Stars only shine in the dark – monitoring artificial light at night at Sydney Olympic Park

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Light pollution from artificial light at night (ALAN) is widely recognised to have negative impacts on biodiversity and ecosystem functions. The Authority collected baseline data on light source, direction and intensity from 197 sites across the Park over 2018 and 2019, to determine the level and extent of ALAN, particularly in sensitive ecological areas. ALAN from car parks, buildings and roads was observed in areas not intended to be lit. The majority of the survey sites (78%) were subject to moderate to high levels of ALAN, with extremely high level of ALAN observed at 8% of survey sites. In spite of encroachment and fragmentation by ALAN, darkness remains in 8% of survey sites, located in areas zoned for environmental conservation and management. In order to preserve dark skies for the protection of natural and cultural heritage, informed and adaptive light management should be implemented in accordance with the National Light Pollution Guidelines for Wildlife and the Australasian Dark Sky Alliance recommendations.

Introduction

Artificial Light at Night (ALAN) has changed human life in virtually all populated areas worldwide, increasing our productivity, feeling of safety, and time for recreation. Research has found that 23% of the world's land surfaces between 75°N and 60°S are exposed to ALAN, but this number goes to up 88% for highly urbanised areas such as Europe. More than 80% of the world lives under light-polluted skies, and one-third of humanity can no longer see the Milky Way at night (Falchi et al., 2016). ALAN is increasing globally by about 2% a year, and is visible from space (Figure 1). Protected areas such as national parks are also affected by light from nearby urban regions (Peregrym et al., 2018).

Light pollution from ALAN is caused by anthropogenic light sources, both internal and external, including vehicle and traffic lights, commercial signage, building lights and public space lightings. Artificial lights are reflected and scattered by particles in the atmosphere, contributing to the brightness of the night sky known as sky glow; artificial lights directed below the horizontal plane that spill into areas not intended for lighting is known as light trespass or light spill (Department of the Environment and Energy, 2020 (hereinafter referred to as DEE, 2020)).

Most organisms have evolved with natural light and dark cycles over geological time, anticipating environmental changes through the daily cycle of day and night, seasonal changes in day length, and the monthly lunar cycle. Virtually all plants and animals possess a circadian clock that regulates activity and physiology on an approximately 24-hour cycle (Gaston et al., 2013). There is growing evidence that disruption of the natural light and dark cycles by increasing ALAN affects circadian rhythm, and this is causing significant, negative effects on species behaviour, physiology and ecological interactions, including growth, foraging, navigation, reproduction, and predation (Gaston et al., 2015).

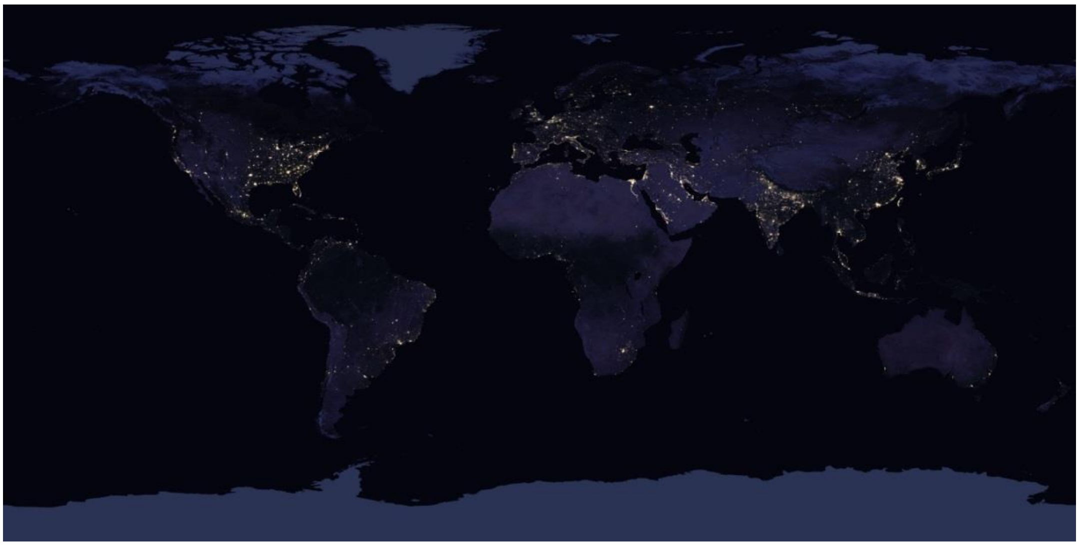

Figure 1. Earth at night in 2016. NASA Earth Observatory images by Joshua Stevens, using Suomi NPP VIIRS data from Miguel Román, NASA's Goddard Space Flight Center

The impact on the natural environment is often the result of the combined effect of all light sources in a region, increasing with the number and intensity of artificial lights in the area (DEE, 2020), often affecting organisms many kilometres away from light sources (Kyba et al., 2011). Understanding the scale and implications of light pollution on the natural world is essential to mitigating negative effects.

ALAN's impact on biodiversity

There is a considerable and growing body of work on the effects of ALAN across a wide range of species. ALAN has been found to:

- Disorient sea turtle hatchlings and ground seabird fledglings so they are unable to reach the sea, causing increased mortality (Rodriguez et al., 2014; DEE, 2020)
- Increase predatory fish behaviour at night, causing a change in the structural assemblage of their prey (Bolton et al., 2017). Clownfish eggs incubated in the presence of ALAN fail to hatch (Fobert et al., 2019)
- Affect plant growth, timing of flowering and resource allocation (DEE, 2020)
- Reduce juvenile toad growth by 15%, and eliminate natural defensive behaviours (Dananay and Benard, 2018)
- Delay births in the Tammar Wallaby, with potential population-scale impacts (Robert et al., 2015)
- Attract and disorient birds, increasing the chance of collision; potentially affect nocturnal roost site selection by migratory shorebirds, with impacts on fitness and migration success (Rogers et al., 2006; DEE, 2020)
- Disrupt insect movement and reproductive success, with flow on impacts for animals that prey on them. Estimates suggest one-third of nocturnal insects both aquatic and terrestrial are drawn to ALAN, with lighting experiments showing large, immediate increase of insect catches at lights (Perkin and Franz, 2014; Holzhauer et al., 2015; Owens et al., 2019). ALAN has resulted in a steep decline in nocturnal moth species richness and abundance (Langevelde et al., 2017; Owens et al., 2019), reducing pollen transport in lit areas (Macgregor et al., 2017). The Bogong Moth, the main food source of the critically endangered Mountain Pygmy Possum, has crashed in numbers due in part to light pollution, prompting the *Lights off for Moths* campaign in south-east Australia (Australian Geographic, 2019).
- Reduce microbat activity, species richness and abundance, particularly slow-flying, light-sensitive microbats that forage in more confined spaces (Spoelstra et al., 2015; Linley, 2016; Foridevaux et al., 2018), even when lights are dimmed (Rowse et al., 2015). ALAN has also been found to delay roost emergence (shortens feeding time), change flight path (Stone et al., 2009), and reduce foraging habitat, with some species avoiding street lights by up to 50m even after the lights were turned off (Azam et al., 2018). Permanent lights have been found to cause roost abandonment (Rydell et al., 2017). Even urban-adapted bat species select darker areas for movement (Hale et al., 2015).

To address the growing impact of ALAN on biodiversity, the Commonwealth Department of the Environment and Energy released the *National Light Pollution Guidelines for Wildlife including marine turtles, seabirds and migratory* *shorebirds* in January 2020 (DEE, 2020) which outline processes for ALAN management with the aim of ensuring wildlife are:

- Not disrupted within, nor displaced from, important habitat; and
- Able to undertake critical behaviours such as foraging, reproduction and dispersal.

In order to implement best practice ALAN management, it is important to understand humans and wildlife do not perceive light in the same way.

Not all light is the same

Humans perceive visible light ranges from 380 nm to 780 nm - between the violet and red regions of the electromagnetic spectrum (Figure 2). White light is a mixture of all wavelengths of light ranging from short wavelength blue to long wavelength red light.

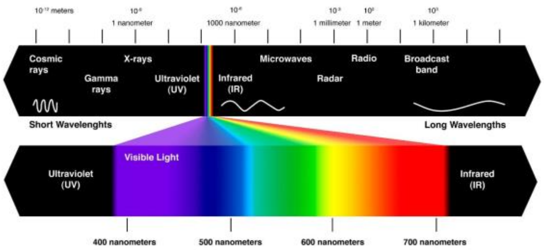

Figure 2. The electromagnetic spectrum. The 'visible light spectrum' occurs between 380-780 nm and is what the human eye can see. Reproduced from the National Light Pollution Guidelines for Wildlife 2020.

In animals, visible light ranges from 300 nm to greater than 700 nm, depending on the species. While light of different wavelengths has different effects on wildlife (Welbers et al., 2017; Voigt et al., 2018), sensitivity to high energy, short wavelength ultraviolet (UV)/violet/blue light from 10 nm to 400 nm is common (DEE, 2020).

Light emitting diodes (LED) are rapidly becoming the most common light type globally as they are more energy efficient than previous lighting technology, requiring less energy to produce the equivalent amount of light. They can be smart controlled to dim and can be instantly turned on and off (DEE, 2020). While LED lights emit less UV radiation, most LED lights contain blue wavelengths (400-500 nm), which generally increase with Correlated Colour Temperature (CCT) measured in degrees Kelvin (Figure 3).

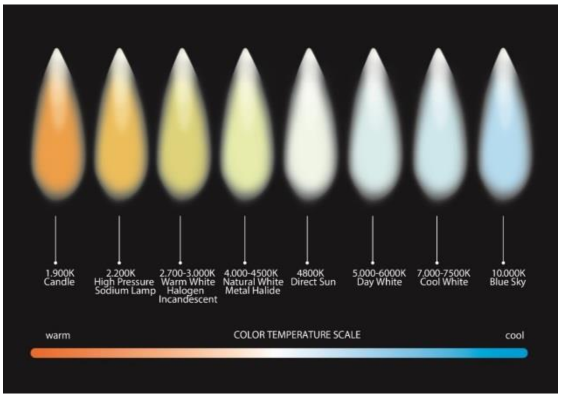

Figure 3. Pictorial representation of the Correlated Colour Temperature (CCT) of LED lights, from warm to cool. Reproduced from the National Light Pollution Guidelines for Wildlife 2020.

However, the only way to tell how much blue light is emitted is to look at the spectral power distribution curve, as two lights of similar colour (CCT) may have very different blue light content, and appear very different to animals with sensitivities to blue light (Figure 4).

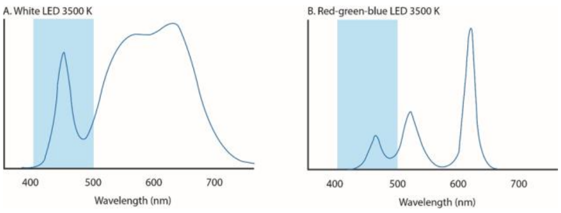

Figure 4. Spectral power distribution curves of two LED lights with the same Correlated Colour Temperature (CCT) but different blue wavelength content. The blue band shows the blue region of the visible spectrum (400-500 nm). Reproduced from the National Light Pollution Guidelines for Wildlife 2020.

Nocturnal animals have dark-adapted vision that allows for the detection of light at very low intensities, which may explain why they are extremely sensitive to white and blue light even at low intensities. Blue light has damaging effects on photoreceptors in the human eye and the same effect is likely to occur in wildlife. The photosensitive retinal ganglion cells in the eye which are involved in entraining circadian rhythms are also particularly sensitive to blue light (Gaston et al., 2013; DEE, 2020).

In addition to increasing the effects of ALAN on blue light sensitive wildlife, short wavelength blue light also scatters in the atmosphere more than longer wavelength light such as green and red, contributing to sky glow. The National Guidelines on Light Pollution (DEE, 2020) recommends only lights with little or no short wavelengths (400-500 nm) violet or blue light should be used to avoid unintended effects on wildlife, with case by case consideration for wildlife sensitive to longer wavelength light. As LED technology offers greater flexibility in wavelength range and lighting intensity, there is potential to manage problematic wavelengths to minimise harm to biodiversity.

ALAN at Sydney Olympic Park

Sydney Olympic Park is an urban park and therefore subject to light pollution from streetlights, traffic lights, building lights and a diversity of other light sources typically associated with urban infrastructure.

Nearly half (304 hectares) of the Park is zoned under NSW planning legislation for environmental conservation and management due to its high ecological values. The Park supports three Endangered Ecological Communities and many threatened species listed under the *NSW Biodiversity Conservation Act* 2016, as well as migratory shorebirds protected under international treaties and agreements including the *Convention on the Conservation of Migratory Species of Wild Animals* (Bonn Convention), and bilateral migratory bird agreements with Japan, China and the Republic of Korea. Nocturnal animals recorded at the Park include the Barn Owl, Southern Boobook, Tawny Frogmouth, Australian Owlet-nightjar, Common Brush-tailed and Ring-tailed Possum, and 12 species of microbats.

The Authority's Master Plan 2030 (2018 Review) provides for a projected daily population of 34,000 workers, 20,000 visitors, 23,500 residents and 5,000 students to ensure an active precinct 18-24 hours a day, seven days a week. Therefore, the number of lit structures and the demand for lighting for wayfinding, security, events and recreation is expected to increase. While the Park's lights are currently concentrated in the Town Centre (the urban core of the Park), roads and car parks, with no pathways in the Parklands illuminated (apart from the East/West Access Corridor through Bicentennial Park and short lit walkways present at Wentworth Common and Newington Armory), there will likely be increasing pressure for lighting in currently dark areas.

Lighting principles for Sydney Olympic Park are contained in both the Sydney Olympic Park Environmental Guidelines 2008 and the Parklands Plan of Management 2010:

- The Sydney Olympic Park Environmental Guidelines requires the Authority to minimise light pollution by limiting use of lights at inappropriate times, locations, and intensities; and avoiding loss of habitat values or natural ambience for open spaces
- The Parklands Plan of Management provides management principles and guidelines for lighting (S3.24.9). Lighting of the Parklands are to be kept to a minimum to discourage inappropriate night-time uses and activities, protect environmentally sensitive areas and where present will meet appropriate lighting standards.

The Authority commenced an ongoing luminaire replacement program in 2012 to address lighting requirements for public safety and high patronage events; metal halide lights were replaced with LED luminaires starting from the Town Centre, as LED lights have a useful life 3-5 times longer than metal halide lights, consume up to 65% less energy, and offer higher reliability and operational flexibility. Progressive installation of advanced lighting control (City Touch system) began in 2017-18, and all Town Centre streets were relamped in 2018-19. The LED lights are approximately 4000K and include a high proportion of blue light. The environmental impacts of lighting on the ecological values of the Park have not been considered in this program.

It is important to understand ALAN at the Park, including light source, direction, intensity and duration, as these may be managed to limit the ecological impacts of ALAN on wildlife, particularly in areas of high ecological values. In order to assist management in informed decision-making and design selection with regards to lighting, targeted surveys of light spill (light outside the area/object intended for illumination) were conducted across the Park over two years.

SOP light spill survey 2018 and 2019

The 2018 and 2019 light spill surveys were conducted with the following aims:

1. To collect data on light levels within Sydney Olympic Park to provide for long-term comparison between years
2. To understand the level of artificial light at night in areas of high ecological significance to inform management of these areas
3. Include targeted survey of areas where proposed development may cause increases in light spill into Parklands zones.

Survey sites were selected on the following basis and shown in Figure 5.

- Centre or representative site for the precinct
- Areas of high ecological significance where species or communities of conservation focus as listed in the SOPA Biodiversity Management Plan 2019 are known to occur
- Sites where future development may change light intensity or source
- Within 20m of a light source
- To examine how vegetation reduces light spill

- To examine light in the East-West Access Corridor, a well-lit thoroughfare in Bicentennial Park.

Surveys began one hour after sunset and were scheduled to coincide with the new moon so that only artificial light levels would be measured. At each site, surveyors took three light level readings in lux from a Tenmars TM-209M Multi LED Light Meter. Notes were taken on sky glow, and the direction and source of artificial light. Sites were surveyed between 7pm and midnight across the Park's 18 precincts over one day in 2018 (97 sites) and 2019 (100 sites).

Figure 5. 2018 and 2019 light spill survey locations at Sydney Olympic Park

Just how bright is it at night?

A wide range of lighting intensities were found, from a low of 0.03 lux in several locations, similar to a clear moonless night with some sky glow, to 256.4 lux underneath floodlights installed for security.

The sites were categorised by their light level in comparison to natural light conditions.

- The majority of the survey sites (101 or 51%) fit into the **moderate** category and are close to the light of a full moon (0.1-0.3 lux), with average lux levels ranging from 0.05–0.3
- A large proportion of sites (54 or 27%) were in the **high** category, equivalent to twilight (1-10 lux) due to spill from nearby light fixtures. Another 10 sites or 5% had slightly higher light level, ranging from 10 to 19 lux
- 16 sites or 8% were in the **very high** category (20-50+ lux), with light levels similar to a family living room at the higher end; these were located in Bicentennial Park, Wentworth Common and Newington Armory, all in car parks or directly under streetlights
- Only 16 sites (8%) fit into the **low** category, ranging between 0.002-0.04 lux, similar to illuminance on a clear night with some sky glow and no moon. These sites were in Blaxland Riverside Park (1), Badu Mangroves (4), Haslams Reach (1), Kronos Hill (5), Narawang Wetland (1), Newington Armory (2), Newington Nature Reserve forest (1) and the Brickpit (1); however, none were close to starlight (approximately 0.001 lux).

The majority of the Park (78%) is subject to moderate to high artificial light; the small zones of darkness within ecologically sensitive environments are all the more important for their rarity.

Nature surrounded and by fragmented by light

Figure 6 shows the average brightness of each of the 18 precincts. Six precincts are considerably higher in artificial light at night. Surprisingly, the Town Centre precinct did not have the highest average brightness. Archery Park, the brightest precinct in the survey, illustrates common sources of ALAN in urban areas, both internal and external. It contains a venue and car park lit throughout the night, and borders a brightly lit and busy road with the high density residential area of Wentworth Point on the other side. It is also one of the primary nesting habitats of the Red-rumped Parrot, a species identified for conservation focus in the SOPA Biodiversity Management Plan 2019.

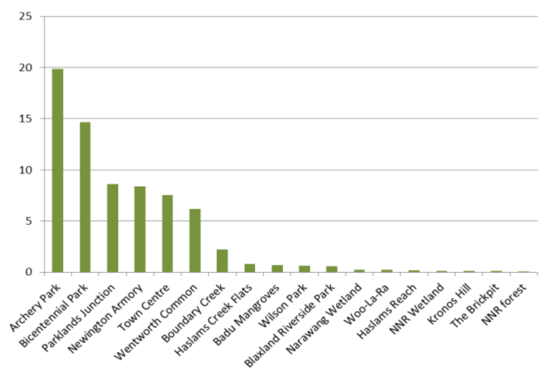

Figure 6. Average brightness (lux) of each precinct based on data collected during the 2018 and 2019 light spill surveys at Sydney Olympic Park

Bicentennial Park, the second brightest precinct, is open to public access 24/7; the thoroughfare between Concord West and Sydney Olympic Park is well lit, as are car parks throughout the night. It is also impacted by floodlights measuring 150 lux mounted on venues and landmarks (Figure 7a, b), with some lights directed upwards contributing to sky glow, and casting light more than 60m into Badu Mangroves, home to the Waterbird Refuge where migratory shorebirds from Alaska and Siberia overwinter. An external review of lighting in Bicentennial Park conducted in June 2019 by lighting engineers noted the impact of light on deciduous trees, where the only remaining leaves were on branches around the lights (Sydney Olympic Park Authority, 2019).

Parklands Junction contains three car parks lit throughout the night and borders busy Hill Road, so it is no surprise it is one of the brightest precincts. On the other side of Hill Road is Narawang Wetland, habitat of the endangered Green and Golden Bell Frog.

Of particular note, the precinct of Newington Armory is experiencing high levels of light pollution, exceeding even the Town Centre, even though it is closed to the public after sunset. Newington Armory lies adjacent to Newington Nature Reserve wetland and forest, an area of significant ecological value. The Reserve contains the only example of complete estuarine zonation in the Parramatta River, from mudflat to Coastal Saltmarsh (Endangered Ecological Community or EEC), Mangroves (protected marine vegetation), Swamp Oak Floodplain Forest (EEC) to Sydney Turpentine Ironbark Forest (Critically Endangered Ecological Community). The Reserve supports over 210 native plant species, an abundance of hollow-nesting fauna including microbats due to the presence of large hollow-bearing trees absent in the rest of the Park, and has been the nest site of a pair of White-bellied Sea-Eagles, listed as vulnerable under NSW legislation, for more than 10 years. Newington Armory is highly variable in light level, with some very low-light areas. The surveys found the darkness of Newington Armory is punctuated by the uncapped floodlight on the entry gate measuring 256.4 lux (the highest level recorded during the survey) that extended at least 40m into adjacent frog habitat; bollard lights along the path to buildings even though there were no event on either night of the survey necessitating access to those buildings, and internal street and building lights shining into areas with known maternity bat roosts in the Reserve (Figure 7c), and Green and Golden Bell Frog habitat in adjacent Narawang Wetland. Identification of these significant contributors of ALAN is useful, as this provides an opportunity to reduce or eliminate light pollution by addressing the management of specific light sources.

Not all light sources can be managed by the Authority. External light fixtures impact on many precincts. For example:

- Light from the Royal Agricultural Society is visible from Kronos Hill
- Residential building lights from Wentworth Point, Newington, Rhodes and Ermington can be seen in Wilson Park, Woo-la-ra, Narawang Wetland, Haslams Creek Flats, Archery Park, Badu Mangroves and Newington Nature Reserve (Figure 7d). In Bicentennial Park, slopes facing the Australia Avenue residential towers recorded light at 0.26 lux, compared to 0.14 lux on slopes facing away from the buildings. A similar impact was observed at Woo-la-ra where light cast from the Wentworth Point development reached a maximum of 0.41 lux
- Floodlights from Silverwater Correctional Centre cause significant light trespass into Blaxland Riverside Park, reaching more than 100m into the precinct and measuring 0.5 lux adjacent to frog habitat (Figure 7e).

Furthermore, almost all precincts were surrounded by streetlights and traffic lights, encroaching on and fragmenting dark patches; the only precincts protected from direct street and traffic light spill were high ecological value precincts restricted to public access i.e. the Brickpit and Newington Nature Reserve. The Authority is obligated under the *Sydney Olympic Park Authority Act* 2001 to protect and enhance the natural heritage of the Park. However, it is clear that the Park's natural heritage is surrounded and impacted by ALAN. These findings make it clear it's critical to identify internal light fixtures and make sure they are fit for purpose whilst causing least amount of light pollution. There are several ways this could be done:

- Limiting the duration of lighting of venues or amenities to hours of operation, such as the toilets at Wentworth Common (Figure 7f) as well as Bicentennial Park and Wilson Park
- Eliminating lighting in precincts that are locked at night, such as the bollard and car park lights in Blaxland Riverside Park which contribute significantly to sky glow
- Shielding light fixtures to focus light on area/object intended to be lit
- Installing light barriers or plant screening vegetation along light-sensitive areas to buffer light spill; the survey found that where tree corridors are present, light spill is considerably reduced (by an average of 84%)
- Where LED smart control technology is available, deploy controls such as dimming, time or motion based trigger for lighting.

Darkness needs our protection

Despite the prevalence of ALAN in the Park, locations where light level was close to a dark, moonless night (<0.1 lux) still exist. These were found in:

- Blaxland Riverside Park (1 site)
- Newington Armory (1 site)
- Woo-la-ra (1 site)
- Narawang Wetland (2 sites)
- Haslams Reach (multiple sites)
- Wentworth Common (multiple sites)
- Kronos Hill (North/west slope)
- Little Kronos Hill (North Slope)
- Eastern Pond
- The Brickpit (multiple sites)
- Badu Mangroves (multiple sites)
- Newington Nature Reserve wetland (multiple sites)
- Newington Nature Reserve forest (multiple sites)

A map of the core dark zones of Sydney Olympic Park was developed to clearly identify areas that require management action for protection from ALAN (Figure 8).

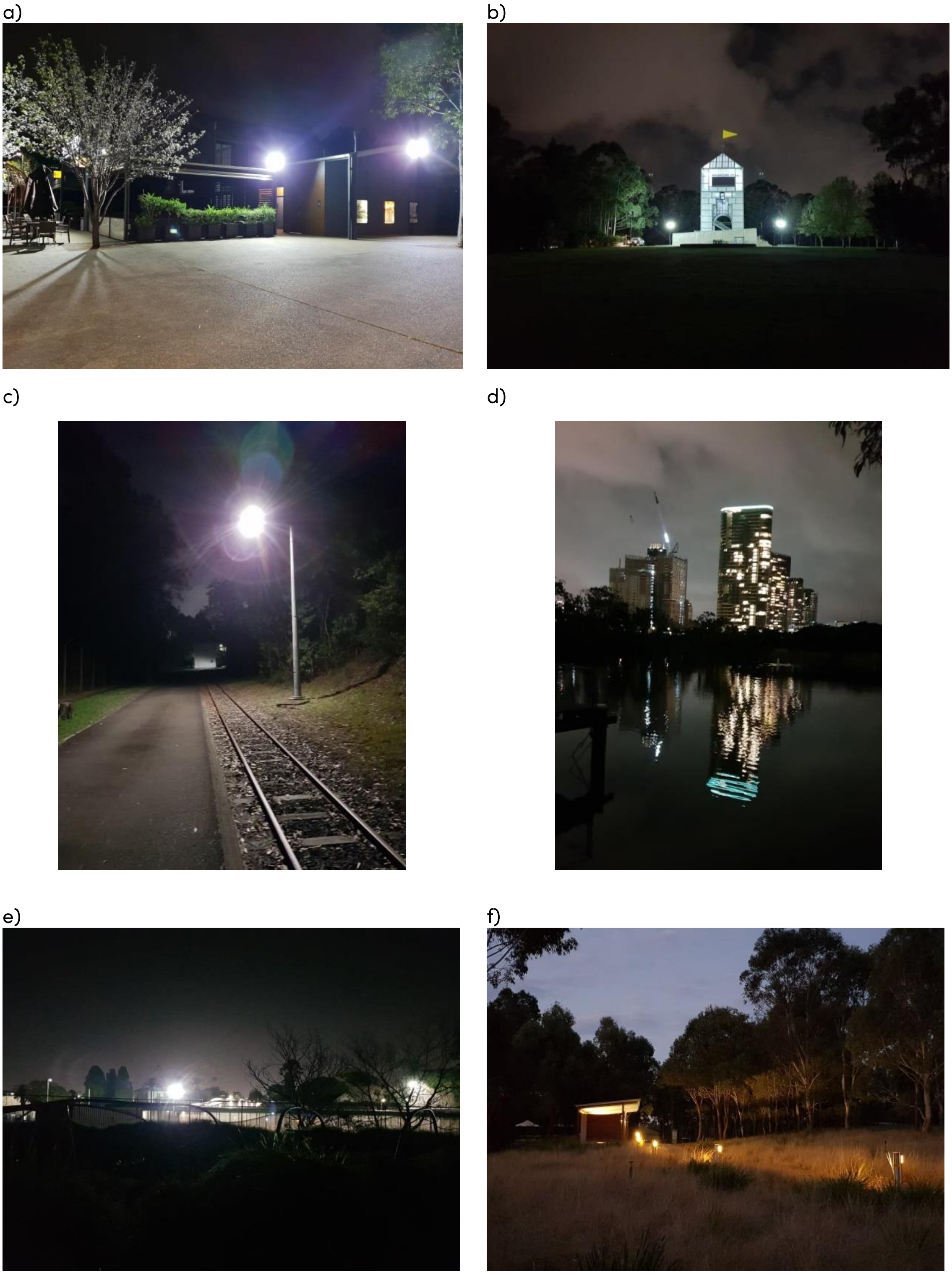

Figure 7. a) Six floodlights light up a closed function centre in Bicentennial Park; b) The Treillage Tower at Bicentennial Park lit up by upward facing floodlights; c) Lighting inside a sensitive ecological area, Newington Armory; d) Residential towers casting light into Lake Belvedere, a regionally important waterbird nesting habitat; e) Floodlights from Silverwater Correctional Centre spill into Blaxland Riverside Park; f) Lights from bollards and the locked amenities block at Wentworth Common after sunset.

Figure 8. Parklands core dark zones where artificial light at night is generally below 0.05 lux

Mechanisms for ALAN management

The National Light Pollution Guidelines for Wildlife were released by the Commonwealth government in January 2020. The principles of best practice lighting design are already reflected in the Authority's Parklands Plan of Management 2010 guidelines for lighting (Table 1). To protect environmental conservation areas, particularly core dark zones from light pollution, new lighting in the Parklands should be avoided as a priority and in accordance with DA conditions where applicable, and any new lighting programs should follow basic design principles from the Guidelines to reduce the impact of ALAN on ecological processes and threatened species.

Where new or replacement/upgrading of existing light installations are necessary, managers should also consider the Australasian Dark Sky Alliance (ADSA) recommendations for dark sky friendly designs and approved luminaires. There are three categories of ADSA approved luminaires, including those that provide greater control over sky glow and glare, and sensitivity to wildlife and ecosystems with features including upward waste light of 0%, ≤2700K CCT and less than 2% blue light (400-500 nm) content.

Table 1. Comparison of National Light Pollution Guidelines for Wildlife with Sydney Olympic Park Authoity's guidelines for lighting

National Light Pollution Guidelines for Wildlife 2020 – **Best practice lighting design**	Parklands Plan of Management 2010 – **Lighting guidelines**
Start with natural darkness and only add light for specific purposes.	Lighting of the Parklands will always be kept to a minimum to discourage inappropriate night-time uses and activities, and where present will meet appropriate lighting standards No lighting should interfere with the nocturnal activities of wildlife, particularly in the wetland areas. Alternatives to lighting, as a means of protecting or highlighting elements of an area, should always be given careful consideration during planning and design.
Use adaptive light controls to manage light timing, intensity and colour	Lighting should be non-intrusive to neighbouring residents or Parklands users and be considerate of the cumulative effects with other lighting - within and outside the Parklands.
Light only the object or area intended – keep lights close to the ground, directed and shielded to avoid light spill.	Lighting that is necessary, should not exceed fitness for purpose nor extend beyond the area of intended illumination while also being appropriate to the setting. Lighting should not be used in the Parklands for the sole purposes of decoration or promotion.
Use the lowest intensity lighting appropriate for the task. Use non-reflective, dark-coloured surfaces	Lighting controls should be managed judiciously to limit hours of operation to suit the circumstances of the site; ensure a lack of lighting to deter visitation to inappropriate areas and to support visitation to areas where after-dark use is desirable or invited.
Use lights with reduced or filtered blue, violet and ultra-violet wavelengths.	

Discussion

Measuring the effect of ALAN on wildlife and their habitat is an emerging area of research and development, and it is important to acknowledge the limitations of the light spill surveys. There is currently no globally recognised standard method for monitoring light for wildlife, and most commercial light instruments and modelling programs are biased towards the part of the spectrum that's visible to humans. The most appropriate instruments for monitoring and measuring light for wildlife management are radiometric instruments that detect and quantify light equally across the spectrum; however, they are expensive and require specialised technical skills for operation, data analysis, interpretation and equipment maintenance (DEE, 2020). Lux meters are an affordable alternative; they are easy to use and provide data that may be compared to other studies. However, they are not capable of measuring sky glow. Furthermore, although the lux meter used for the surveys was designed to detect LED lights in various colours, it does not provide information on the amount of blue light being emitted. The only way to determine whether a light source is appropriate for wildlife is to obtain the spectral power distribution curve from manufacturers or suppliers, an essential step to inform any ALAN monitoring and management plan.

The light spill surveys were valuable in obtaining baseline information on the level and extent of ALAN in the Park, and the findings of these surveys are being considered by Park management at time of writing. The surveys found ALAN was not limited to the Town Centre; in fact there was significant encroachment of ALAN on the Park's environmental conservation areas. The effect of ALAN can be hard to measure and biological values may be lost before attempts are made to address the threatening process. For example, the local abundance of migratory shorebirds may be decreasing through pressures such as habitat loss on the East Asian-Australasian Flyway, and/or due to displacement from artificially lit nocturnal roosts. A precautionary approach should be taken and any known threatening process including ALAN should be considered in an ALAN management plan.

While darkness appears to persist in parts of the Park, nocturnal wildlife sensitive to light trespass do not perceive darkness in the same way humans do. When ALAN abuts or spills over into bushland, it reduces the availability of suitable habitat and reduces fauna activity at the interface, confining some species to the interior of remnant forests or bushland (Threlfall et al., 2013; Marcantonio et al., 2015; Haddock et al., 2019). Even urban adapted microbats will select darker areas for movement, and a buffer of 50m between streetlights and ecological corridors has been suggested to ensure their use by light-sensitive microbats (Hale et al., 2015; Azam et al., 2018). If wildlife is to persist in an urban area, their needs must be met. The preservation of core dark zones (including foraging grounds, roosting areas and movement corridors) and prevention of light encroachment is essential for the persistence of light-sensitive species.

Outside of core dark zones where ALAN is required for human needs, sensitive solutions may be achieved if wildlife is considered a stakeholder and the preservation of natural heritage is of equal priority to human needs. Mitigation measures include lighting what is absolutely necessary, lighting at the minimum acceptable level, careful positioning of light fixtures, placement of artificial or vegetative screens, and use of technology for remote and responsive control of lighting duration, direction and intensity. Understanding the ecology of target species for conservation will better inform which mitigation measures should be implemented and how. For example, many municipalities in Europe have already adopted part-night lighting (PNL) where lights are switched off between midnight and 5am to reduce carbon footprint, save energy and mitigate negative impacts on light sensitive fauna. Studies have recommended turning the lights off earlier to allow for greater levels of bat activity to occur in darkness – over 50% of bat activity would occur in darkness if the lights are switched off at 11pm, and more than 80% of bat activity would occur in darkness if lights are switched off at 10pm (Azam et al., 2015; Day et al., 2015). However, insect and bat activity peak around dusk to just after sunset, when the lights are turned on (Griffiths, 2010), and alternative mitigation measures are required.

Trials may be required to ascertain the correct lighting regime. For example, motion based lighting has been touted as a potential solution to achieve a balance between human safety and wildlife functioning. However, it has been suggested intermittent or flashing lights could flush out shorebirds and force them to leave the area, especially if the light is persistent (DEE, 2020). An example of a balanced approach to lighting is the illumination of an existing car park at Dorothy House Hospice Care in the UK, located in an Area of Outstanding Beauty. The uncontrolled, high glare car park lights with excess spill were replaced with fixtures with zero upward light, aimed to achieve 0.5 lux at sensitive boundaries. Low levels of amenity lighting are provided for pedestrians accessing the car park, and lights are switched off when not in use; when required, it is manually activated. The project was awarded a Commission for Dark Skies 'Good Lighting' award for a design which respects the habits of the Greater Horseshoe Bat (Lux Review, 2019[1]).

With the advent of LED lights, and the propensity of wildlife to be sensitive to blue light, LED with little or no short wavelengths (400-500 nm) light should be chosen; where wildlife are sensitive to longer wavelength light (e.g. some bird species), consideration should be given to wavelength selection on a case by case basis (DEE, 2020). While the light spill survey did not incorporate spectral distribution curve assessment, such information can be obtained from manufacturers or suppliers, and should be used to inform an ALAN management plan, particularly for slow-flying, light-averse species, which have been found to be least disturbed by red light (Spoelstra et al., 2017; Haddock, 2018).

These findings have already been applied in real life. Red LED lights have been installed over a highway crossing in the UK to provide a bat friendly crossing of about 60m in width (Lux Review 2019[2]); the town of Zuidhoek-Nieuwkoop in the Netherlands, home to many threatened animals and plants, also use bat-friendly red LED lights which are dimmed late at night. Ameland, one of the Netherland's northern most islands, supports the Dark Sky World Heritage Wadden Sea Region UNESCO program. Its street lights emit a light spectrum specially designed to be friendly to migratory birds, in a subtle blue-green colour that improves human perception at night. The streetlights are connected to a smart control system that enables remote control of individual lights, and incorporates a human motion sensor so that lighting automatically dims to a level equal to moonlight when no activity is detected (Signify, 2017).

With principled and judicious use of light outside of core dark zones, it may be possible to balance human need with wildlife conservation in some areas of the Park currently undergoing fragmentation and encroachment from ALAN. The baseline data collected by the surveys will inform the development of an ALAN management plan, and future lighting assessments and adjustments in areas identified for improvement.

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Jennifer O'Meara, Andrew Jack, Tina Hsu and Viveca McGhie conducted the 2018 and 2019 light spill surveys. The SOPA light spill survey 2018-19 report was written by Jennifer O'Meara.

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