) reproduction.

Effects of artificial light on biodiversity

Physiology

Eyesight. Vertebrates with nocturnal habits generally have dark-adapted eyes; this adaption includes large pupils to admit more light, large lenses to minimise spherical aberration and rod-rich retinas (Walls 1942; Beier 2006). Sudden increases of light cannot only disrupt and reduce an animal's vision but, depending on the brightness of the light, can require a long recovery period (up to several hours) before their eyes return to a dark-adapted state (Buchanan 1993; Fain *et al.* 2001; Beier 2006; Frank 2006).

The most common types of lights used for outdoor lighting are tungsten, halogen, fluorescent, mercury vapour, metal halide, high- and low-pressure sodium and more recently light-emitting diodes (LED). Fluorescent, mercury vapour and metal halide have colour ranges that extend into ultraviolet light, while LEDs typically have one or more symmetrical emission curves with the peak varying greatly amongst models (Gaston *et al*, 2012), giving a full spectrum of colour, with none to minimal amounts of UV (van Langevelde *et al.* 2011). There have been very few studies that have examined the effect of the non-visible colour spectrum of light pollution on animals (Longcore & Rich 2004; Johnsen *et al.* 2006; van Langevelde *et al.* 2011; Becker *et al.* 2013). Birds, reptiles, frogs, moths and some mammals including marsupials all have vision with sensitivity in the ultraviolet range (Arrese *et al.* 2002; Buchanan 2006; Frank 2006; Gauthreaux & Belser 2006; van Langevelde *et al.* 2011; Tyler *et al.* 2014). These taxa are likely to see their environment differently from humans, which means it is difficult to speculate how light pollution may affect foraging and mating behaviour of crepuscular and nocturnal species (Gauthreaux & Belser 2006; Johnsen *et al.* 2006) without direct and specific empirical evidence.

Light-polluted night skies also have a high concentration of long-wavelength light that substantially alters the appearance of objects and how they are perceived (Frank 2006; Johnsen *et al.* 2006). Barth (1985) describes how mercury vapour lights, which are rich in ultraviolet energy, would accentuate ultraviolet markings on flowers, but that low-pressure sodium vapour light that contains no ultraviolet energy would conceal them. Little is known about the effect this could have on the nocturnal organisms that use such markings for feeding. Furthermore, artificial light may also affect plants and fungi that require nocturnal animals for pollination or spore dispersal. Many plants and fungi show activity at night such as flowering, emitting-fragrance, growing, assimilating, spore dispersal or germination and therefore could be affected by light pollution (Holker *et al.* 2010). An example of a species that might be affected is the nocturnal flowering Australian Slender Wire Lily (*Laxmannia gracilis*), an eastern Australian woodland species that has pink or white flowers that only open at night, and is mostly pollinated by a nocturnal invertebrate.

Circadian cycles. The light and dark cycles of the earth are used by many organisms for their biological timekeeping. This is called the 'circadian cycle' (Hotz Vitaterna *et al.* 2001), and the hormone used to regulate this timekeeping is melatonin (McAllan *et al.* 2008). The circadian cycle is thought to have evolved to maximise foraging efficiency, to reduce risk of predation and to enhance parental care (Beier 2006). Artificial lighting that causes shortening or brightening of the night can adversely affect animals by disrupting that circadian cycle (Beier 2006; Rich & Longcore 2006; Navara & Nelson 2007). Affected animals' circadian cycles also may be out of phase with neighbouring individuals living in a natural light–dark cycle. This could potentially affect mating success, group-mediated anti-predator vigilance and other processes in more social animals (Beier 2006).

It is logistically very difficult to conduct research on wild populations examining the effect of artificial light on the circadian cycle (Beier 2006). Therefore, it is difficult to evaluate the effects in the wild. Most studies that have been conducted on circadian cycles have used captive animals under experimental conditions. One study demonstrated that using a brief pulse of light (10–15 minutes) with a bright light (about 1000 lux) stimulated a shift in the circadian cycle by 1–2 hours (Beier 2006 and references therein). This finding, gained under controlled conditions, suggests that artificial night lighting may disrupt circadian patterns in the wild (Beier 2006).

Behaviour

Interference with responses to moonlight. A large proportion of animals globally are nocturnal, 30% of vertebrates and more than 60% of invertebrates (Holker *et al.* 2010). Australia also has a high proportion of animals that are nocturnal, including all the bats species and 80% of the marsupial species (Beier 2006). Numerous studies have shown that bats, nocturnal rodents and other nocturnal mammals respond to moonlight by shifting their activity periods, reducing their activity, travelling shorter distances and consuming less food. For example, Brush-tailed Rock-wallaby (*Petrogale penicillata*) has been observed to be very unsettled on moonlit nights (Carter & Goldizen 2003). Similar results have been observed using artificial light, under both experimental and field conditions. For example, the Santa Rosa Beach Mouse (*Peromyscus polionotus leucocephalus*) reduced the amount of time they spent under street lights and consumed less food (Bird *et al.* 2004).

Effects on foraging. Artificial lighting of similar intensity to moonlight can reduce activity and movement of many nocturnal animals, particularly those that rely on concealment to reduce predation risk during nocturnal foraging (Beier 2006). The Australian Standard (AS 2560) for sports lighting recommends that the minimum lighting required for sports ground ranges from 50 to 1000 lux depending on sport type and the level of play (Table 1), and this is 167–3333 times the lux levels of a full moon (0.3 lux). Street lighting has a much lower level of intensity (3–21 lux AS 1158), but it is still is much stronger than the illuminancy of a full moon (Kramer & Birney 2001; Rich & Longcore 2006). Car park lighting illuminancy level can be 10 lux, and this is approximately 30 times the level of illumination of a full moon (Rich & Longcore 2006). While some small animals respond to moonlight conditions by shifting foraging and ranging activities to darker conditions, this option is not available to animals experiencing artificially increased illumination throughout the night (Beier 2006). Under these circumstances, animals are faced with three options:

1. To accept the increased predation risk, as observed by Alkon and Saltz (1988) in Crested Porcupine (*Hystrix indica*) when there were food shortages in summer (see Beier 2006);
2. To continue to minimise predation risk, even at the cost of body mass, as observed in a experiment on the Darwin's Leaf-eared Mouse (*Phyllotis darwini*) (Vasquez 1994) (see Beier 2006);
3. To no longer be able to survive in the area, such as for the Giant Water Bug (*Lethocerus deyrollei*) that has a greatly reduced probability of habitat occupation within 1 km of artificial lighting (Choi *et al.* 2009).

A 'perpetual full moon' from artificial lights could favour light-tolerant species and exclude others (Longcore & Rich 2004). If the darkest natural conditions never occur, those species that maximise foraging during the new moon could be compromised (Longcore & Rich 2004). Artificial lighting has been shown to benefit the foraging of some animals (Appendix S1). Increased illumination may extend diurnal behaviours into the night-time environment by improving an animal's ability to see and orient itself (Longcore & Rich 2004). Many usually diurnal birds (Hill 1990) and reptiles (Schwartz & Henderson 1991) will forage under artificial lights (Longcore & Rich 2004). This could increase competition between nocturnal animals that feed on the same prey during the night. Furthermore, it could disrupt the interactions of groups of species that show resource partitioning across illumination gradients (Longcore & Rich 2004).

It has been recently discovered that marsupials' eyes differ from eutherians, by retaining an ancestral visual pigment (Arrese *et al.* 2002), possibly making them more susceptible to artificial light. Two different studies on Australian marsupials showed different responses to artificial lighting: the Sugar Glider (*Petaurus breviceps*) and the Tammar Wallaby (*Macropus eugenii*). Both animals are nocturnal, and the studies were conducted under captive conditions. Under street lighting conditions, the foraging and activity of the glider were negatively impacted by reducing the time spent foraging, to the point under high street light illumination (12 lux) where almost all high level activity (foraging) was ceased (Barber-Meyer 2007). This was potentially due to artificial lighting aiding the Sugar Glider's predators (owls, kookaburras, goannas and cats) (Barber-Meyer 2007). In contrast, wallabies tended to forage more and allocate less time to anti-predator vigilance under artificial light conditions (Biebouw & Blumstein 2003). In this situation, the artificial lighting probably helped the animals to observe their predators from a distance. Many species of micro-bats aggregate at street lamps to exploit groups of moths and other insects that are attracted to the light (Beier 2006 and references therein). These aggregations are not natural, nor are they beneficial to the insect prey of the bats (Beier 2006). Potentially, this could also alter the community structure of bats, so that faster-flying species that are able to hunt for insects benefit from the lighting conditions, while the slower-flying bats that avoid the lights are negatively impacted (Frank 1988; Longcore & Rich 2004). These examples indicate how artificial light could both positively and negatively affect Australian animals, with the potential to have ramifications for community structure and ecosystem function.

Effects on spatial behaviour. Artificial lighting can either attract or repel animals depending on their phototactic preference (see references in Appendix S1), which can increase the edge effect (Benitez-Lopez *et al.* 2010) depending on how far the light penetrates into the habitat. This can have an effect on the dispersion and movement of animals, which has been observed in the Cougar (*Felis concolor*) (Beier 1995), the slow-flying Lesser Horseshoe Bat (*Rhinolophus hipposideros*) (Stone *et al.* 2009) and Gould's Long-eared Bat (*Nyctophilus gouldi*) (Threlfall *et al.* 2013). Disruptions to an animal's spatial behaviour can decrease energetic gains and increase costs by increasing travel time, stress and cortisol (a hormone produced in times of stress to increase metabolism) levels, which may in turn reduce survival and reproductive success (Stone *et al.* 2009).

Reproduction

Reproductive behaviours may be altered by artificial lighting (Longcore & Rich 2004). This includes territorial and mating communications (singing, calling and visual), mate and nesting site selection and breeding timing and readiness. A study conducted by Baker and Richardson (2006) showed that when Green Tree Frog (*Rana clamitans melanota*) individuals were exposed to artificial light, they produced fewer advertisement calls and moved more frequently, when compared with ambient light; this could potentially reduce recruitment rates and change population dynamics (See Appendix S1 for more examples). Artificial light has also been shown to alter the rate of larval development in frogs and effects their behaviour and physiology (Perry *et al.* 2008). Artificial light pollution could also reduce the population sizes of animals through the direct loss of individuals and reproduction failure, or alter sex ratios (Perkin *et al.* 2011). Again, research on this issue in Australia is minimal.

Effects of noise pollution on biodiversity

Physiology

Hearing. Different animal taxa have different hearing ranges and sensitivities (Table 3) that affect their perception of social and other important signals that influence survival. Animal ears are most susceptible to noise within their 'best' range (the bandwidth they hear best, (Bowles 1995)). Among mammals, rodents and bats hear best at high frequencies, and more generally, nocturnal mammals have the most sensitive hearing among the terrestrial vertebrates (Bowles 1995). Birds and reptiles are also highly sensitive to the vibrations that low-frequency noise can induce in an animal or adjacent substrate (Bowles 1995). In laboratory animals, strong and long-lasting noise, also know as 'chronic noise', causes physiological changes that can affect their health (Kempf & Huppop 1996).

A review undertaken by Aitkin (1995) of the auditory systems of marsupials found very little difference between the auditory anatomy of marsupials and eutherians. International literature may therefore have some general applicability in Australia with regard to noise effects. This may mean that species that share the same habitat and lifestyles, for example arboreal possums and squirrels, may have greater similarities in hearing than between species of different lifestyles within either of these groups, for example arboreal possum and carnivorous dasyurid, such as a quoll (Aitkin 1995).

Behaviour

Species richness and abundance and habitat avoidance. There have been seven studies, on birds in particular, showing that as the noise levels increase in an area, abundance and species richness significantly decreased. For example, a study on tropical forest birds in Costa Rica found that the abundance and species richness significantly decreased with increasing traffic noise (Arevalo & Newhard 2011) (Appendix S2). Wild animals can abandon favoured habitat in response to disturbances or incur energetic expenses after reacting repeatedly when they cannot escape (Bowles 1995). For example, a study in South Australia on the impacts of traffic noise and volume on the birds of roadside habitats found that the probability of detecting the Grey Fantail (*Rhipidura fuliginosa*) and the Grey

Table 3. Hearing ranges and sensitities of different taxa from Bowles 1995

Animal	Hearing range (Hz)	Sensitivity (dB)
Amphibian	100–2000	10–60
Reptile	50–2000	10–20
Bird	100–10,000	0–10 owls are 15–20 dB more sensitive in their best range than other birds
Mammal	10–150,000	−20
Humans	20–20,000	–

–, No data.

Shrike-thrush (*Colluricincla harmonica*) on a visit to a site declined considerably with increasing traffic noise and volume (Parris & Schneider 2009).

Vigilance, foraging and predator avoidance. Noise has been found to increase predator vigilance, which results in reduced foraging efficiency (Appendix S2). For example, relatively high levels of noise may cause wild animals to become irritable and restless, and this may then affect food intake, social interactions or parenting; these effects could eventually result in population declines (Bowles 1995).

Most nocturnal moth species, and some other nocturnal insects, have tympanic organs, that are sensitive to ultrasound, that they use in the defence against bats (Faure *et al.* 1990). A study on free-flying winter moths (*Operophtera* spp.) exposed to noise generated by mercury vapour lights failed about half the time to exhibit their normal evasive behaviours to electronically simulate ultrasonic bat signals, thus interfering with the moth's defensive behaviour, making them vulnerable to bat predation (Svensson & Rydell 1998).

Many animals form groups to increase vigilance and early detection of predators. Individuals use alarm calls to alert each other to possible danger. Among different bird species, alarm calls are not always present. A recent Australian study on the Crested Pigeon (*Ocyphaps lophotes*) suggested that the take-off noise of aeroplanes could provide a cue of alarm in many flocking species (Hingee & Magrath 2009). This means that the vocalisation of an animal is not the only type of communication that may be masked by urban noise, and more subtle communication between animals may be also be affected, potentially putting them at risk from predators.

Reproduction

Reproductive behaviours and success may be altered by increased noise (Bowles 1995; Radle 1997; Barber *et al.* 2010). This includes territorial and mating communications (singing and calling), mate and breeding site selection (Appendix S2). Acoustic masking of signals can impair acoustic communication severely, therefore leading to difficulties in mate attraction and territory defence (Brumm 2004b; Barber *et al.* 2010). Birds (including begging signals of young), primates, and frogs have been known to adjust their vocalisation to reduce the masking effects of noise, and these adjustments include a shift in vocalisation (frequency, amplitude and time period), and increase or decrease in communication (see Appendix S2). For example, the urban European Robin (*Erithacus rubecula*) has developed a new behaviour in response to noise pollution. Rather than shifting its vocalisation, it has reduced acoustic interference by singing during the night (Fuller *et al.* 2007). This was originally thought to be due to the ambient artificial light from outdoor lighting, but the amount of daytime noise had a greater effect on nocturnal singing activity than night-time light levels.

In another example, an Australian study found that female frogs of some species prefer lower-pitched calls, which indicate large, more desirable males (Parris *et al.* 2009). Several studies have demonstrated that with low-frequency background noise produced by traffic, frogs and birds call at a higher pitch to be heard over the masking noise (Slabbekoorn & Peet 2003; Parris *et al.* 2009; Francis *et al.* 2011) (See Appendix S2). This, therefore, represents a trade-off between audibility and attractiveness to potential mates.

Research into distances from a source of noise

Studies on the ecological effects of roads on avian communities in the Netherlands found that effect-distances (the distance from the road at which a population density decrease was detected) were greatest among birds in grasslands than birds in woodland areas (Forman & Alexander 1998). The effect-distance for the most sensitive of the bird species increased from 305 m to 810 m in woodlands, and from 365 to 930 m in grasslands, when traffic density increased from 10,000 to 50,000 vehicles per day (Forman & Alexander 1998).

Similarly, a study examining grassland birds in the USA found light traffic volumes (3000–8000 vehicles/day) had no significant effects on the presence or breeding of grassland birds, but when the volumes increased to a heavier volume of traffic (15,000–30,000 vehicles/day), presence and breeding were reduced within 700 m, to the extreme where the volume of traffic was greater than 30,000 vehicles/day the bird presence and breeding were reduced within 1.2 km (Forman *et al.* 2002). In another study, the Mexican Spotted Owl (*Strix occidentalis lucida*) recorded no flushes (movement from a nest) when noise stimuli (helicopter or chainsaw) were >105 m away (Forman & Alexander 1998), indicating that 105 m buffer zone for helicopter overflights would minimise spotted owl flush response and any potential effects on nesting activity.

Implications

A need for more Australian research into effects of light and noise on biodiversity

Strikingly, given the likely negative consequences for biodiversity, our study has shown that there is a relative lack of research on the effects of artificial light and noise on biodiversity and protected areas in Australia (16 behavioural studies for light effects and four studies looking at noise effects on reproduction). Given the rapid development of new suburbs in Australian cities and the building of associated facilities such as sports grounds, transport corridors, entertainment and recreation venues, there is an urgent need for research on the effects of artificial light and noise pollution and ways of mitigating those effects.

Further research is needed into the effects of different types of artificial light (each with a different wavelength) on Australian animals, and how this changes their attraction to, and behaviour towards, the light. It is also important to undertake research on whether illumination output levels fall within the different light spectra that animals can perceive. This is especially important because it has been discovered that some Australian marsupials are ultraviolet-sensitive (Arrese *et al.*

2006). This type of research would particularly be timely because night lighting is changing to become more energy efficient. For example, the European Eco-Design Directive is planning to phase out energy-intensive lighting (e.g. high-pressure mercury lamps) and replacing with more efficient LEDs (Perkin *et al.* 2011). Little is known about the potential effects of LED lighting on animals' behaviours, reproduction or physiology, other than LED light producing very little UV in the light spectrum (van Langevelde *et al.* 2011).

Implications for biodiversity

Despite the relative lack of research data on light and noise pollution on biodiversity in Australia, it is still possible to infer some probable generic effects on Australian fauna and possible precautionary methods for avoidance and mitigation. We identified seven potential effects of light and noise that should be considered in future development planning in Australia:

1. **Ecological community composition** could potentially be negatively impacted in the immediate vicinity of the source, and for large distances surrounding the source, depending the sensitivity of the organism and the nature of the lighting. This could also have flow-on effects to other parts of a protected area, through competition for resources. Behavioural plasticity will help some organisms to adjust to the new environment, but not all organisms are able to adapt to a changing environment (Dukas 2013; Sih 2013; Slabbekoorn 2013; Sol *et al.* 2013).
2. **Reproductive success** in birds, moths and frogs in the area close to the source could potentially be significantly reduced, which in turn will also have further effects on trophic relationships and community composition.
3. **Niche competition changes** could occur between species, where there is resource partitioning or when diurnal species become active at night or exploiting the congregation of insects around a light source. This could put greater pressure on key resources and reduce a species' fitness in the changed environment.
4. **Loss of ecosystem function** with the loss of organisms that are unable to adapt to the light, noise or increased pressure, such as predation, competition and foraging. For example, the local extinction of one organism in an area could have flow-on effects and impact other organisms in the ecosystem.
5. **Effects on existing and reintroduced animals** could cause substantial changes in foraging, and anti-predator behaviour and reproductive success. This may not only effect existing fauna, but also the re-establishment of reintroduced species and their long-term survival in protected areas.
6. **Reduction in effectively conserved habitat** in a protected area due to loss or reduced usable habitat and/or resource values to biodiversity. Such effects are likely to be overlaid on top of predicted effects of climate change on biodiversity.
7. **Precedent setting and additive effects from subsequent developments.** Existing development can be expected to set the level of acceptable compliance to environment assessment regulators. Where planning standards are insufficient to minimise light and noise effects, this can be expected to set a precedent for other developments near protected areas. Further, while individual developments may not have major impact on biodiversity, the cumulative or additive effects of multiple developments through time should be considered in strategic planning. Planning to minimise and mitigate light and noise effects should therefore be included at the earliest stages.

Implications for conservation management and planning

The lack of empirical data on the effects of light and noise on Australian biodiversity is a challenge for managers and planners. This points towards the use of the precautionary approach. There are a number of avoidance and mitigation approaches that could be considered in the absence of additional data. While the following is not intended to be comprehensive, it provides a starting point for considering the effects of light and noise in conservation planning.

Baseline mapping and ongoing monitoring for light and noise pollution

A critical first step will be to implement baseline monitoring programmes for light and noise pollution to generate measurements that allow modelling of current conditions. Such baselines will allow modelling of likely impacts of different scenarios for new developments. This would also allow assessment of overall urban emissions for light and noise, and would assist government agencies and planning authorities to monitor changes through time. In particular, situations, where emissions are high adjacent to protected/sensitive areas, and measures to reduce light and noise effects could be considered. International research has successfully shown that using remote sensing and modelling can identify where high emission hotspots are, and by using different management techniques, how it reduce effects (Luginbuhl *et al.* 2009; Biggs *et al.* 2012; Kuechly *et al.* 2012; Duriscoe *et al.* 2014; Kephalopoulos *et al.* 2014).

Light

Possible solutions to decreasing the levels of urban light pollution and point sources of light and the effects on Australian animals could involve using light shields, reducing the number of lights and adjusting the colour spectrum produced by external lighting towards the low-level red lighting (e.g. orange sodium street lamps) and away from the highly disruptive high-energy blue lighting (Rydell 1992; Navara & Nelson 2007; van Langevelde *et al.* 2011; Duriscoe *et al.* 2014). International guidelines could be helpful in reviewing Australian Standards. Currently, Canada, New Zealand and Spain have much stricter restrictions on the lighting angles permitted for outdoor lighting (Teikari 2007) than Australia.

Shielding of lights is probably one of the most economical solutions to reducing light pollution. Manufacturers have begun to produce well-shielded to fully shielded lighting suitable for sport lighting, outdoor security and signs, which provide a major reduction in offsite spill and reduce or eliminate direct uplight (light that goes directly up into the night sky) (International Dark-Sky Association 2003). This can have a big effect on the amount of sky glow, but it may still cause ecological light pollution (Rich & Longcore 2006). Street lights can be replaced with full cut-off fixtures (all light directed downward – no light emitted upward) and fitted with energy efficient lamps. It may also be possible to automatically switch lighting off or dim lights after certain hours at night.

Noise

Sound barriers can reduce noise, but they are expensive and may also create barriers to the movement of terrestrial vertebrates, contributing to habitat fragmentation and the isolation of populations (Forman & Alexander 1998; Forman *et al.* 2002; Parris & Schneider 2009). Alternatives to sound barriers include careful planning of new roads and urban development that reduces the impact of noise on animals that communicate acoustically (Parris & Schneider 2009). Changing road surfaces or decreasing the speed of vehicles, rerouting existing roads around important habitat for threatened species or even closing off roads and areas during certain times of the year can reduce noise levels (Slabbekoorn & Ripmeester 2008).

Planning the interface between urban and protected areas so as to avoid and mitigate light and noise effects will be an essential ingredient of urban edge design. Strategically planning the positioning of particular types of development or activities that are known to produce high levels of light and noise pollution, near or adjacent to protected areas, may be one way to limit their light and noise effects in the absence of more ecosystem- or species-specific data. Furthermore, development of national principles and guidelines for the width and structure of buffers between types of development and protected areas would be an important part of a precautionary approach to the issues of light and noise pollution in Australia. From a management perspective, it is important to consider and incorporate the mitigation of potential ecological impacts and losses of biodiversity and ecosystem services into policy development and new urban planning principles (Rich & Longcore 2006; Holker *et al.* 2010; Perkin *et al.* 2011). A first step will be the recognition of the issue in the planning and development process, and an increase in fundamental and applied research regarding the effect of light and noise on Australian biodiversity.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:
Appendix S1 Summary of research into artificial lighting and its effects. *indicates Australian research and °review papers.
Appendix S2. Summary of research into artificial noise and its effects. *indicates Australian research.