SydneyOlympicPark

20 years of healing:

Delivering the ecological legacy of the Green Games

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20 years of Healing: delivering the ecological legacy of the Green Games

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Introduction

Penelope Figgis AO
Chair of the Sydney Olympic Park
Parklands Advisory Committee (2001-2011)

In 2001 I had the honour of being invited to serve on the board of the newly created Sydney Olympic Park Authority (SOPA), which was charged with the post-Olympics development of the site. I was subsequently appointed the Chair of the Parklands Advisory Committee, which oversaw the continuing development of one of the great legacies of the Olympics, the surrounding 425 hectares of public parklands.

This role, which I held over the following decade, took me into a largely new area of policy. Most of my life I had been an advocate for creating protected areas in large natural areas for their critical ecological, biodiversity, social and cultural values. I understood urban parks primarily as important recreational resources for relaxation, community gatherings, picnics, jogging, cycling and walking. The Board felt that as SOPA developed the urban core of the park as a hub for major business and residential development, the parklands would be a great asset to both residents and people in the wider area. However, working with our excellent staff, I soon realised that my familiar role of defending biodiversity was just as applicable to this unusual area. During the preparation for the Olympics various studies had been done which highlighted that despite its blighted industrial history surprising areas of both flora and fauna survived in the diverse environments of mangroves, saltmarshes, forest, grasslands and wetlands.

Our initial challenge was integrating the separate components of the parklands into a coherent whole. While Bicentennial Park was established and key areas of final parklands had been constructed, other areas were effectively remnants. Transforming these zones, which included a large dump site, into modern parklands would take time. We looked for a strategy to engage users to the park while enhancements occurred. The 35 kilometres of cycling and walking paths provided a rich and regionally rare resource. We engaged the cycling community, from the professionals to family groups, and sought their advice in making it a cycling haven. This resulted in a substantial number of people regularly using the parklands and discovering their multiple values as the pieces of the jigsaw like Wentworth Common, Newington Armory and Blaxland Common were transformed into healthy parklands, and other sites like the Brickpit and Badu wetlands were enhanced into welcoming spaces over the decade.

As each element of the parklands was planned we were very fortunate to have dedicated professional staff, excellent scientific advisors and designers, and good planning. As the new parklands zones were developed the commitment to biodiversity remained a priority (though there were many quips on the Board about what other directors thought were better uses of the Brickpit than frog habitat!).

The story of the conservation of the endangered Green and Golden Bell Frog, the continued role of our wetlands for native and migratory birds, and the successful repeat breeding of White-bellied Sea-Eagles are some of the inspiring stories we are celebrating on this anniversary. These environments are relaxation and health assets to all users of the park - local communities, visitors, residents and workers. They also provide a wonderful education asset to the people of Sydney allowing city children to really experience nature close to home.

I write this as Australia and the world struggles with the often overwhelming implications of COVID-19 pandemic. We are all reflecting on the way we live and how we might live better in future. Many global experts have identified the rapid destruction of the natural world as a key component of this event. Even the World Economic Forum has published an article entitled '*Scientists warn worse pandemics are on the way if we don't protect nature*[1]'.

There is also a strong argument that unless people have contact with nature, they will not value it and defend it. Hence urban parks have an important role in providing contact with nature to urban populations; to help in building the essential constituency of support needed for biodiversity conservation measures.

Parklands have played an important role through this immense challenge. Many people have discovered or rediscovered the joy of nature and the immense importance of green spaces both large and small in maintaining their physical and mental health. In doing so, they confirm growing scientific evidence around the world which supports that spending time in nature improves physical and mental health. Interestingly Australia, particularly through Parks Victoria, has been a leader in the concept of Healthy Parks Healthy People. This nature/health relationship will be a major theme at the next International Union for Conservation of Nature (IUCN) World Conservation Congress.

During the IUCN World Parks Congress held in Sydney Olympic Park in 2014, the primary recommendation of the improving health and well-being stream was to *"Unlock the values of parks and protected areas for health and well-being, while conserving biodiversity."* This seems a very useful summary of what I believe has been the vision of the Authority and what I hope remains its guiding mission.

Penelope Figgis AO
Vice Chair, Oceania
IUCN World Commission on Protected Areas
Chair of the Sydney Olympic Park Parklands Advisory Committee (2001-2011)

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[1] https://www.weforum.org/agenda/2020/05/scientists-pandemics-coronavirus-nature-covid19-health/

The road to recovery – delivering the ecological legacy of the Green Games

Kerry Darcovich
Sydney Olympic Park Authority

The 2000 Olympic and Paralympic Games triggered a comprehensive and multidisciplinary effort to conserve and restore the ecological systems of Sydney Olympic Park, creating an enduring legacy of urban ecosystems rich in native flora and fauna. Today we are 25 years into a 100-year plus restoration project that began with the clean-up of over 200 hectares of contaminated land and hand-planting of over 8 million individual native plants on newly-formed landscapes. Subsequent works have targeted improvements to individual systems and target species, addressing historical damage and fostering long-term resilience. Today the Park is well-known as an urban biodiversity hotspot. It supports endangered ecological communities and a high abundance and diversity of native plants and animals that are now uncommon in the Sydney region. Visitor surveys have ranked the Park's biodiversity, and opportunities to connect with nature, as the highest-rated values of the Park.

Introduction

The Parklands of Sydney Olympic Park are a legacy of the remediation, conservation and development efforts carried out in the lead-up to the Sydney 2000 Olympic and Paralympic Games. Following the Games, the Olympic precinct and adjacent lands formerly managed by the Bicentennial Park Trust came under the stewardship of the Sydney Olympic Park Authority. The natural heritage values of these lands continue to be protected and enhanced in accordance with the legislated duties and obligations set out in the *Sydney Olympic Park Authority Act 2001.*

Nearly half (304 hectares) of Sydney Olympic Park is zoned under NSW planning legislation for environmental conservation and management due to its high ecological values, and 47 hectares of this is gazetted as a nature reserve. The Park supports over 400 native plant species and over 250 native animal species including more than 200 native bird species, seven frog species, 12 bat species, 18 reptile species, native fish species and many thousands of species of invertebrates. Key habitats include estuarine and freshwater wetlands, remnant eucalypt forest, saltmarsh meadows, bushland and grassland (Figure 1). Three of the Park's plant communities are listed as Endangered Ecological Communities under New South Wales and/or Federal Legislation and another (Mangrove Forest) is listed as Protected Marine Vegetation. The Park is an urban hotspot for species that are disappearing from the urban environment – including a breeding pair of White-bellied Sea-Eagles, the Superb Fairy-wren, Red-browed Finch and Eastern Blue-tongue Lizards. The Park provides breeding habitat for these species, as well as a refuge or stepping stone for nomadic and migratory species including migratory shorebirds. The estuarine wetlands of Newington Nature Reserve and Badu Mangroves, totalling 100 hectares, are both listed on the Commonwealth's Directory of Important Wetlands in Australia, and are classified as 'key fish habitat' under NSW legislation.

Pre-Games restoration works

Redevelopment of the land that is now Sydney Olympic Park began in the 1990s. A suite of baseline ecological studies was commissioned shortly before the outcome of the Olympic bid was announced to provide input to site remediation and land use planning. At that time, only small areas of remnant estuarine and forest vegetation remained. Most of the site was dominated by exotic grasslands, swampy landfills, ephemeral ponds in low-lying depressions, and waterbodies built as abattoir wastewater management systems. These highly disturbed habitats were interwoven with buildings, roads, carparks, and areas undergoing extensive earthworks for remediation. The disused Brickpit had developed into a freshwater wetland strewn with scattered piles of quarrying debris and dumped building rubble. Next door to the site, Bicentennial Park, with its 60 hectares of estuarine wetlands and 40 hectares of picnic grounds had been remediated and opened to the public a few years previously, showing what was possible at the site.

The baseline studies revealed that the site's terrestrial and wetland systems supported ecologically significant species of plants and animals including large meadows of coastal saltmarsh, a stand of remnant eucalypt forest, visiting migratory shorebirds, mangrove forest, and a high diversity and abundance of native birds, bats, reptiles and fish (OCA 1995). These studies also identified what was considered to be the largest and

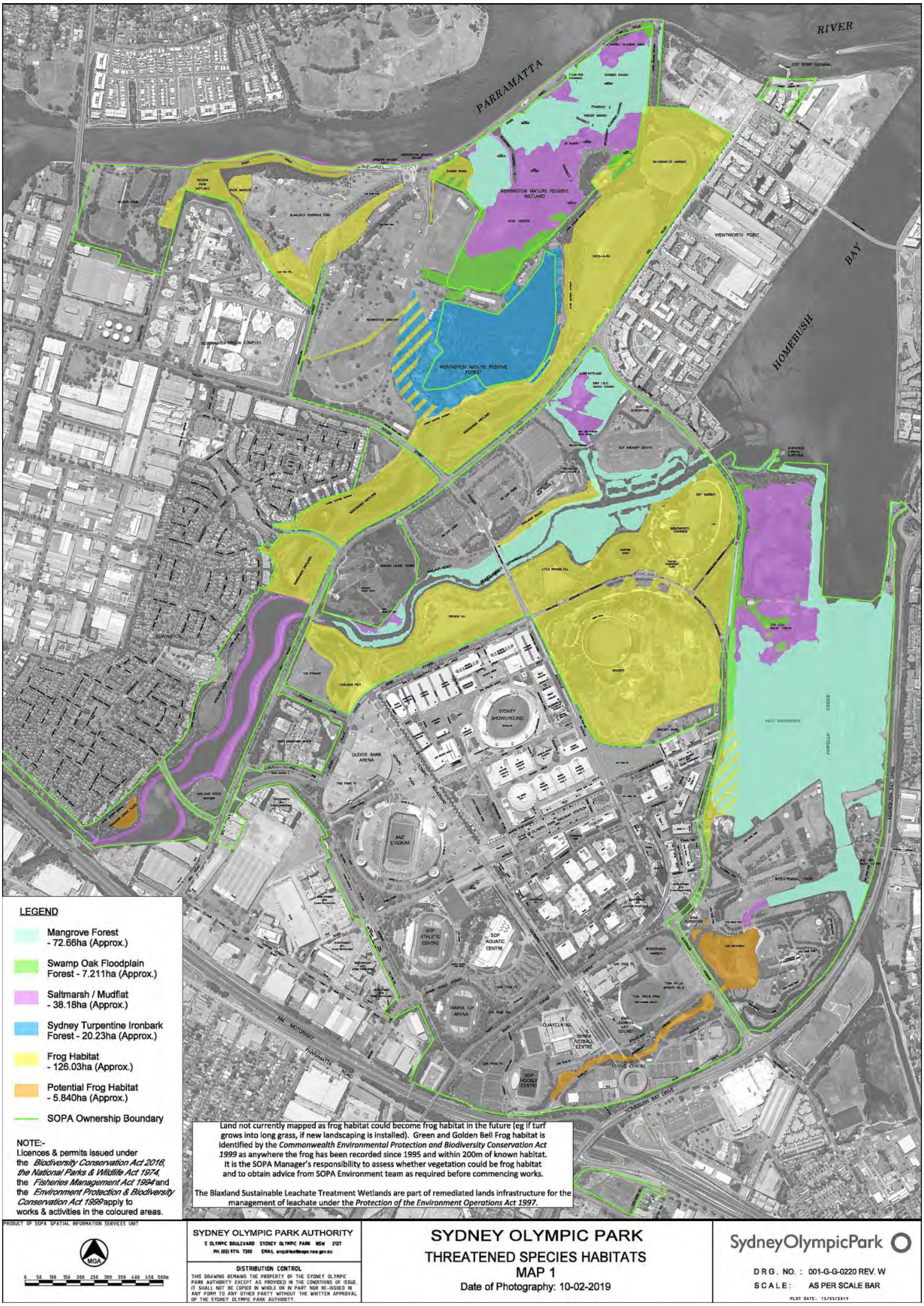
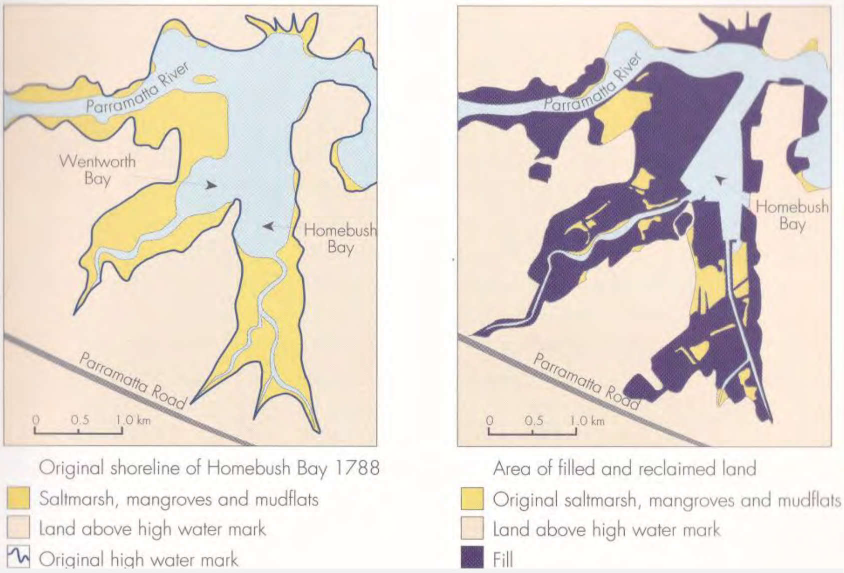


Figure 1 Threatened species habitats of Sydney Olympic Park 2019

Box 1: Sydney Olympic Park land use history

Two hundred years ago, Homebush Bay and Wentworth Bay formed an estuary surrounded by vast intertidal mudflats fringed with mangroves, saltmarsh and woodlands of Eucalyptus and Casuarina (diagram). These were the traditional lands of the Wann-gal people, whose lands stretched along the southern shores of the Parramatta River from Cockle Bay to Rose Hill.



Landfilling of Homebush and Wentworth Bays (Olympic Co-ordination Authority undated)

Within 10 days of the arrival of the First Fleet in Australia, scouting parties had ventured up the Parramatta River, and within a few years the colonial government had granted the majority of the riverside land to new settlers. For these early settlers, the mudflats, forests and tides were an inconvenience - land was needed for farming and for industries such as flour and fabric mills, a lime kiln, saltpans and timber-cutting. As early as the mid-1800s the wetlands were being drained and cleared, and by 1891 retaining walls had been built to exclude tidal waters.

In the 20th century, the land around Homebush Bay became the site of Sydney's abattoirs, its major Brickworks, and the Royal Australian Navy's armaments depot. Reclamation of tidal mudflats to create new waterfront industrial land began in earnest in 1948 and continued until the early 1960s. These practices, combined with decades of landfilling with Sydney's municipal and industrial waste, dramatically altered the face of Homebush Bay, and in particular its creeks and foreshores.

The potential for redevelopment of the area was explored in planning proposals dating back to 1973, but gained impetus as government-owned industries closed down or relocated during the 1980s and nearly 800 hectares of land in the demographic heart of Sydney became available for urban renewal. But this land had become a brownfield site - an urban wasteland with its once-extensive mudflats gone, little native vegetation remaining, pollution leaking into the waterways, and natural creeks converted into concrete-lined stormwater canals.

In 1990 the NSW Property Services Group prepared a business plan for the site, which included clean-up of its industrial past. Homebush Bay had been identified as the only site in Sydney that could be used to stage the Olympics - thus the plan contained two options, depending upon whether or not Sydney was chosen to host the 2000 Summer Olympic Games.

On-site containment was decided upon as the most appropriate way of dealing with the estimated nine million cubic metres of domestic, commercial and industrial landfill waste, and a policy of minimising the total area of contamination and providing for its safe confinement on site was adopted. This involved relocating smaller volumes of waste to the major dumping sites, installing a leachate collection system, and stabilising and capping the waste in preparation for landscaping.

Concurrently, work was underway to better-understand Homebush Bay's remnant natural communities, to input this thinking into the remediation program. The area was anecdotally regarded as having high ecological values despite a history of habitat alteration and industrial use, and its ecological isolation in urban surrounds (Greer 1994). An expert panel of professional ecologists and environmental scientists was established to define the necessary range of baseline studies, and experienced biologists were contracted to complete the work. Soon after the work was commissioned, Sydney was awarded the 2000 Olympic and Paralympic Games, and a new era began for the lands adjoining Homebush Bay.

most viable population of the endangered Green and Golden Bell Frog remaining in the Sydney region (Greer 1994).

The International Olympic Committee announced that Sydney had won the right to host the 2000 Summer Olympic Games in September 1993, leaving only seven years to remediate the site and construct the Games venues and infrastructure. The urban renewal program was fast-tracked to meet this deadline and an intensive site development program began.

The ecological component of the works sought to rebuild functional naturalistic ecosystems within an urban parkland environment. Protection and expansion of the local ecology was a key design objective. Works included:

- protection of remnant eucalypt forest and estuarine wetlands (this land was subsequently gazetted as a 'nature reserve' under the *NSW National Parks and Wildlife Act 1974* the day before the Olympic opening ceremony)
- remediation of 160 hectares of contaminated land to address soil and water pollution
- design and construction of new grassland, wetland, forest, saltmarsh and intertidal habitats on waste containment mounds and newly remediated parklands landscapes
- manufacture of soils from crushed sandstone and biosolids, and hand-planting with over 8 million native plant seedlings
- removal of two kilometres of concrete stormwater canal and replacement with a naturalistic estuarine creek with broad gabion-lined embankments built at a level to sustain saltmarshes
- construction of a new 20-hectare freshwater wetland, comprising 22 individual habitat ponds, an ornamental lake and three large irrigation storages
- construction of freshwater wetlands for stormwater treatment
- restoration of tidal flushing to land-locked estuarine wetlands to improve vegetation health and habitat for internationally-protected migratory shorebirds

Ecological studies continued throughout these works, including trials of saltmarsh transplanting and propagation, bird monitoring, and investigations of benthic organisms in sites restored to tidal flushing.

Pre-Games frog conservation

The Green and Golden Bell Frog played a pivotal role in shaping the lands that would become the Parklands of Sydney Olympic Park.

It was one of the first species to be listed as endangered when threatened species legislation first came into effect in NSW in 1991, and its local stronghold was the abandoned Brickpit, which was slated to become the site of the Olympic Tennis Centre. The regulatory authority rejected an application to relocate the frogs into newly built ponds outside the Brickpit, and with the Games then only six years away and needing to deliver on the 'Green Games' promise, site managers relocated the Tennis Centre to its present position, leaving the Brickpit to the frogs (Darcovich & O'Meara 2008).

Bell frogs also utilised habitats outside the Brickpit – these were overgrown grasslands and wastewater treatment systems associated with the former abattoir that were to become the site of the new railway station, a road network, the Sydney showground and sporting stadiums. This redevelopment would destroy or disrupt much of the existing ephemeral Bell frog habitat outside the Brickpit, and would also reduce opportunities for the species to disperse across the landscape and result in the death of individual frogs.

The regulatory authority approved the works outside the Brickpit subject to implementation of a comprehensive set of mitigative measures and offsets that included creation of artificial habitat (including around 30 ponds in the areas now called Kronos Hill and Wentworth Common), construction of road underpasses suitable for frog movement, erection of frog-proof fencing between roads and frog habitats, relocation of frogs and tadpoles from development sites, and continued protection of Brickpit habitats from development and general public access. This was the first attempt to create habitat de novo for any animal species in Australia - there was limited available ecological data about the species and many ponds were constructed on a trial and error basis (White 2013). Subsequently remediation of land west of Haslams Creek and creation of a water storage reservoir in the lower levels of the Brickpit for the site's recycled water system resulted in construction of another 40 ponds and associated terrestrial foraging habitats as compensatory and offset habitats.

The Brickpit, new frog habitats, and other open-space areas, were included in the newly-defined 'Millennium Parklands' in 1997 (Hassell 1997). A Frog Management Strategy (OCA 1997) contained ongoing mitigative measures for the proposal to minimise impacts of parklands development on the areas identified as the most important Bell frog habitat outside the Brickpit (Cogger 1997). This Strategy formed the basis of environmental assessment by the regulatory authority and hence for the development consent that was subsequently issued for development of the Parklands.

In all, over ninety freshwater ponds, ten road underpasses and over five kilometres of frog fencing were constructed specifically for the Green and Golden Bell Frog in the lead-up to the Games, set within approximately 125 hectares of grassy foraging and dispersal habitat. The frogs became a flagship species for the Park and for threatened species generally due to national and international media attention, and on World Environment Day 2000, the project was awarded Australia's highest environmental award, the Gold Banksia Award.

Olympic environmental framework

Ecological restoration works benefited from the environmental initiatives that applied to all of Sydney's Games developments. Sydney was the first host city to include a comprehensive commitment to the environment as part of its bid to host the Olympic and Paralympic Games. The Environmental Guidelines for the Summer Olympic Games (Sydney Olympics 2000 Bid Limited 1993), formed part of Sydney's bid and contained more than 100 environmental commitments, including a commitment to preservation and protection of natural ecosystems and endangered species.

The Environmental Guidelines were drafted just a few months after the ground-breaking 1992 United Nations Earth Summit, where 172 governments worldwide adopted Agenda 21, a global plan of action for sustainable development, and where the International Convention on Biological Diversity was opened for signature by contracting nations. President of the IOC Juan Antonio Samaranch said Sydney's commitment to the environment was a factor in it winning the right to host the 2000 Games, and the international Olympic Committee subsequently made environment the third pillar of Olympism, along with sport and culture.

> "*Protection of nature and the environment so that people may practice the sport of their choice is an essential part of the contribution to the quality of life, which should be based on sustainable development*"
> Juan Antonio Samaranch, President IOC.

When the Olympic Co-ordination Authority took over management responsibility for the site in 1995, the *Olympic Co-ordination Authority Act 1995* and the State Environmental Planning Policy 38 required the Environmental Guidelines to be applied to all Olympic developments. Companies tendering for construction contracts were required to demonstrate how they would satisfy the Environmental Guidelines (OCA 1996). Environmental management plans addressing the guidelines were prepared for all design and construction projects. Environmental training was provided to staff and construction contractors (OCA 2000), and performance was regularly audited by independent environmental watchdogs (Greenpeace 2000; Earth Council 2001).

After the Games

With the large-scale earthworks that characterised the pre-Games era complete, attention quickly shifted from building new habitats to managing them, under the auspices of the new Sydney Olympic Park Authority. Apart from the Bell frog projects, pre-Games restoration works had largely been designed at a broad landscape scale. Moving into the management phase there was a need to more closely define long-term ecological objectives for the Park and develop management strategies around them.

Concurrently, fences around the parklands' construction sites were coming down and public access was being introduced for the first time, bringing new opportunities for community engagement but also new management challenges around siting of new pathways and playgrounds, lighting, visitor behaviour, litter and dogs. A Plan of Management was adopted for the Parklands in 2003 (Sydney Olympic Park Authority 2003; revised 2010), based on detailed technical analysis of the particular characteristics, legislative controls, ecological values and visitor opportunities provided by each of 17 individual parklands precincts. This Plan sought to balance the various management objectives for each precinct to achieve the legislated objectives for the Parklands overall (*NSW Sydney Olympic Park Authority Act* s28).

Further ecological studies were commissioned to characterise the new Park's ecology - the landscapes were very different to when the original baseline studies had been done just seven years previously. How had fauna responded? What species were moving into the new habitats and what could we expect as habitats matured? How were formerly landlocked estuarine communities responding to newly-introduced tidal regimes? How should new weirs be operated to benefit ecological communities? How do 90 artificial frog ponds need to be managed in terms of water level and vegetation coverage? What needed to be done about weeds, gambusia, foxes?

Information derived from these ecological studies, as well as technical advice from the many ecologists who had steered the Park's ecological systems through pre-Games development, was consolidated into a comprehensive Biodiversity Management Plan, now at its third revision (Sydney Olympic Park Authority 2019). The Biodiversity Management Plan informs ongoing management, monitoring and evaluation of the Park's habitats. It sets out corporate commitments to biodiversity conservation, consolidates the many legislative requirements for biodiversity management, identifies threats and pressures, and drills down to provide detailed management objectives, conservation actions and performance indicators for 13 species and communities of particular conservation significance that are identified as focal species and communities for the Park.

These focal species and communities and their conservation status are listed in Box 2.

A comprehensive ecological monitoring program assesses the status of each of these focal species over time, as well as providing broader information about the diversity and abundance of birds, reptiles and frogs. The majority of monitoring is performed in-house by Authority staff, with four long-term studies being supported by volunteers from special interest groups focusing on birds (16 years), frogs (14 years), reptiles (14 years) and White-striped freetail bats (11 years).

These monitoring programs are critical for providing insights into trends in abundance and diversity, leading to a greater understanding of ecological impacts of management practices, supporting evidence-based decision-making. All fauna records, including incidental sightings, are entered into a database, and reporting of performance against biodiversity indicators is undertaken annually.

Post-Olympic ecological restoration and management works

Following the Olympics, ecological management programs and restoration works have been directed at increasing ecological values and functionality of the landscape, particularly targeting the identified focal species and communities. While the aim is for landscape systems to be as naturalistic and self-sustaining as possible, the small size and altered nature of the Park's habitats, along with the many competing management objectives imposed upon them, means that they require ongoing active and adaptive management to achieve and sustain their ecological functions. In effect, this means farming nature to achieve the desired ecological outcomes.

Box 2: Conservation focal species and communities for Sydney Olympic Park

Sydney Turpentine Ironbark Forest ....threatened (NSW & Commonwealth)
Green and Golden Bell Frog.............................threatened (NSW & Commonwealth)
Coastal Saltmarsh & *Wilsonia backhousei*....threatened (NSW & Commonwealth)
Mangrove forest ....protected marine vegetation (NSW)
Swamp Oak Floodplain Forest ....threatened (NSW & Commonwealth)
Migratory shorebirds ....international migratory (Commonwealth)
Latham's Snipe ....international migratory (Commonwealth)
Woodland birds ....declining (NSW & Australia)
Microchiropteren bats ....threatened (5 species, NSW)
Horned pondweed *Zannichellia palustris*......threatened (NSW)
Red-rumped parrot ....declining (Sydney basin)
Raptors ....threatened (4 species, NSW); declining (Sydney basin)
Black-winged Stilts..declining (Sydney basin)

Post-Olympic works and programs have included:

- Rehabilitation of 1.5 kilometres of the newly constructed embankments of Haslams Creek to enable natural recolonisation by saltmarsh. This work followed several years of trials to investigate why initial plantings had failed and to identify the barriers to natural recolonisation
- Hydrological studies of the wetlands of Newington Nature Reserve to establish weir settings that balance a matrix of ecological management objectives
- Ongoing landscape maintenance by skilled bush regenerators of over 200 hectares of terrestrial land and wetlands
- Regular removal of mangrove seedlings from mapped saltmarsh and mudflat conservation areas, in accordance with conditions of a regulatory Permit
- Long-term staged removal of established extensive stands of lantana, pampas grass and *Juncus acutus* in the Brickpit, and replacement of habitat with new native plantings – the final stand of lantana was removed in 2020, in the fourteenth year of the program
- Retrofitting of terrestrial landscapes to improve structural complexity for woodland birds and ground-dwelling fauna
- Implementation of an annual cyclic pond draining program for control of the noxious fish *Gambusia holbrooki* in Narawang Wetland; installation of bunding and fish fences to reduce spread between ponds
- Testing of new frog pond design, construction and management techniques
- Restoration of tidal exchange to a landlocked wetland in Bicentennial Park to address algal blooms and to favour migratory shorebirds
- Installation of nest and roost boxes for Red-rumped parrots, microbats and possums
- Installation of floating reedbeds to replace lost macrophytes in a water treatment pond; Installation of floating and constructed islands to provide safe roosts and breeding sites for waterbirds
- Introduction of fire to the remnant forest of Newington Nature Reserve, where fire had been excluded for over a hundred years
- Installation of screening around sensitive wetlands where new pathways brought visitors too close to shy bird species
- Excavation of new drainage channels in Badu Mangroves and restoration of overgrown historic channels
- Building of fishways to link waterbodies separated by artificial barriers
- Installation of new stormwater treatment devices such as litter booms, gross pollutant traps, bioretention systems, rain gardens and sediment basins to capture litter and pollutants (mostly generated in catchments upstream on the Park) before it reaches the Park's habitats

Over 110 constructed and naturally-formed freshwater ponds are managed for the Green and Golden Bell Frog

Natural and assisted regeneration works have resulted in the area of critically endangered Sydney Turpentine Ironbark Forest increasing from 13 to 20 hectares

1.5 kilometres of saltmarsh meadow has regenerated on constructed tidal mudflats on the embankments of the dechannelised Haslams Creek

Mangrove drainage channels are hand-cleared to maintain tidal flows and thus prevent ponding and dieback

Nest and roost boxes are supporting breeding populations of red-rumped parrots and microbats

Ponds in a 20-hectare constructed wetland are drained each spring to control *Gambusia holbrooki* ahead of the frog breeding season

Constructed earthen and floating islands provide safe roosts and breeding sites for waterbirds

Tidal flushing has been restored to landlocked estuarine wetlands. Inundation is managed seasonally to control algal growth and to balance migratory shorebird, saltmarsh, mangrove and mosquito needs

Tree thinning and retrofitting of simplistic planted landscapes has increased structural and species diversity of the vegetation, and increased usage by woodland birds, rather than Noisy Miners

Figure 2 A snapshot of post-Olympic conservation and restoration works at Sydney Olympic Park

Monitoring, research, expert advice and lessons from operational experience have been key management tools applied to planning and prioritising works, assessing ecological response to management actions and identifying any changes in management required to achieve long-term objectives.

Reaching the community and sharing experiences

Sydney Olympic Park Authority encourages and promotes community connection with the Park's environment through opportunities in education and tour programs, volunteering and interpretation. Park visitor surveys have ranked the Park's biodiversity and opportunities to connect with nature, as the highest-rated values of the Park, describing the parklands as 'a beautiful green space that values environmental conservation' (Hassall 2019).

The Authority maintains strong links with university researchers, other place managers and government agencies, and runs technical professional development workshops that enable information-sharing with other land managers. Sydney Olympic Park is a 'best practice demonstration site' for the Green and Golden Bell Frog and for Coastal Saltmarsh; best practice management guidelines developed by the former NSW Department of Environment & Climate Change and the Sydney Metropolitan Catchment Management Authority are based on restoration and management practices at Sydney Olympic Park (DECC 2008). Sydney Olympic Park is also a 'priority management site' for the Green and Golden Bell Frog under the state government's Saving Our Species Program, and leads a technical workshop on Green and Golden Bell Frog management each year.

The Park is a living classroom where over 22,000 students attend environmental classes each year. The Authority provides environmental induction training to all contractors working at the

Box 3: Sydney Olympic Park's approach to ecological restoration and management:

Build on strong scientific advice and basic ecological principles – expert input from herpetologists, ornithologists, marine biologists, entomologists, hydrologists, ichthyologists, botanists, zoologists, restoration ecologists and others guide site restoration and ongoing management

Take a multidisciplinary approach – the best results have been achieved when landscape designers, engineers, ecologists, park managers, and asset managers collaborated from early project planning stages, and ecology recognised as a core objective rather than taking a 'maximum legal loss' approach after the project has been scoped

Identify target species and communities to focus management actions –Thirteen 'target' species and communities are the focus of active management and monitoring programs at Sydney Olympic Park

Green the workforce - environmental training is provided to staff and contractors who work in ecologically sensitive environments

Involve the community – Ecofriend partnerships with community bird, frog, reptile and fungi groups have produced a wealth of ecological data, including 16-years of bird census data. 22 000 school students attend classes at the Park each year, and technical professional development workshops enable information sharing with other land managers

Learn from operational experience – evaluate work practices and outcomes and apply adaptive management

Park to ensure the people on the ground are aware of the Authority's requirements and unique environmental considerations. Partnerships with community-based environmental groups have provided a wealth of ecological data through long-running citizen science programs conducted by their members, and ecological information is shared with Park visitors and the community through informational signage, ecological newsletters and interpretive tours.

Concluding remarks

The ecological values of Sydney Olympic Park will continue to grow as the Park's habitats mature – they are only a quarter of the way into what is a hundred-year plus restoration project. In recent years, fire has been reintroduced into the remnant turpentine ironbark forest for the first time in over a hundred years and this has reinvigorated the community. A colony of endangered fishing bats has taken up residence in artificial roost boxes installed within a road culvert, the numbers of internationally-migratory Latham's Snipe using the constructed wetlands has just reached a level classified as significant under Commonwealth legislation, and, in a full reversal of thinking, the Brickpit habitats that were once intended to be destroyed are now valued and promoted as a bell frog 'sanctuary'.

Integral to the ecological recovery of Sydney Olympic Park has been the commitment of the multidisciplinary team of staff, consultants, advisors, contractors and community members who continue to work collaboratively on this project, building on the vision of those who made the Olympic bid commitments a reality.

Not only do the Park's natural environments now support a rich natural heritage valuable in its own right – they are also inextricably linked to the success and offering of Sydney Olympic Park as a greenspace in an urban growth centre. They enrich visitor experience by providing opportunities to connect with nature, provide a living classroom for environmental education programs, and attract businesses and residents seeking proximity to the natural environment.

Growing pressures from the expanding residential population within and neighbouring the Park pose a risk to future conservation of the Park's natural heritage values, but also provide an opportunity for the Park to become a world-class example of a place where people truly live in harmony with nature.

Acknowledgements

The ecological legacy of the Green Games is attributable to the vision of those who began this work in the early 1990s and the many people involved in delivering and furthering this vision over the past thirty years.

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It's a frog's life – reflections on 20 years of habitat management for the Green and Golden Bell Frog

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For 20 years Green and Golden Bell Frog habitat has been actively managed at Sydney Olympic Park through the manipulation of terrestrial and aquatic habitat elements. These require ongoing management in order to maintain their value and are supported and informed by a monitoring program that provides feedback on frog distribution, abundance and activity. The challenges presented by a diversity of landscapes, an ambiguous target species and balancing threatened species habitats in an urban park has resulted in a wide range of management techniques that have generated knowledge for other conservation programs and supported research. Since the frog's presence was confirmed in 1993, much has come to light regarding the Green and Golden Bell Frog's ecology but the species continues to challenge, delight and outright confound those committed to its conservation.

Introduction

The Green and Golden Bell Frog *Litoria aurea* (bell frog) is a charismatic species that has come to symbolise the unique and complex character of Sydney Olympic Park. By coming into prominence as a threatened species in the middle of the development for the Sydney 2000 Olympics, this species has inspired a long-term commitment to frog conservation and management at the site (Darcovich and O'Meara 2008). This commitment resulted in conservation of the frog population in the Brickpit and establishment of three new subpopulations in built habitats on remediated and restored lands at Narawang Wetland, Kronos Hill/ Wentworth Common and Blaxland Riverside Park/Wilson Park.

In the years beyond the public spotlight created by the Olympic event, the Brickpit and constructed habitats continue to be actively conserved and enhanced. The freshwater wetlands, grassland corridors and constructed ponds that constitute frog habitat are now woven into the Park's landscape character.

The bell frog population at Sydney Olympic Park is now recognised as one of the largest populations of this endangered species in New South Wales and has been classified by the State Green and Golden Bell Frog Recovery Team as a 'key population', important for the recovery of the species. The Park is a Priority Management Site under the State Government's Saving Our Species program, important for the continued conservation of the species.

During the 20 years that the Sydney Olympic Park Authority has managed frog habitat, much has been learnt about this enigmatic frog and its habitat needs.

Bell frog ecology

The bell frog's original distribution was across the eastern Australian coastal plain with a distribution of 2,275,995 square kilometres (Atlas of Living Australia) and was associated with a wide range of vegetation communities. The bell frog is described as a habitat generalist (Pyke and White 2002) and was recorded in almost all types of waterbodies; natural still waterbodies (both ephemeral and permanent) and constructed wetlands (dams, abandoned construction sites, swimming pools, small ornamental ponds, industrial ponds). The frog's diet is also that of a generalist (Bower *et al.* 2014) and the species is known to be incredibly fecund (Hamer *et al.* 2007). Based on this information, management of habitat for this species should be simple to accomplish.

However, nothing important is easy. From the 1970's the bell frog was rapidly lost from 90% of its range and there are now about 40 extant populations focussed within 1 km of the east coast of Australia (Goldingay *et al.* 2017), with the Sydney Olympic Park population among the largest. Research undertaken at the Park indicates that the age structure of the population is skewed towards first year adults and the probability of females surviving to be their second year is less than about 2% (Pickett *et al.* 2014). Females are not reproductive until they reach about 18 months of age and their second season (Pickett *et al.* 2014). This high mortality amongst adults has been attributed to chytridiomycosis caused by the fungus *Batrachochytrium dendrobatidis* (chytrid) (Murray *et al.* 2010, Stockwell *et al.* 2011). The impact of chytrid has now been the subject of extensive investigations (Stockwell and Mahony 2007, Stockwell *et al.* 2015) and the diseases source, impacts and transmission are better understood. At the time of writing, there are no practical solutions for the disease in the field, making the understanding of habitat needs and the associated population and community ecology even more important.

The work done at Sydney Olympic Park and other bell frog sites focuses on buffering the species against the impacts of the chytrid fungus until the tools are available to mitigate this threat.

Frog habitat management at Sydney Olympic Park

For management purposes, the Authority's Biodiversity Management Plan defines frog habitat at Sydney Olympic Park by the distribution of the bell frog population since 2000. These areas have been categorised and mapped as frog habitat or potential frog habitat as shown in Figure 1. This includes precincts where habitat has been specifically constructed for the frog or where the frog has colonised and been recorded as present. In total, the Park contains 145 constructed and natural ponds of varying size and hydrological regimes and 126 hectares of terrestrial environments designed to provide habitat and movement corridors. Any of these areas, depending on the season and year, may at times be highly significant to the viability of population.

An active management program to conserve the habitat of the bell frog has been in place at Sydney Olympic Park from 2000, as the Park moved from the development phase to an operational phase. Active management within frog habitats includes vegetation management, pond hydrology management, Gambusia control, habitat enhancement works, and management of visitation activities. Because the frog is a threatened species, a regulatory licence under the New South Wales *Biodiversity Conservation Act 2016* applies to management activities within frog habitat. The licence is expressed through a Biodiversity Management Plan which contains conservation actions and key indicators for the bell frog. Standard procedures provide a management framework whereby stringent conditions are applied to maintenance works and visitor programmes within frog habitat to ensure continued conservation of the Park's population.

Habitat management aims to provide the essential requirements of bell frogs; access to water, food, breeding habitat, refuges and ability to disperse within a mosaic of habitat stages, by implementing a periodic renewal disturbance regime (including manipulation of pond wetting and drying cycles, and terrestrial and aquatic vegetation renewal).

Following is a description of the main activities undertaken to support and enhance frog habitat at Sydney Olympic Park.

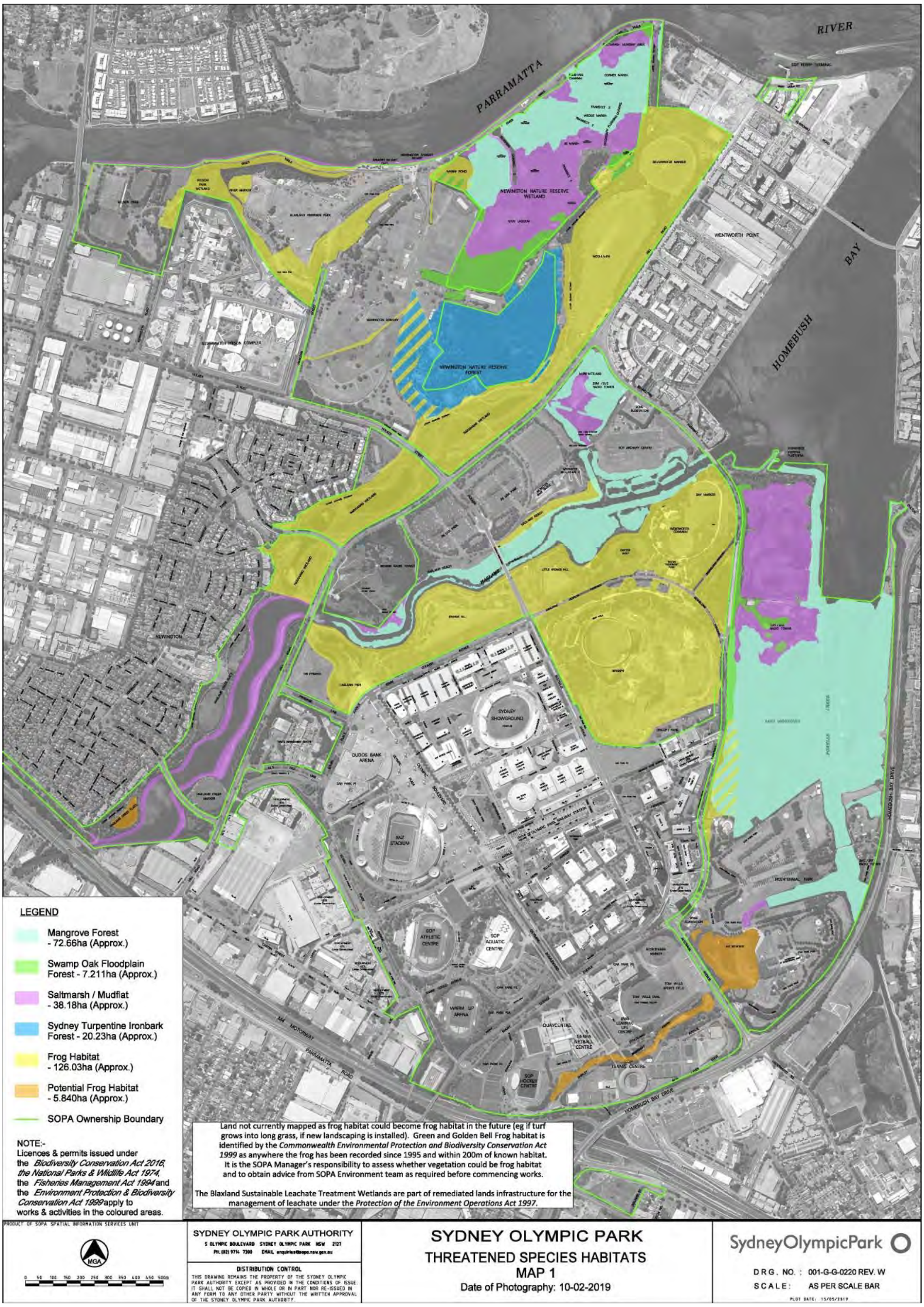

Figure 1 Frog habitat at Sydney Olympic Park. Bell Frog habitats are shown in yellow and cover 126 hectares.

Managing predation - Gambusia

Narawang Wetland is a constructed wetland covering 20 hectares and consists of 22 habitat ponds and three large water storage ponds. The wetland provides habitat for the bell frog but also functions as a floodplain for the adjacent creek. Soon after construction in 2000, *Gambusia holbrooki* invaded the wetland following flooding. Gambusia is predatory on the eggs, tadpoles and possibly juveniles of bell frogs and is listed as a key threatening process under New South Wales legislation (Hamer *et al.* 2002, NSW NPWS 2003).

An annual cyclic draining program was introduced to the 22 habitat ponds in 2003 utilising the water circulation system and associated electrical system present in the wetland. A sump within which a pump can be placed to control water levels is present in all ponds (Figure 2). Each year, one third of the ponds are drained to assist in the control of Gambusia, providing a fish-free window during the bell frog breeding season (O'Meara and Darcovich 2008).

Ponds scheduled for draining typically comprise six - eight ponds, on a three-yearly cycle. Draining and filling of ponds and supply of pumps is conducted by a contractor commencing in July/August each year. Pumping out a set of eight ponds typically takes two to three weeks, depending on rainfall and other difficulties encountered during pumping. Ponds are then ideally left for three to four weeks for the sediment to dry and crack. At that time fish-free water is returned via water points located at each pond.

Reinfestation of drained ponds with Gambusia is usually caused by flooding of the wetland after rainfall. The period of time ponds remain fish-free varies widely, with some dry years resulting in no fish for the whole breeding season and others where flooding occurred immediately after the ponds were refilled. Research on the program has found that male bell frogs preferentially selected fish-free ponds as breeding sites and concluded that pond draining to remove Gambusia is an effective strategy that can be used to greatly increase bell frog reproductive success (Pollard *et al.* 2017a).

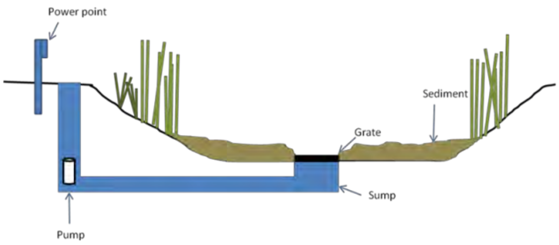

Figure 2 Typical Narawang Wetland habitat pond structure

Fish fences

As the cyclic draining program in Narawang Wetland is a temporary measure in the control of Gambusia, a trial fish fence was installed in 2016 to restrict the entry of fish to a single pond. Constructed of a sediment fence approximately 900mm high, dug 200mm into the soil and 70m long, this fence was successful at keeping the pond fish free for three years. Subsequently, a second fence was constructed in the southern part of the wetland 200m long and 600mm high (Figure 3), enabling four ponds to be fish free for two years. As the fences are a physical barrier to fauna movement, ramps made of shade cloth and rocks were installed to assist in facilitating movement.

The main challenge for these structures is flooding – the area of the second fence floods to a height of 600mm once or twice per year. The sediment fence has a pore size of 360 μm to screen out tiny fish resulting in very low transfer of water and increased risk of fence collapse under the weight of a wall of water.

Figure 3 The second Gambusia fence (600mm high) with shade cloth ramp.

Managing predation - birds

With only a small number of adult bell frogs contributing to the next generation, every tadpole becomes important. Bird netting has been added to many breeding ponds from 2016 to reduce predation by birds. Netting is also used as a response to the sighting of tadpoles in ephemeral ponds with three nets deployed in the 2019-20 season to temporarily cover ponds containing bell frog tadpoles (Figure 4).

Figure 4 Temporary netting placed over an ephemeral pond in the Brickpit in early 2020. Supplementary water was also supplied until tadpoles metamorphosed.

Pond management - age

Pond age may influence the density of vegetation, productivity, predators and competition, among other factors. In order to prevent the loss of desired habitat values, seen as a mosaic of pond types, depths, vegetation coverage and more, regular intervention is required to 're-set' a pond to the desired form.

A rolling program of pond renewal is implemented across frog habitat as early phase wetlands with limited competition are thought to play an important role in bell frog habitat selection (Pike and White 1999). This perturbation program incorporates periodic disturbance, and water level management. Works are undertaken during the frog activity season when frogs are active and visible.

Disturbance ranges from hand removal of vegetation to the drying and scraping out of whole ponds by a bobcat. There is no set formula, but an annual review of habitat condition against set parameters of the Biodiversity Management Plan identifies where intervention may be required. In each renewal activity, no other disturbance is conducted in the area until the vegetation/pond is fully restored, usually a period of 2-3 years or more.

An example of re-setting a pond can be seen in Figures 5 and 6. Over a period of 10 years, a pond became heavily vegetated and increasingly shallow. The pond was drained and hand cleared over three days during the frog activity season when frogs are able to move away from disturbance of their own accord. To ensure no fauna remains within the worksite, a hand clearance by ecologists occurs before the last vegetation is cleared.

Works then consisted of a bob-cat removing the accumulated sediment. Patches of emergent vegetation are left in situ to recolonise the pond after completion. As this pond had had bell frog breeding in the past, bird netting was placed over hoops of irrigation pipes to prevent bird access.

The two adjacent ponds were not disturbed and left as refuges.

Figure 5 This pond became totally covered in emergent vegetation with no open water.

Figure 6 The pond was cleared of excessive plant growth, scraped free of accumulated sediment and netted to prevent bird predation.

Pond management - hydrology

Frog ponds are managed to provide a wide range of depths, temperatures and vegetation and have a minimum retention of water for eight weeks. The majority of ponds at Sydney Olympic Park are connected to an irrigation system and can be filled when necessary. Ponds are required to be more than 80% full during the frog activity season (September to March). Weekly pond level checks by Authority staff and contractors ensure ponds don't dry out due to equipment failure.

During winter, water levels are allowed to drop for emergent plant health and certain ponds selected for 100% drying on a cyclic basis. These ponds are dried to mimic ephemerality, being filled at the start of the activity season or when storms are predicted. Fluctuating water levels may also improve macrophyte health. Some ephemeral ponds adjacent to breeding ponds are also opportunistically filled prior to hot and stormy weather (Box 1).

All wetlands and ponds are subject to water depth reduction due to sediment accumulation. Where possible, sediment is removed to create deeper sections to increase water holding capacity. This provides refuges for tadpoles as water levels recede during periods of low rainfall. In suitable situations, excavated sediments are retained and reformed as islands.

Pond liners are vital to maintaining good hydrology and connectivity. At Sydney Olympic Park, many types of liners have been trialled and are discussed in Box 2.

Pond management - vegetation

Pond vegetation management aims to have the majority of ponds containing 30% - 60% open water, with the perimeter macrophyte zone being at least 1.5m wide where possible. Where vegetation exceeds this parameter, vegetation is hand cut below the water level. Often, the rhizome is also removed to increase water depth.

The plant species is not as important as the structure it provides – bell frogs need something that will hold their weight, enabling them to bask. At Sydney Olympic Park, fast growing species such as Typha and Phragmites are restricted to a small number of ponds due to both aesthetics and their ability to cover a pond rapidly. Planted emergent species include *Baumea articulata*, *Schoenoplectus validus, Triglochin procerum* and *Eleocharis sphacelata.*

Box 1: Water manipulation in ephemeral ponds

Adult bell frogs show high wetland fidelity especially during dry periods with greater than 95% of all recaptured bell frogs being captured within 50m of the site of first capture (Hamer *et al.* 2008, Urlus and Braakhuis 2019). However, frogs are known to move opportunistically over larger distances in periods of high rainfall, inhabiting ephemeral ponds temporarily. In 2019, the irrigation system within the Brickpit was extended to allow watering of vegetation planted as part of a staged removal program for pampas grass *Cortaderia sp*. Water level manipulation within one ephemeral pond in the Brickpit to attract breeding has been ongoing successfully since 2013. The irrigation extension into more remote parts of the Brickpit opened up the opportunity to manipulate water levels in further ephemeral ponds.

In the Brickpit the permanent wetlands are less than 150 metres from a minimum of five ephemeral ponds ranging in size from 70m^2 to 630m^2. Distances between permanent wetlands and ephemeral ponds are shown in Figure 7.

Artificially filling ephemeral ponds has resulted in observations of males calling within 24 hours in a pond up to 126m from the closest permanent wetland. Bell frog tadpoles have been observed in ponds deliberately filled prior to stormy weather conditions whether the subsequent rainfall was enough to fill other ephemeral ponds or not. Only a selection of ponds is filled each year, allowing natural ephemerality to occur in the majority. Artificially filled ponds are monitored closely and only maintained with water if tadpoles are present.

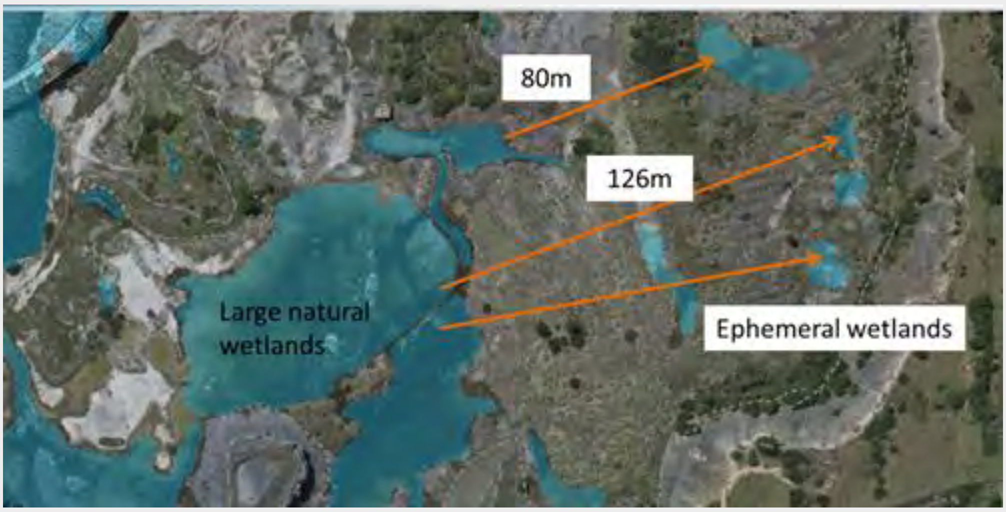

Figure 7 Example of distances between permanent wetlands to ephemeral wetlands in the Brickpit. Breeding has occurred every year in the permanent wetlands and management of water levels in the ephemeral ponds can encourage breeding in smaller ponds.

Terrestrial vegetation management

Terrestrial vegetation management includes weed management, slashing, planting, mulching, and pruning, in many cases to provide habitat perturbation and a wide variety of habitat ages and densities.

Observations of bell frogs at the Park indicate that adults stay close to ponds; primarily within 5m but range up to 50m and juveniles disperse over even larger distances (Garnham *et al.* 2015, Urlus *et al.* 2020). Some adults have a high site fidelity with the same adult observed even within the same plant over years.

Management of terrestrial vegetation aims to maintain a perimeter zone of tall dense grasses (over 30 cm high) extending a nominal 5 m from pond edges, free of invasive exotic grasses (e.g. kikuyu, water couch).

Any large scale vegetation removal must follow the procedures of the Biodiversity Management Plan. Under these conditions, any area greater than 5x5m must be cleared in stages, generally cutting the vegetation to progressively lower heights, leaving the site overnight then cutting more the next day in an attempt to encourage fauna to leave due to the disturbance and gradual removal of cover.

Most wetlands occupied by bell frogs are not strongly shaded by trees. Trees can reduce water temperature by shading and thinning of edge/emergent plants through competition for the sun. Ponds are generally managed to achieve no shading between 10am and 4pm.

Frog corridors:

Connectivity between frog ponds is vital to facilitate dispersal movement of frogs (Muir 2008, Patmore and Osborne 2008). Unshaded grassy corridors a minimum of 20m wide and dominated by tall dense grasses (over 30cm high) covering at least 70% of the nominated corridor are maintained across the site. These corridors are mapped and condition reviewed on an annual basis.

Habitat stacks

Log piles and coarse mulch assist in increasing food and shelter habitat for reptiles, amphibians and insects. 'Naturalistic' areas not requiring high presentation standards are managed to increase the density and complexity of the ground layer. Any cut tree is left onsite in log piles to increase the complexity of the mulch/ground layer.

Pest/invasive weed control

Fox and cat control programs are implemented across the site and invasive weeds targeted before they form habitat. Where invasive weeds form a large portion of the habitat, a staged removal program is utilised.

Generally invasive weeds are controlled by hand pulling as the use of herbicides in frog habitat is generally not permitted. Herbicide use can be approved on a case by case basis and involves the application of a staged frog habitat removal prior to the control of weeds.

Fauna underpasses and frog fences

In order to prevent frogs and other species from moving onto roads, 6km of purpose-designed shade cloth fencing were installed in 2000 to channel animals to underpasses under the roads to facilitate movement and genetic exchange. There are 10 underpasses in total at Sydney Olympic Park.

Shelter boards

Shelter boards in the guise of roof tiles and plywood sheets have been placed in many locations around the Brickpit. Incidental observations show that tiles are well used by juvenile frogs, particularly during cooler weather.

Box 1 Pond liners

All constructed ponds were originally lined with bentonite, and over time, some have required re-lining and new ponds added to increase water availability and connectivity. Experimentation with different pond liners has occurred throughout the Park.

Liner type	Description
Sheep trough with float valve 	The installation of a sheep trough with float valve is not expensive, allows easy management of emergent vegetation, control of predators such as reptiles and competing frog species and very easy water level control. Sheep troughs have now been used in multiple sites across the Park and have attracted dispersing juveniles, females and breeding dependant on their location within the landscape.
Rubber 	Rubber liners have been used successfully in several ponds and to date have retained water for more than 10 years. One of the most successful ponds ever constructed at the Park was a 1700m^2 rubber-lined pond located within 20m of a persistent breeding population and consisted of two large cells 200mm deep and lined with black rubber leading to high water temperatures. Bell frogs colonised and bred within the pond on a regular basis.
Reinforced plastic 	Trials of reinforced plastic liners (tarps) as pond liners have shown that these temporary liners can hold water for up to 6 years. Larger ponds up to 200m^2 were re-lined in the 2017-18 season and attracted bell frog breeding in the 2018-19 season. Reinforced plastic liners are now used in the Brickpit to extend the water holding capacity of drier areas. Observations show these ponds have been used regularly by dispersing juvenile bell frogs. The low cost of this thin liner is balanced by the high risk of breaching; foot access for vegetation and surveys must be minimised.
Fiberglass 	A fiberglass swimming pool was trialled in 2009 and while it has excellent longevity and strength, installations costs are higher than other liners. Bell frogs have been observed using the vegetation, although no breeding has been recorded in this particular pond. The same swimming pool was used successfully in the Brickpit, attracting breeding within the same year.

Observations of the same tiles show that under summer conditions, no frogs are present indicating that their use is temperature dependant and may form an important function for the dispersal of juveniles.

Pond/wetland design

Thanks to modelling by the Saving Our Species Program and others (Hamer 2008, Bower *et al.* 2013) it has been shown that large permanent wetlands closely connected to ephemeral ponds and within one kilometre of other wetlands increases occupancy rates. Based on pond occupancy at Sydney Olympic Park, bell frogs have typically demonstrated a preference for large, permanent and closely connected wetland habitats over smaller ponds (Urlus *et al.* 2020).

Management actions that create new wetlands and increase connectivity are likely to increase the proportion of sites occupied by bell frogs within management zones.

Active intervention

As part of research programs and in response to subsequent increased knowledge, active intervention activities including translocation and captive breeding of the Green and Golden Bell Frog have taken place.

1. In 2012-13, a research project by the University of Newcastle investigating water quality/pond occupancy involved the release of 11,500 captive bred tadpoles into 6 ponds. The project concluded that predation, rather than chytrid or pond quality was the limiting factor for tadpole survivorship (Pollard *et al.* 2017b).
2. In 2014-15, funding was provided by the Office of Environment and Heritage for a captive breeding project for the Brickpit population in response to findings that the population had inbreeding depression. The aim was to increase genetic diversity by translocating new alleles into the Brickpit from the Narawang Wetland population. A total of 928 late stage tadpoles were released into the Brickpit tubs in February 2015.
3. To conclude the Brickpit translocation project and test the outcomes of the 2014-15 introduction, genetic sampling of the Brickpit population was undertaken in 2019.

Monitoring

The frog population has now been intensively monitored since 1998, primarily by ecological consultants, but between 2008 and 2013 as part of a broader research program conducted by the University of Newcastle in partnership with the Authority, under an Australian Research Council grant program. This latter program included research that has greatly enhanced understanding of the Park's frog population and species biology.

The current methodology was recommended by Bower *et al.* (2014) and consists of two visual encounter surveys in December and February. This is supplemented by incidental observations by Authority staff, particularly of breeding events and pond occupation outside of the survey window and two auditory surveys by the Frog and Tadpole Study Group. The objective of the monitoring program is to gather data and information which will identify population demographics and long-term trends at the Park to assist in measuring the success of ongoing habitat maintenance and enhancements. The data is also provided to the NSW Saving Our Species program to contribute to understanding of frog habitats across all eight Priority Management Sites.

The surveys take place across 127 ponds and the morphology of each captured frog recorded, and a PIT tag inserted.

Recapture rates are extremely low - only 3% of frogs were recaptured in 2019-20 from the previous season. This supports the findings of Pickett *et al.* (2014) that the population has a very high turnover rate.

For the Sydney Olympic Park population, monitoring and research show that the key ecological issues affecting viability include:

- infection by chytrid fungus;
- low recruitment from the tadpole stage, including predation of tadpoles and metamorphs by fish, insect larvae and birds;
- loss of females prior to breeding age;
- inbreeding depression.

Reflections

Sydney Olympic Park's bell frog program continues to be one of ongoing active and adaptive management. The best available ecological advice has been applied throughout the course of the project but much still remains unknown about the ecology and habitat requirements of this threatened species. As a result, many of the management approaches described in this paper have been reached through a process of trial and error, where the negative results have been as valuable as the positives in learning more about the species. Some of the learnings from this process are described here.

Some ponds have worked better than others, sometimes for no obvious reason. Two ponds may appear the same - the same distance from a large wetland, have similar depths and vegetation but the frog perversely chooses one over the other (or neither!). This fine tuning of habitat is still done by intuition following known broad guidelines but is not evidence based and is part of providing a habitat mosaic. If in doubt, provide as many options as possible to suit the frog during different climactic conditions and life cycle stages.

It seems obvious now but constructing bell frog ponds in a flood plain was not going to end well. The introduction and continuous reintroduction of Gambusia to Narawang Wetland was unfortunate and has led to the channelling of resources to offset its impacts. In a perfect scenario, bell frog ponds would be clustered into large compartments with dykes and drainage sumps that allow the manipulation of water levels to manage possible infestations by pest fish.

For Sydney Olympic Park, constructing small ponds (<15m^2) greater than 50m apart in long corridors linking large wetlands has not been successful. These ponds were also constructed on a young landfill; the settling movement of the landform has caused some ponds to crack and leak. The landfill capping makes the retrofitting of larger ponds or clustering of more ponds very expensive.

The vegetation management protocols of the Authority's Biodiversity Management Plan are more closely aligned to bush regeneration principles and practices than traditional horticulture and urban park management. The frog habitats at Sydney Olympic Park are managed as 'natural areas' where presentation standards allow coarse mulch and vegetation complexity to support biodiversity.

Management actions aimed at disturbing ponds to encourage pond use have had variable effects. It is now becoming more evident that efforts should be concentrated adjacent to currently active ponds within reach of dispersing adults and juveniles (within 50m). If pond occupation increases, then efforts can be moved further out from the core ponds.

The bell frog never ceases to surprise. Auditory monitoring by the Frog and Tadpole Study Group in December 2019 found 4 male frogs singing hopefully in a decorative reflection pool where they have never been recorded in that pond's 20-year history. A static concrete pond with no vegetation – it was a far cry from the beautifully crafted naturalistic ponds within 100m from where they sat. Further monitoring of the pond found, of course, tadpoles.

Conclusions

The Authority has accepted the challenge to provide for on-going bell frog persistence at Sydney Olympic Park by investing in long term habitat management and monitoring. What wildlife would remain at the Park if legal drivers had not triggered this commitment to a far-reaching amphibian conservation program? The success of this project is that a sizeable population of bell frogs has been maintained throughout a period when most other populations across the Sydney region have disappeared, and this has been achieved on a restored landscape in the midst of a rapidly developing urban centre.

There have been many lessons learned along the way about creating and managing habitats where bell frogs can survive and breed, though there are no definitive easy answers and the need for ongoing innovation and adaptive management remains. Conservation of this endangered species remains a high priority and the bell frog continues to be an iconic symbol for the environmental values of Sydney Olympic Park.

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Bringing back the bush: Regeneration of critically - endangered remnant forest

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Remnant critically-endangered Sydney Turpentine Ironbark Forest has been conserved, improved and expanded in an ecological management and restoration program spanning 20 years. The program includes primary, secondary and maintenance weeding, assisted and natural regeneration, and the introduction of controlled burning. Vegetation condition is assessed through five-yearly systemic floristic survey, as well as two-yearly condition assessment. These assessments have shown an increase in species diversity and condition over time, with corresponding increase in resilience. The forest now supports over 210 flora species, and 19 of 20 hectares is classified as being in good condition, with the remainder continuing to undergo rehabilitation. Collection of local provenance seed has enabled extension of forest species and their genetics across the Park.

Introduction

Sydney Turpentine Ironbark Forest (STIF) is listed as a 'critically endangered' ecological community under both the *NSW Biodiversity Conservation Act 2016* and the federal *Environment Protection and Biodiversity Conservation Act 1999*. Less than 10% or 2,940 hectares of the original pre-European extent of STIF remains intact. Of this, only 280 hectares is protected in conservation reserves, including 13 hectares located within Newington Nature Reserve at Sydney Olympic Park. A further seven hectares of the community is situated immediately adjacent to the Reserve on lands within Sydney Olympic Park.

Sydney Olympic Park Authority manages STIF across the two land tenures as one 20-hectare land management unit, working in close collaboration with the NSW National Parks and Wildlife Service and in accordance with the adopted Plan of Management for Newington Nature Reserve (SOPA & NPWS 2003).

This remnant forest is considered to be a good representative of the community, however it is highly isolated. Wallumatta Nature Reserve at Ryde, approximately 10 kilometres away and north of Parramatta River, contains the closest neighbouring remnant in good condition.

The forest is located within a highly urbanised part of Sydney, and the surrounding landscape to the east and south has been significantly remediated, remodelled and replanted over the past 25 years. This manufactured landscape is planted with native vegetation and provides ecological connection and buffering to the forest.

To the north, the forest forms part of an estuarine zonal succession – as the ground level drops towards the Parramatta River, STIF progressively gives way to Swamp Oak Floodplain Forest, saltmarshes, then mangrove wetlands. This zonal succession is contained within the 47-hectare Newington Nature Reserve.

The forest has been subject to a range of disturbances in the past. It was used for timber-cutting and grazing in colonial times, then throughout the 20th century the forest was part of the Royal Australian Navy Armament Depot, Newington, which was managed by the Commonwealth Department of Defence.

The Department of Defence constructed a series of explosives storehouses within and around the forest in the 1930s, and the forest understorey was mown until the 1980s to protect stored armaments from the risk of accidental wildfire. This lack of fire history makes the forest different to most other remnant woody vegetation in the Sydney region.

The forest has no water courses running through it. Past and present land tenures have excluded public access to the forest core for well over a hundred years.

Air photos indicate the forest extent has remained constant since 1932 (Clarke & Benson 1988). Most of the existing forest canopy is secondary or later regrowth and the multi-layered sub-canopy of small trees and shrubs is likely to be the result of these past management practices (Urban Bushland Management Consultants, 1997). The forest supports many mature endemic trees with hollows and spouts, stags, dense middle and lower storey vegetation, dense litter cover, good burrowing soils and a relatively undisturbed environment (Mt. King Ecological Surveys 2001). It is the only area of mature woodland vegetation with large numbers of hollows in the Homebush Bay region, providing an ecologically-important roost and nest site for microbats and birds.

Vegetation Management

A program of works to restore and enhance the ecological values of the forest began in 1997 and has been mostly continuous since that time.

In 1997, the forest exhibited widespread symptoms of degradation including weed invasion and inappropriate fire regimes. The understorey had begun to regrow after being suppressed for over 90 years to control the threat of fire but the forest extent was reduced to just 13 hectares, creating substantial edge impacts. A small area of the forest that was formerly used by Department of Defence as a burning pit was remediated in 1997 and replanted with local species, and an initial primary weeding program was conducted to address widespread weed invasion.

A regular weed management program was commenced in 2001, and soon after, a regeneration plan was developed with the objective of expanding the total area of the forest community. Seven hectares of land outside the gazetted boundary of the Reserve was identified for restoration. The regeneration area was mapped according to the type of treatment to be applied – natural regeneration, assisted regeneration, or total re-creation (Figure 1). Cultural heritage values of the wider area were also considered – view corridors free of tall shrubs and trees needed to be maintained across part of the restoration area, and former explosives storehouses still needed to be protected from damage due to wildfire. The wider precinct is now listed on the NSW State Heritage Register due to its natural and cultural heritage significance (listed as Newington Armament Depot and Nature Reserve) and the majority of the forest is now classified as being in 'good" condition (Figure 2).

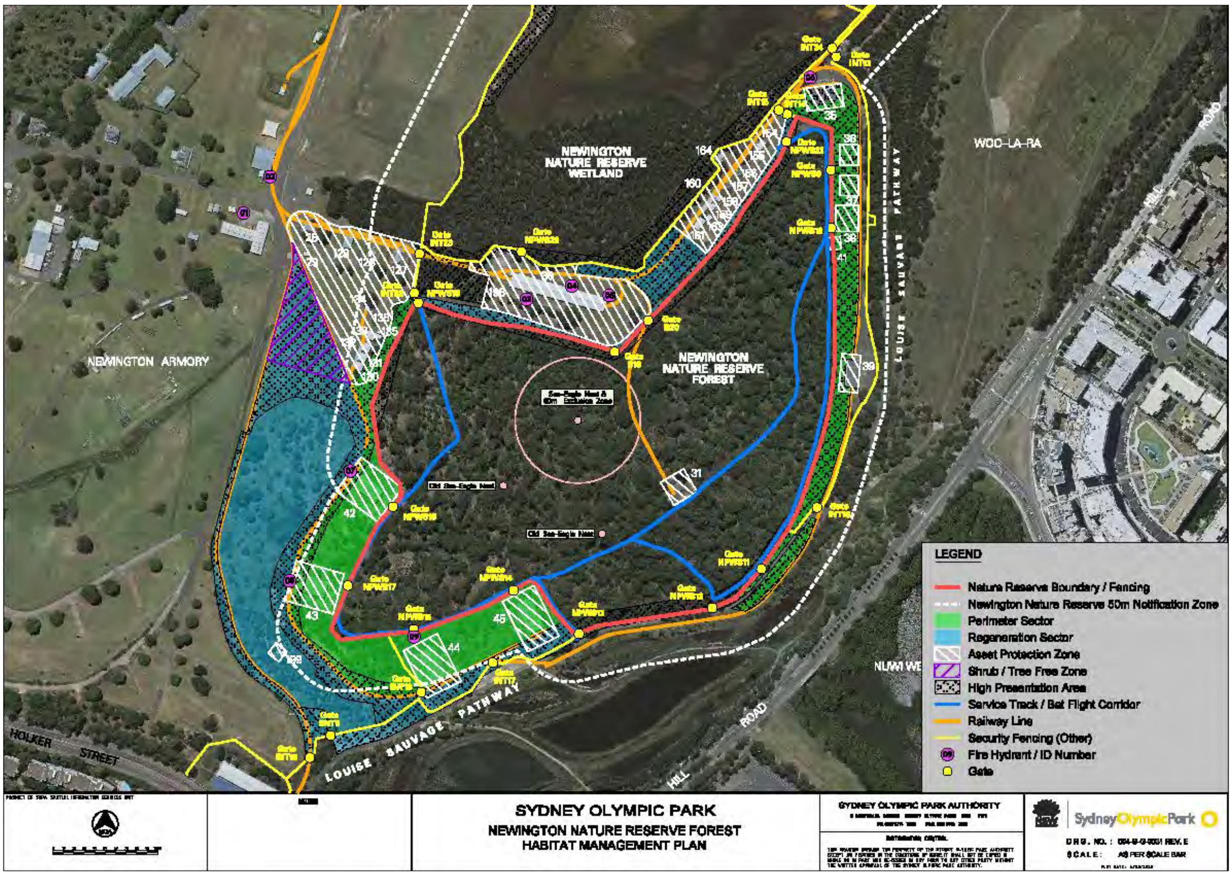

Figure 1: Sydney Turpentine Ironbark Forest management zones

Figure 2: Change in forest condition over time

Top: area classified as 'good' condition in 2002 (red)

Bottom: area classified as 'good' condition in 2019 (green); 'fair' condition (yellow) and 'poor' condition (red)

Weed Control

The annual weed control program commenced in 2001 has been ongoing with the exception of the 2004-05 period. Qualified bush regenerators conduct regular weed sweeps across the forest to remove target weeds.

Initial works concentrated on the primary and secondary treatment of woody weeds, vines and scramblers. Dominant weeds were predominantly species spread by birds and included Boneseed (*Chrysanthemoides monilifera* ssp. *monilifera*), Lantana (*Lantana camara*), African Olive (*Olea europaea* ssp. *africana*), Ochna (*Ochna serrulata*), Camphor Laurel (*Cinnamomum camphora*), Asparagus Fern (*Asparagus aethiopicus*), Blackberry (*Rubus fruticosus* species aggregate) and Moth Vine (*Araujia sericifera*). More than 1,400 labour hours were spent targeting woody weeds, vines and scramblers during 2001-02 across the nature reserve and perimeter and regeneration sectors. This amount reduced to approximately 700 labour hours during 2002-3 and 600 labour hours in 2003-04, as management moved into a maintenance phase.

Significant resources have also targeted exotic grasses including Kikuyu (*Cenchrus clandestinus* syn. *Pennisetum clandestinum*), African Lovegrass (*Eragrostis curvula*), Paspalum (*Paspalum dilatatum and P. urvillei*), Whisky Grass (*Andropogon virginicus*), Briza (*Briza subaristata*) and Carpet Grass (*Axonopus fissifolius*), among other species. More than 600 labour hours were spent targeting exotic grasses in 2001-02, with similar resourcing (between 400-600 labour hours) being required per year since.

Two new invasive species have been introduced to the forest during the last 20 years, requiring substantial resourcing to control. Both are introduced and spread by birds. They are the exotic vine species Corky Passionfruit (*Passiflora suberosa*) and the native tree species Tuckeroo (*Cupaniopsis anacardioides*). The Tuckeroo is a favoured plant species in landscape design and has been planted in landscape areas within Sydney Olympic Park and adjoining suburbs such as Newington. This species is not a component of the STIF plant community, and so is considered to be a local weed species. Since the elimination of legacy stands of Boneseed and Lantana from the forest, Tuckeroo has become one of the most abundant woody weed species in the forest and is routinely targeted during maintenance sweeps.

Bush regenerators primarily use hand weeding methods to control weeds. Herbicide use is limited to cut and paint or scrape and paint methods. Spray application of herbicide has not been used within the nature reserve since around 2003 (other than on hardstand areas around built structures). Outside the nature reserve, spraying is restricted to one-off primary treatments of established stands of Kikuyu in the perimeter and regeneration sectors.

Revegetation and restoration treatments

While much of the regeneration area outside the nature reserve has regenerated naturally with time and effective weed management, some areas were so badly degraded that more intensive regeneration approaches were required.

Assisted regeneration was applied to the west of the nature reserve. Local provenance plantings of shrub clusters and scattered canopy trees were established in 2004 (southern section – ~ 1,000 plants) and 2008 (northern section ~ 1,116 plants). These plantings provided a direct seed source and 'roosting nodes'

Figure 3 - Vegetation change 2001 – 2019

A combination of natural and strategic planting regeneration techniques was applied in the 'regeneration sector', west of the nature reserve

Figure 4 – Vegetation change 2004 to 2019

The restoration zone was deep-ripped, mulched and planted with local provenance seedlings to create a vegetative link between the STIF community and the SOFF community to encourage seed spread by bird species. Some subsequent planting has taken place after 2008 (Table 1). The results of this program can be seen in changes to vegetation structure and are evident in comparison of aerial photography between 2001 and 2019 (Figure 3). Natural recruitment in both areas continues to improve structure and diversity.

Total restoration was conducted to the north of the forest. A vegetative link was established across a barren service corridor that separated STIF from Swamp Oak Floodplain Forest (SOFF). Highly compacted mown turf was deep-ripped and mulched, then planted with local provenance seedlings (Figure 4).

Table 1: Local Provenance Planting – Regeneration Sector west of Nature Reserve

Species	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	Total
Trees							
Eucalyptus fibrosa	20						20
Eucalyptus globoidea	20						20
Eucalyptus racemosa	40						40
Eucalyptus longifolia	20						20
Eucalyptus paniculata	20						20
Eucalyptus punctata	20						20
Syncarpia glomulifera	20						20
Total	160	0	0	0	0	0	160
Shrubs							
Acacia longifolia	122						122
Acacia myrtifolia	20				24		44
Acacia paradoxa					13	7	20
Allocasuarina littoralis	105						105
Daviesia ulicifolia	120						120
Dodonaea triquetra	509						509
Hakea propinqua				6			6
Hakea sericea	11						11
Hovea longifolia	34						34
Kunzea ambigua					75		75
Melaleuca nodosa					240		240
Podolobium ilicifolium	15	20					35
Pomaderris discolor		80					80
Pomaderris lanigera		40					40
Pultenaea villosa	20						20
Total	956	140	0	6	352	7	1461
Total	1116	140	0	6	352	7	1621

Reintroduction of fire

STIF is a fire-dependent ecological community. Best practice guidelines for managing STIF state that the minimum recommended fire frequency is seven years and the maximum recommended fire frequency is 30 years, with only a small area of a remnant to be burnt at any one time. Ideally, prescribed burns should be conducted between 15 and 30 years apart (DECC 2008).

Fire was re-introduced to part of the STIF community in April 2018 (Figure 5) after not being present since at least the 1940s, due to historical management drivers. This fire-free interval is substantially longer than the natural fire regimes to which the plant community is adapted, leaving the community vulnerable to the loss of fire-dependent species and the gradual increase in mesic species.

The controlled burn was conducted as a joint venture between NSW National Parks & Wildlife Service and NSW Fire & Rescue as the fire footprint crossed over two land management jurisdictions - NPWS (Newington Nature Reserve) and SOPA (Newington Armory). The initial proposed burn dates during 2017 were postponed due to conditions being unfavourable during scheduled burn windows. Windows were restricted by the location of the site, being next to residential areas and a major events precinct (events such as Royal Easter Show need to be taken into consideration), and the nesting time of the resident pair of White-bellied Sea-Eagles that nest within the forest each winter/spring.

Approximately seven hectares was burnt in a low-intensity burn in April 2018, following careful preparation to protect hollow-bearing trees, cultural heritage items and Park infrastructure.

Vegetation recovery was initially slow due to low rainfall following the burn, however two years after the burn there has been abundant regrowth and recruitment of shrubs, vines and groundcovers (Figure 6), enhancing vegetation structure and increasing the distribution of certain species (eg. *Gompholobium minus and other pea species, Stackhousia viminea).*

The Regeneration Sector to the west of the nature reserve has generally responded very well to the fire, with recruitment of species not present before the burn. This area was a mix of exotic and native grasses in 2001, and there appears to be a degree of resilience in the soil seedbank despite fire being absent from the area for at least 70 years and the area being managed as a grassland until recently (Figure 7).

The remainder of the nature reserve, perimeter and regeneration sectors are proposed to be burned over the next five to six years in a minimum of two stages.

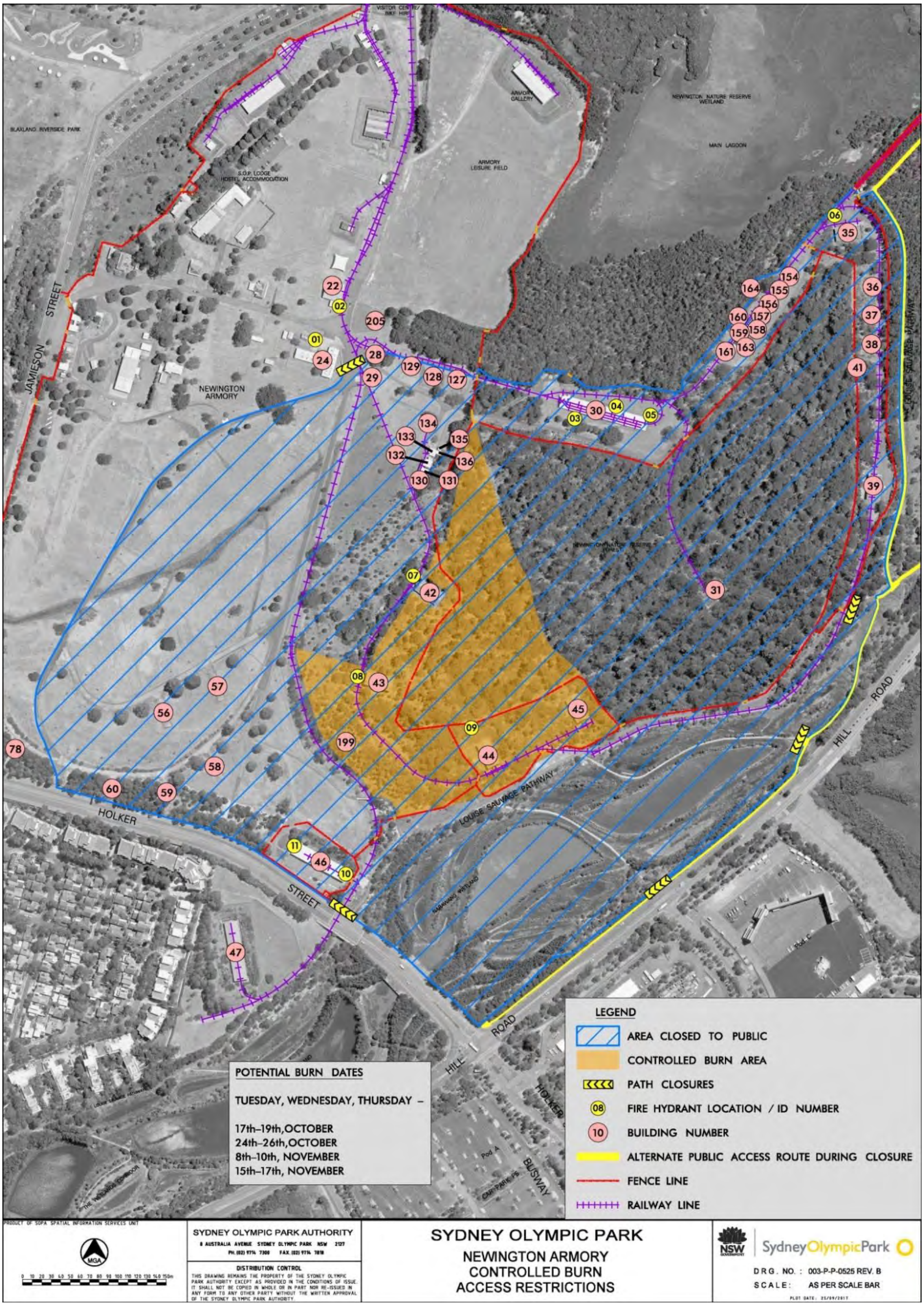

Figure 5 – 2018 controlled burn area

Figure 6 – Regeneration of the April 2018 burn area two years on

Nature Reserve (top); Perimeter sector (centre, bottom). Photography date April 2020

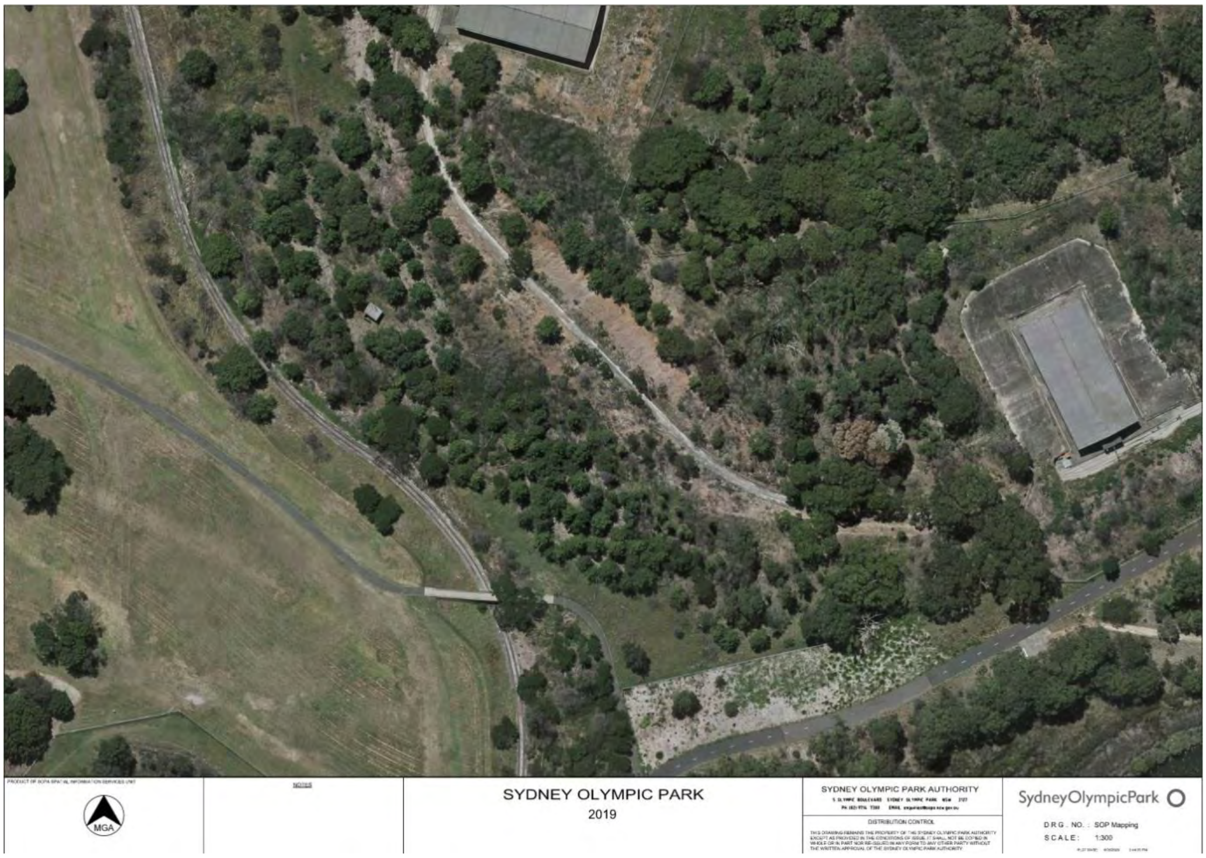

Figure 7 – Vegetation change south-west corner of the forest 1943 - 2019

Local provenance planting

Seed collected from the forest was used in some pre-Olympic revegetation programs within Sydney Olympic Park. Since 2006, regular collection has been undertaken to create a source of local provenance seedlings for replanting programs. These programs have aimed to:

- increase the area of the STIF remnant and the vegetative buffer around it
- increase the distribution of STIF species and local genetics across Sydney Olympic Park
- link areas of high biodiversity within and outside the Park.

A specialist seed collector and nursery is contracted to collect seed on three to four occasions per year, between spring and autumn, and to grow seedlings to hiko cell/50 mm tube size. Authority staff also opportunistically collect seeds from remnant vegetation within Newington Armory for direct broadcast.

Initial plantings of local provenance seedlings were concentrated within the regeneration sector (Figure 1) and terrestrial areas adjacent to the nature reserve estuarine habitats, in accordance with SOPA's regulatory licence requirements which restrict use of first generation plant material to within a 300 metre radius of the reserve. Once these plantings matured, second generation seeds were available for planting of locally provenance plants across other parts of Sydney Olympic Park. This has allowed more structurally complex habitats to be created for native fauna, particularly woodland birds, and to achieve aesthetically pleasing habitats containing self-recruiting local STIF species.

The STIF restoration program has been successful in assisting in the extension of the STIF community and increasing the genetic and disturbance buffer to Newington Nature Reserve. The program has successfully established and enhanced secondary source of local seed for planting programs in areas away from the reserve.

In total, over 127,000 local provenance plants have been propagated from primary and secondary seed sources since the program commenced in 2006 (Appendix 1).

Monitoring

Detailed floristic survey of 15 permanent monitoring quadrats (Figure 8) is conducted on a nominal five-yearly cycle (to date in 2003, 2007, 2012 and 2018). Random meander surveys supplement this data, and an expert ecologist conducts a qualitative assessment of forest condition every two years. This program allows updating of floristic information, assessment of change over time and in response to management actions, and provides guidance for the ongoing management of the community.

The surveys have shown that species richness in the STIF community has increased from 106 species in 2002 to over 210 species during the 2018 survey. A total of 227 native species have been identified in the STIF since 2001 (Appendix 2).

The controlled burn which took place in April 2018 burned 4 of the 15 quadrats used in the periodic floristic surveys (Quadrat 1, 3, 4 & 14 – Figure 8). The burn was followed by an extended dry period where little germination occurred and it was not until after the rains in late spring 2018 (Table 2) that there was a flush of seed germination. The floristic survey conducted in December 2018 recorded a high abundance and diversity of seedlings and juvenile plants within these quadrats, indicating an increase in diversity as a result of the fire (Table 3).

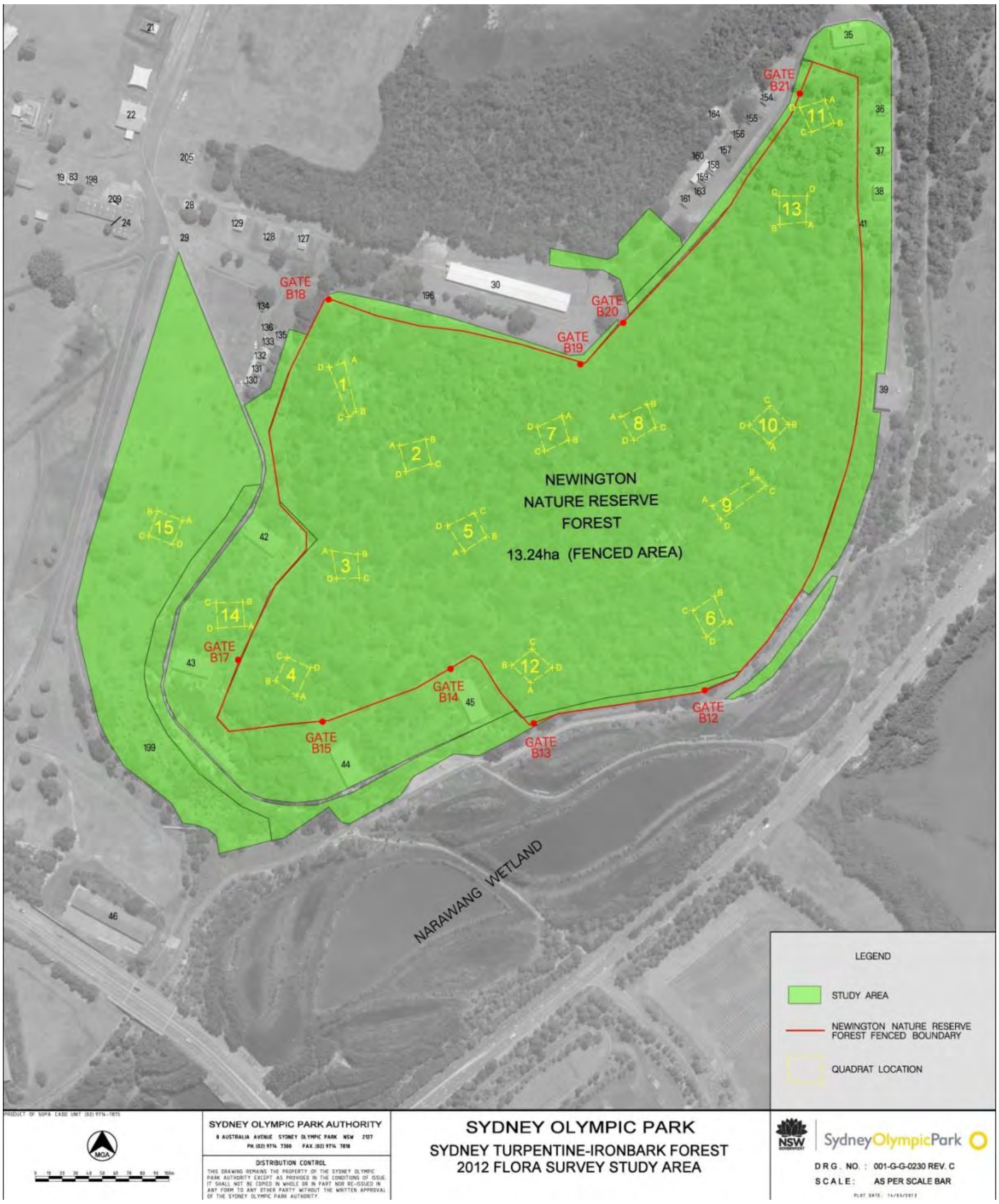

Figure 8 – Floristic survey monitoring quadrat locations

Table 2: Rainfall at Sydney Olympic Park Apr-Dec 2018

Month	Apr 18	May 18	Jun 18	Jul 18	Aug 18	Sep 18	Oct 18	Nov 18	Dec 18
Rainfall (mm)	15.2	11.8	103.6	3.6	8.0	40.4	222.8	128.8	66.0

Table 3: Number of species (native) recorded in quadrats which were burnt in April 2018

Quadrat	2002	2007	2012	2018
1	17 (9)	36 (21)	40 (22)	64 (45)
3	28 (27)	45 (44)	48 (44)	57 (46)
4	23 (17)	34 (28)	40 (29)	65 (47)
14	30 (22)	43 (29)	51 (39)	52 (44)

Concluding remarks

The condition, extent and floristic diversity of the Sydney Turpentine Ironbark Forest community at Sydney Olympic Park has greatly improved over the course of this long-term project.

The extent of STIF considered to be in good condition has expanded from 14.22 hectares in 2002 to 19.00 hectares in 2019 (Figure 2), and the majority of the forest now has low levels of weed infestation. Works to improve the remainder are continuing.

There has been a significant reduction in the number of labour hours required for weed treatment within the boundaries of the nature reserve, dropping from over 1,300 hours in 2001-02 to around 300 hours in 2018-19. As a consequence, works have shifted from being predominantly within the nature reserve boundary to now being largely in the perimeter and regeneration sectors of the forest, adjoining the reserve. This shift in management focus is an indication of the improved condition and resilience of the forest within the nature reserve due to having a regular maintenance program in place.

While public access to the nature reserve continues to be highly restricted to ensure its ongoing conservation, expansion of the forest to adjoining lands within Sydney Olympic Park has created opportunities for people to more closely connect with this critically endangered community through guided tours, botanical trails, and casual walking and cycling.

Acknowledgements

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Appendix 1: Local Provenance Seed Collection and Propagation

Seed Collected and Propagated from STIF Nature Reserve + Perimeter Areas

C=Collected; P=Propagated

Species	2005/06		2006/07		2007/08		2008/09		2009/10		2010/11		2011/12		2012/13		2013/14		2014/15		2015/16		2016/17		2017/18		2018/19	
Canopy species	C	P	C	P	C	P	C	P	C	P	C	P	C	P	C	P	C	P	C	P	C	P	C	P	C	P	C	P
Eucalyptus fibrosa	X		X			73																						
Eucalyptus eugenoides													X															
Eucalyptus globoidea			X			129							X			161												
Eucalyptus haemastoma	X		X			63																						
Eucalyptus haemastoma x racemosa			X			102																						
Eucalyptus longifolia	X					95							X															
Eucalyptus paniculata	X		X			128										44												
Euclayptus punctata	X		X			113																						
Syncarpia glomulifera	X					90			X				X			175				2								
Shrub species																												
Acacia falcata	X		X		X	189		70	X	137	X	10		1425	X	770	X	165	X	842	X	906	X	1131		935	X	30
Acacia fimbriata									X	29	X	17		18		8												
Acacia longifolia	X		X		X	232			X	44	X	30		133	X		X		X	295	X	170		245		15		27
Acacia myrtifolia			X		X	61	X	90	X	239	X	93		14	X	24		235		10			X			305		6
Acacia paradoxa													X			13		8										
Acacia parramattensis																							X			88		
Acacia stricta	X					66					X			382	X	82	X	196	X	607	X	854	X	520		240		9
Acacia ulicifolia					X		X	440	X	301	X	14		6					X		X	117		25				
Allocasuarina litoralis	X					200	X	100		52			X			238		537		1								
Bossiaea prostrata											X			26														
Breynia oblongifolia									X			28																
Bursaria spinosa																							X					
Clerodendrum tomentosum									X		X		X															
Daviesia ulicifolia	X		X		X	200	X		X	235	X	97		586	X	705	X	412	X	263		1281		695				
Dillwynia sieberi									X		X	25		200		15		4	X			1074		390		50		455
Dodonaea triquetra	X		X		X	809	X	1000	X	330	X	2		1886	X			534	X	109	X	1150	X	685		95	X	1056
Gonocarpus tetragynus							X			19																		
Hakea aff. propinqua											X			16			X											
Hakea sericea							X	38	X	221		2			X		X	490	X	51	X	544	X	254	X	360		214
Hovea linearis																			X					292				
Hovea longifolia			X		X	46		74		54											X	323	X			74		136
Kunzea ambigua											X		X			3000	X	180	X	1543		1569	X	677		510	X	512
Lasiopetalum ferrugineum			X				X								X			18			X		X					
Logania albiflora							X			48	X																	

Melaleuca decora																			X				X	782		40		429
Melaleuca nodosa													X		X	760		480	X	246	X			520				504
Myoporum boninese															X													
Notelaea longifolia	X						X						X		X		X		X		X							
Ozothamnus diosmifolium	X		X			180	X		X	489	X	2035		1		59	X	240	X	57							X	
Pittosporum revolutum									X			174		108	X		X	68	X	4	X	20	X	80		506		70
Platylobium formosum			X		X	80	X			59	X			13														
Podolobium ilicifolium			X		X	95	X	115	X	84											X			17				
Polyscias sambucifolia											X		X				X		X				X					
Pomaderris discolor	X				X		X	15		331	X					195		55		17	X			809				
Pomaderris ferruginea							X			15							X	183			X			265				
Pomaderris lanigera							X			198	X			699	X	253		2		5		26	X			360		
Pultenea villosa			X		X	120		350	X	161	X	27		200	X		X	108	X	12	X	48		95				
Zieria smithii									X		X			201	X	17	X	7	X			212	X				X	
Groundcover species																												
Aristida ramosa									X	520	X	9	X	256	X	186		174	X		X	148		80				
Aristida vagans	X								X	300	X	532	X	280	X		X	111	X		X	178		68			X	32
Aristida warburgii	X																		X		X	96		356				
Austrodanthonia bipartita	X					61																						
Austrodanthonia sp.							X	280		740		35			X						X		X	2320		760		6
Austrodanthonia tenuior	X		X		X	146			X		X	760		636									X			1400		
Austrostipa pubescens							X		X			192																
Austrostipa ramosissima			X			240			X	132	X		X	856	X	666		229	X		X	600	X	815	X	1255		1385
Bothriochloa macra									X		X	288		160	X		X	240	X		X	332	X	320	X	547	X	350
Calotis cuneifolia					X			140	X	184	X	526		850	X		X						X			198		
Calotis lappulacea											X			154	X													
Cymbopogon refractus	X								X	248	X	2600	X	542	X	971	X	1949	X	64	X	1051	X	810	X	265	X	840
Dianella caerulea							X			414		3							X		x	61	X	62		156		
Dianella longifolia																			X			29						
Dianella revoluta									X			10							X			13						
Dichelachne micrantha	X		X		X	918	X	1000	X	1117	X	35	X	492	X	480	X	1041		9			X			798	X	575
Digitaria ramularis									X			240																
Echinopogon caespitosus							X	160	X	358	X	448	X	1420	X	304	X	458	X	4							X	
Entolasia marginata													X		X	56		143		8								
Entolasia stricta																	X				X	54		37				
Eragrostis brownii	X					240			X		X	798		507	X	440		1280		6	X			1353		408		200
*Eragrostis elongata**																												1517
Eragrostis leptostochya									X	343																		
Lepidosperma laterale	X				X																							
Linum marginale											X			300														
Lomandra longifolia			X						X			1580		33	X		X	26	X			101					X	
Lomandra multiflora											X			21					X									
Microlaena stipoides									X			5328	X		X	1439	X	2101	X	896	X	503	X	800	X	797	X	1371
Panicum effusum																					X							
Panicum simile	X					74					X			40	X			165										

Pomax umbellata					X				X	18	X			106														
Rytidosperma sp.																											X	
Rytidosperma tenuior																											X	80
Themeda australis											X			64	X	260	X	65	X	207	X	1363	X	400		524	X	
Vernonia cinerea											X	173																
Vines Scramblers																												
Billardieria scandens																											X	
Clematis aristata											X			91									X			120		
Clematis glycinoides	X		X				X			437	X			1123		686			X				X					
Desmodium varians																					X			43				
Eustrephus latifolius																							X					
Glycine clandestina									X					47	X			3										
Hardenbergia violacea			X						X	5									X			133	X			238	X	
Kennedia rubicunda	X						X	135	X	212		15	X	2							X		X	65		58		
Pandorea pandorana	X		X		X		X	93	X	357	X			349					X			216						
Tylophora barbata																							X			11		
						4750		4100		8431		16126		14243		12007		11907		5258		13172		15011		11113		9804

Appendix 2

PLANT SPECIES RECORDED AS AT 2018 IN SYDNEY TURPENTINE IRONBARK FOREST FLORA SURVEYS

KEY

O - Species of local or regional conservation significance (NPWS 1997).

⊙ - Species of National or State conservation significance.

***** - Introduced or non-indigenous species.

Study

1 – UBM (2003) - Wetland (**W**); Terrestrial (woodland) (**T**); Woodland Buffer (**B**)

2 – UBMP – Draft Newington Woodland Bush Regeneration Annual Report 2002-2003.

3 – Burchett & Pulkownik (1995) – Wetland (Mangrove Community [**M**] & Saltmarsh[**S**]); Transition (Casuarina Forest[**C**]) and Terrestrial (Eucalypt Forest & Grassland Community)

4 – Kachka (1993) - Mangrove Community (**M**); Saltmarsh Community (**S**); Bulrushland (**B**); Rushland (**R**); Casuarina Forest (**C**); Eucalypt Forest (**E**); Shrubland (**H**) and Grassland (**G**). (Note some of these study sites were reconstructed and revegetated as part of site remediation)

4a - Hamilton (1919) (quoted in Kachka, 1993) – Estuarine Wetland (**W**)

4b - Price (1988) (quoted in Kachka, 1993) – Estuarine Wetland (**W**); Terrestrial (**T**)

4c – Clarke & Benson (1988) (quoted in Kachka, 1993) – Estuarine Wetland (**W**); Terrestrial (**T**)

4d - GHD (1990) (quoted in Kachka, 1993) – Estuarine Wetland (**W**); Terrestrial (**T**)

5 – Adam (1991) – Freshwater Wetland, Saline Areas and Grassland Areas

6 – UBM (2007) – Newington Nature Reserve Flora Survey Update (Woodland and Buffer Zone)

7 – SOPA (2012) – Newington Nature Reserve Flora Survey Update (Woodland and Buffer Zone)

8 – SOPA (2018) – Newington Nature Reserve Flora Survey Update (Woodland and Buffer Zone)

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
FILICOPSIDA														
Adiantaceae	*Adiantum aethiopicum*	Common Maidenhair Fern										✓		✓
Cyatheaceae	*Cyathea sp.*													✓
Lindsaeaceae	*Lindsaea microphylla*	Lacy Wedge Fern												✓
Schizaeaceae	*Cheilanthes sieberi* ssp. *sieberi*	Mulga Fern	T					T	T			✓	✓	✓
CYCADOPSIDA														
Zamiaceae	*Macrozamia spiralis*											✓	✓	✓
DICOTYLEDONS														
Acanthaceae	*Brunoniella pumilio*	Dwarf Blue Trumpet												✓
Acanthaceae	*Pseuderanthemum variabile*	Pastel Flower										✓	✓	✓
Amaranthaceae	*Alternanthera nana*	Hairy Joyweed											✓	✓
Amaranthaceae	*Alternanthera philoxeroides**	Alligator Weed		✓							✓		✓	✓
Apiaceae	*Centella asiatica*		W TB					T	T			✓	✓	✓
Apiaceae	*Cyclospermum leptophyllum**						W	W	W		✓	✓	✓	✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Apiaceae	*Foeniculum vulgare**	Fennel	W			H				T	✓		✓	
Apiaceae	*Hydrocotyle peduncularis* O							T				✓	✓	
Apocynaceae	*Gomphocarpus fruticosus**	Cotton Bush	W					T	T			✓	✓	✓
Apocynaceae	*Parsonsia straminea*	Common Silkpod	T					T				✓	✓	✓
Araliaceae	*Astrotricha latifolia*	Broad-leaved Sneeze Bush										✓	✓	✓
Araliaceae	*Polyscias elegans*													✓
Araliaceae	*Polyscias sambucifolia*	Elderberry Panax	TB			E		T	T			✓	✓	✓
Asclepiadaceae	*Araujia sericifera**	White Moth Vine									✓		✓	✓
Asclepiadaceae	*Tylophora barbata*	Celery Wood	T					T	T			✓	✓	✓
Asteraceae	*Ambrosia tenuifolia**	Lacy Ragweed											✓	✓
Asteraceae	*Aster subulatus**		W				W			W	✓		✓	✓
Asteraceae	*Bidens pilosa**	Cobbler's Pegs	W TB			H		W	W		✓	✓	✓	✓
Asteraceae	*Calotis cuneifolia* O	Blue Burr-daisy	TB									✓	✓	✓
Asteraceae	*Calotis lappulacea* O	Yellow Burr-daisy						T				✓	✓	✓
Asteraceae	*Cassinia arcuata* O		TB					T				✓	✓	✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Asteraceae	*Chrysanthemoides monilifera* ssp. *monilifera**	Boneseed										✓	✓	✓
Asteraceae	*Cirsium vulgare**	Spear Thistle	W			H					✓	✓	✓	✓
Asteraceae	*Conyza bonariensis**	Flax-leaved Fleabane									✓	✓	✓	✓
Asteraceae	*Cyanthillium cinereum (Syn. Vernonia cinerea)**							T				✓	✓	✓
Asteraceae	*Euchiton gymnocephalus*	Cudweed											✓	
Asteraceae	*Gamochaeta coarctata**	Cudweed											✓	✓
Asteraceae	*Hypochaeris radicata**	Catsear	TB								✓	✓	✓	✓
Asteraceae	*Lactuca saligna**	Willow-leaved Lettuce												✓
Asteraceae	*Ozothamnus diosmifolius*	Dogwood	TB									✓	✓	✓
Asteraceae	*Senecio hispidulus*○							T					✓	✓
Asteraceae	*Senecio madagascariensis**	Fireweed	W TB									✓	✓	✓
Asteraceae	*Senecio pterophorus**	Chinese daisy											✓	

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Asteraceae	*Senecio quadridentatum*												✓	✓
Asteraceae	*Sigesbeckia orientalis*	Indian Weed												✓
Asteraceae	*Sonchus oleraceus**	Common Sow Thistle	W TB					W	W		✓	✓	✓	✓
Asteraceae	*Taraxacum officinale**	Dandelion									✓	✓	✓	
Asteraceae	*Vittadinia cuneata*	Fuzzweed											✓	✓
Asteraceae	*Vittadinia sp.*													✓
Bignoniaceae	*Jacaranda* sp.*	Jacaranda	B										✓	
Bignoniaceae	*Pandorea pandorana*	Wonga Wonga Vine	TB					T	T			✓	✓	✓
Boraginaceae	*Heliotropium amplexicaule**	Blue Heliotrope										✓	✓	
Brassicaceae	*Lepidium africanum**	Peppercress	B										✓	✓
Campanulaceae	*Wahlenbergia gracilis*	Native Bluebell						W	W			✓	✓	✓
Cannabaceae	*Trema tomentosa*	Native Peach												✓
Cassythaceae	*Cassytha glabella*	Slender Devil's Twine	T					T						✓
Cassythaceae	*Cassytha pubescens*	Devil's Twine	TB					T	T			✓	✓	✓
Casuarinaceae	*Allocasuarina littoralis*	Black She-oak										✓	✓	✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Casuarinaceae	*Allocasuarina torulosa*	Forest Oak	T					T				✓	✓	✓
Casuarinaceae	*Casuarina glauca*	Swamp Oak	W TB	✓	C	C		W	W	W	✓	✓	✓	✓
Celastraceae	*Cassine australis* O								T			✓	✓	✓
Celastraceae	*Maytenus silvestris* O			✓		E						✓	✓	✓
Chenopodiaceae	*Einadia hastata*		TB	✓								✓	✓	✓
Chenopodiaceae	*Einadia nutans* ssp. *linifolia* O										✓	✓	✓	✓
Chenopodiaceae	*Einadia nutans* ssp. *nutans* O												✓	✓
Chenopodiaceae	*Einadia trigonos* O			✓									✓	✓
Clusiaceae	*Hypericum gramineum*	Small St John's Wort						T	T			✓	✓	
Convolvulaceae	*Convolvulus erubescens* O	Bindweed		✓									✓	✓
Convolvulaceae	*Dichondra repens*	Kidney Weed	TB					T	T			✓	✓	✓
Convolvulaceae	*Polymeria calycina* O							T				✓	✓	✓
Dilleniaceae	*Hibbertia aspera*	Rough Guinea Flower	TB					T	T			✓	✓	✓
Dilleniaceae	*Hibbertia diffusa*											✓	✓	✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Droseraceae	*Drosera auriculata*	Sundew											✓	
Epacridaceae	*Astroloma humifusum*		T					T	T			✓	✓	✓
Epacridaceae	*Lissanthe strigosa*		T					T	T				✓	✓
Epacridaceae	*Leucopogon juniperinus* ○	Bearded Heath	TB			E		T	T			✓	✓	✓
Euphorbiaceae	*Euphorbia* sp.*									T				
Euphorbiaceae	*Homalanthus nutans* *Syn. Omalanthus populifolius*	Bleeding Heart	W										✓	✓
Fabaceae: Faboideae	*Bossiaea prostrata* ○								T			✓	✓	✓
Fabaceae: Faboideae	*Daviesia ulicifolia*	Gorse Bitter Pea	T					T	T			✓	✓	✓
Fabaceae: Faboideae	*Desmodium varians*		T	✓								✓	✓	✓
Fabaceae: Faboideae	*Dillwynia sieberi*	Prickly Parrot Pea										✓	✓	✓
Fabaceae: Faboideae	*Glycine clandestina*	Love Creeper	TB					T	T		✓	✓	✓	✓
Fabaceae: Faboideae	*Glycine microphylla* ○											✓	✓	✓
Fabaceae: Faboideae	*Glycine tabacina*	Love Creeper	T					T				✓	✓	✓
Fabaceae: Faboideae	*Gompholobium minus*	Wedge-pea						T				✓	✓	✓
Fabaceae: Faboideae	*Hardenbergia*	False Sarsparilla	W			H		T	T	T		✓	✓	✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
	violacea		T											
Fabaceae: Faboideae	*Hovea linearis*											✓	✓	✓
Fabaceae: Faboideae	*Hovea longifolia*		T					T	T				✓	✓
Fabaceae: Faboideae	*Indigofera australis*								T				✓	✓
Fabaceae: Faboideae	*Kennedia rubicunda*	Dusky Coral Pea	W TB			H		T	T			✓	✓	✓
Fabaceae: Faboideae	*Lotus angustissima**		W					W	W				✓	✓
Fabaceae: Faboideae	*Melilotus indicus**		W							WT	✓		✓	✓
Fabaceae: Faboideae	*Platylobium formosum* ○		T					T	T			✓	✓	✓
Fabaceae: Faboideae	*Podolobium ilicifolium* *Syn. Oxylobium ilicifolium*	Native Holly	TB					T	T			✓	✓	✓
Fabaceae: Faboideae	*Pultenaea villosa*							T	T			✓	✓	✓
Fabaceae: Faboideae	*Vicia sativa**	Vetch	W B					W	W		✓	✓	✓	✓
Fabaceae: Faboideae	*Zornia dyctiocarpa* ○			✓								✓	✓	✓
Fabaceae: Mimosoideae	*Acacia binervia*	Coast Myall											✓	✓
Fabaceae: Mimosoideae	*Acacia decurrens*	Green Wattle	TB					T				✓	✓	✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Fabaceae: Mimosoideae	*Acacia falcata*	Sickle-leaved Wattle	TB			H		T	T			✓	✓	✓
Fabaceae: Mimosoideae	*Acacia falciformis* O	Broad-leaved Hickory		✓									✓	✓
Fabaceae: Mimosoideae	*Acacia fimbriata* O	Fringed Wattle										✓	✓	✓
Fabaceae: Mimosoideae	*Acacia floribunda*	Sally Wattle											✓	✓
Fabaceae: Mimosoideae	*Acacia longifolia* var. *longifolia*	Sydney Golden Wattle	W TB			CEH		T	T			✓	✓	✓
Fabaceae: Mimosoideae	*Acacia mearnsii*	Black Wattle										✓	✓	
Fabaceae: Mimosoideae	*Acacia myrtifolia* O	Myrtle Wattle	T					T	T			✓	✓	✓
Fabaceae: Mimosoideae	*Acacia paradoxa* O	Kangaroo Thorn	B	✓								✓	✓	
Fabaceae: Mimosoideae	*Acacia parramattensis*	Parramatta Green Wattle	W TB			EH		T	T			✓	✓	✓
Fabaceae: Mimosoideae	*Acacia stricta* O							T	T			✓	✓	✓
Fabaceae: Mimosoideae	*Acacia suaveolens*	Sweet Wattle	TB			H			T				✓	✓
Fabaceae: Mimosoideae	*Acacia ulicifolia*	Prickly Moses	TB			H		T				✓	✓	✓
Fagaceae	*Quercus* sp.*	Oak	B										✓	✓
Gentianaceae	*Centaurium erythraea**	Common Centaury						W	W		✓	✓	✓	
Gentianaceae	*Centaurium tenuiflorum**										✓	✓	✓	✓
Geraniaceae	*Pelargonium*													✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
	inodorum													
Goodeniaceae	*Goodenia hederacea*	Ivy Goodenia	T					T	T			✓	✓	✓
Goodeniaceae	*Goodenia ovata*	Goodenia									✓		✓	✓
Goodeniaceae	*Goodenia paniculata*	Goodenia						T					✓	
Haloragaceae	*Gonocarpus tetragynus*							T	T			✓	✓	✓
Lauraceae	*Cinnamomum camphora**	Camphor Laurel	W			E					✓	✓	✓	✓
Linaceae	*Linum marginale* ○	Native Flax										✓	✓	✓
Linaceae	*Linum trigynum**	French Flax										✓	✓	✓
Lobeliaceae	*Lobelia dentata*												✓	
Lobeliaceae	*Pratia purpurascens*	White Root	TB					T	T			✓	✓	✓
Loganiaceae	*Logania albiflora*			✓								✓	✓	✓
Loranthaceae	*Muellerina eucalyptoides*												✓	✓
Malvaceae	*Modiola caroliniana**	Red-flowered Mallow												✓
Malvaceae	*Sida rhombifolia**	Paddy's Lucerne	W T								✓	✓	✓	✓
Menispermaceae	*Sarcopetalum harveyanum* ○		T					T	T			✓	✓	✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Moraceae	*Ficus macrophylla**	Moreton Bay Fig	B			H							✓	✓
Moraceae	*Ficus rubiginosa*	Port Jackson Fig				M							✓	✓
Myoporaceae	*Eremophila debilis* ○	Winter Apple	T	✓				W	W			✓	✓	✓
Myoporaceae	*Myoporum boninense* ○			✓								✓	✓	✓
Myrtaceae	*Backhousia myrtifolia*	Grey Myrtle											✓	✓
Myrtaceae	*Callistemon salignus*	Willow Bottlebrush												✓
Myrtaceae	*Callistemon viminalis**	Weeping Bottlebrush											✓	✓
Myrtaceae	*Corymbia gummifera*	Red Bloodwood	T					T	T			✓	✓	✓
Myrtaceae	*Eucalyptus acmenoides* ○	White Mahogany										✓	✓	✓
Myrtaceae	*Eucalyptus fibrosa* ssp. *Fibrosa*	Broad-leaved Ironbark	TB			E		T	T			✓	✓	✓
Myrtaceae	*Eucalyptus globoidea* ○	White Stringybark	TB			E		T	T			✓	✓	✓
Myrtaceae	*Eucalyptus haemastoma* ○	Scribbly Gum	TB			E		T	T			✓		
Myrtaceae	*Eucalyptus longifolia*	Woollybutt	TB			E		T	T			✓	✓	✓
Myrtaceae	*Eucalyptus microcorys**	Tallowwood												✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Myrtaceae	*Eucalyptus moluccana*	Grey Box						T				✓	✓	✓
Myrtaceae	*Eucalyptus paniculata* ○	Grey Ironbark	TB			E		T	T			✓	✓	✓
Myrtaceae	*Eucalyptus pilularis* ○	Blackbutt	T			E		T	T			✓	✓	✓
Myrtaceae	*Eucalyptus punctata*	Grey Gum	TB			E		T	T			✓	✓	✓
Myrtaceae	*Eucalyptus racemosa*	Hard-leafed Scribbly Gum											✓	✓
Myrtaceae	*Eucalyptus resinifera* ssp. *resinifera*	Red Mahogany	TB			E		T	T			✓	✓	✓
Myrtaceae	*Kunzea ambigua*	White Tick Bush	WT			E		T	T			✓	✓	✓
Myrtaceae	*Melaleuca decora*	Honeymyrtle	WB									✓	✓	✓
Myrtaceae	*Melaleuca nodosa*	Ball Honeymyrtle	T					T	T			✓	✓	✓
Myrtaceae	*Melaleuca quinquinervia**	Broad-leaved Paperbark	B										✓	✓
Myrtaceae	*Syncarpia glomulifera*	Turpentine	TB			E		T	T			✓	✓	✓
Ochnaceae	*Ochna serrulata**	Mickey Mouse Plant										✓	✓	✓
Oleaceae	*Ligustrum lucidum**	Large-leaved Privet				C					✓	✓	✓	✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Oleaceae	*Ligustrum sinense**	Small-leaved Privet	W								✓		✓	
Oleaceae	*Notelaea longifolia*	Mock Olive	T			E		T	T			✓	✓	✓
Oleaceae	*Olea europaea* ssp. *africana**	African Olive	B								✓	✓	✓	✓
Onagraceae	*Epilobium* sp.										✓		✓	✓
Oxalidaceae	*Oxalis corniculata**	Creeping Oxalis	W TB					T	T			✓	✓	
Oxalidaceae	*Oxalis perennans* ○											✓	✓	✓
Passifloraceae	*Passiflora herbertiana*	Native Passionfruit												✓
Passifloraceae	*Passiflora suberosa**	Cork Passionflower										✓	✓	✓
Phyllanthaceae	*Breynia oblongifolia*	Breynia	TB					T	T			✓	✓	✓
Phyllanthaceae	*Glochidion ferdinandi var ferdinandi*	Cheese Tree										✓	✓	✓
Phyllanthaceae	*Phyllanthus gunnii*	Scrubby Spurge	TB					T	T			✓	✓	✓
Phyllanthaceae	*Phyllanthus hirtellus*	Thyme Spurge	T					T	T			✓	✓	✓
Phyllanthaceae	*Phyllanthus virgatus*													✓
Phyllanthaceae	*Poranthera microphylla*							T	T			✓	✓	✓
Phytolaccaceae	*Phytolacca octandra*	Inkweed												✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Pittosporaceae	*Billardiera scandens*	Apple-berry	TB					T	T			✓	✓	✓
Pittosporaceae	*Bursaria spinosa*	Blackthorn							T				✓	
Pittosporaceae	*Pittosporum multiflorum*	Orange Thorn											✓	✓
Pittosporaceae	*Pittosporum revolutum*	Rough-fruited Pittosporum	T					T	T			✓	✓	✓
Pittosporaceae	*Pittosporum undulatum*	Sweet Pittosporum	W TB			CE		T	T			✓	✓	✓
Plantaginaceae	*Plantago lanceolata**	Plantain	W TB							T	✓	✓	✓	✓
Polygonaceae	*Rumex brownii* ○	Mud Dock	B									✓	✓	✓
Primulaceae	*Lysimachia arvensis**	Pimpernel								T	✓	✓	✓	✓
Primulaceae	*Myrsine variabilis (syn. Rapanea variabilis)*	Muttonwood	TB			E		T	T			✓	✓	✓
Proteaceae	*Hakea dactyloides*	Finger Hakea											✓	
Proteaceae	*Hakea* aff. *propinqua*												✓	✓
Proteaceae	*Hakea sericea*	Bushy Needlebush	T									✓	✓	✓
Proteaceae	*Persoonia levis*	Broad-leaved Geebung										✓	✓	✓
Proteaceae	*Persoonia linearis*	Narrow-leaved										✓	✓	✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
		Geebung												
Proteaceae	*Persoonia pinifolia* ○	Pine-leaved Geebung		✓								✓	✓	✓
Ranunculaceae	*Clematis aristata*	Old Man's Beard	TB					T	T			✓	✓	✓
Ranunculaceae	*Clematis glycinoides*	Forest Clematis	T					T	T			✓	✓	✓
Rhamnaceae	*Pomaderris discolor*	Pomaderris											✓	✓
Rhamnaceae	*Pomaderris ferruginea* ○	Rusty Pomaderris	T			E		T	T			✓	✓	✓
Rhamnaceae	*Pomaderris lanigera* ○	Woolly Pomaderris	T			E			T				✓	✓
Rosaceae	*Prunus persica**	Peach												✓
Rosaceae	*Rubus fruticosus**	Blackberry	T			C							✓	
Rosaceae	*Rubus parvifolius*	Native Raspberry											✓	✓
Rubiaceae	*Opercularia aspera*							T				✓	✓	✓
Rubiaceae	*Opercularia diphylla*							T				✓	✓	✓
Rubiaceae	*Opercularia hispida* ○											✓	✓	✓
Rubiaceae	*Opercularia varia*		T					T	T				✓	✓
Rubiaceae	*Pomax umbellata*	Pomax	TB					T	T			✓	✓	✓
Rubiaceae	*Richardia stellaris**											✓	✓	✓
Rubiaceae	*Sherardia arvensis**							W	W				✓	

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Rutaceae	*Boronia polygalifolia* ○	Milkwort Boronia		✓								✓	✓	✓
Rutaceae	*Correa reflexa*												✓	
Rutaceae	*Zieria smithii*	Sandfly Zieria	TB			E		T	T			✓	✓	✓
Santalaceae	*Exocarpos cupressiformis*	Cherry Ballart	TB					T	T			✓	✓	✓
Sapindaceae	*Cupaniopsis anacardioides* ○	Tuckeroo (seedlings)										✓	✓	✓
Sapindaceae	*Dodonaea triquetra*	Common Hop Bush	W TB			E		T	T			✓	✓	✓
Scrophulariaceae	*Veronica plebeia*	Trailing Speedwell	T					T	T			✓	✓	✓
Solanaceae	*Nicandra physalodes**	Apple-of-Peru												✓
Solanaceae	*Solanum aviculare*	Kangaroo Apple												✓
Solanaceae	*Solanum nigrum**	Black Nightshade	W TB									✓	✓	✓
Solanaceae	*Solanum prinophyllum*	Forest Nightshade		✓								✓	✓	✓
Solanaceae	*Solanum sisymbriifolium**											✓	✓	✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Stackhousiaceae	*Stackhousia viminea*							T				✓	✓	✓
Sterculiaceae	*Brachychiton acerifolius **	Flame Tree										✓	✓	
Sterculiaceae	*Brachychiton populneus* ○	Kurrajong	T			E		T	T			✓	✓	✓
Sterculiaceae	*Lasiopetalum parviflorum* ○	Rusty Petals	TB					T	T			✓	✓	✓
Verbenaceae	*Clerodendron tomentosum*	Hairy Clerodendrum	TB			E		T	T			✓	✓	✓
Verbenaceae	*Lantana camara**	Lantana	W TB			MC EH		W				✓	✓	✓
Verbenaceae	*Verbena bonariensis**	Purple Top				H					✓	✓	✓	✓
Vitaceae	*Cayratia clematidea*	Slender Grape	W					WT	T			✓	✓	✓
MONOCOTYLEDONS														
Alliaceae	*Nothoscordum borbonicum** *(N. gracile*)*	Onion Weed									✓		✓	✓
Anthericaceae	*Arthropodium milleflorum* ○	Pale Vanilla Lily											✓	✓
Anthericaceae	*Laxmannia gracilis*							T	T			✓	✓	✓
Araceae	*Livistona australis* ○	Cabbage Palm										✓	✓	✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Araceae	*Phoenix canariensis* *	Canary Island Date Palm										✓	✓	✓
Asparagaceae	*Asparagus aethiopicus**	Asparagus Fern	T									✓	✓	✓
Commelinaceae	*Commelina cyanea*													✓
Cyperaceae	*Carex inversa*												✓	✓
Cyperaceae	*Cyathochaeta diandra*							T	T			✓	✓	✓
Cyperaceae	*Cyperus polystachyos* ○	Sedge									✓		✓	✓
Cyperaceae	*Gahnia aspera*	Saw Sedge											✓	✓
Cyperaceae	*Lepidosperma laterale*	Sword-sedge	TB					T	T			✓	✓	✓
Cyperaceae	*Schoenus apogon*							T	WT				✓	✓
Iridaceae	*Crocosmia X crocosmiiflora**	Montbretia									✓		✓	✓
Juncaceae	*Juncus polyanthemos*												✓	✓
Lomandraceae	*Lomandra filiformis* ssp. *filiformis*											✓	✓	✓
Lomandraceae	*Lomandra glauca*	Mat Rush							T			✓	✓	✓
Lomandraceae	*Lomandra longifolia*	Spiny-headed Mat	TB			E		T	T			✓	✓	✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
		Rush												
Lomandraceae	*Lomandra multiflora*	Many-flowered Mat-rush										✓	✓	✓
Luzuriagaceae (Philesiaceae)	*Eustrephus latifolius*	Wombat Berry	T					T	T			✓	✓	✓
Orchidaceae	*Caladenia carnea*	Pink Fingers											✓	
Orchidaceae	*Caladenia catenata*	White Fingers											✓	✓
Orchidaceae	*Calochilus campestris*	Copper Beard Orchid						T	T			✓	✓	✓
Orchidaceae	*Calochilus gracillimus*	Late Beard Orchid												✓
Orchidaceae	*Dipodium variegatum*	Hyacinth Orchid											✓	✓
Orchidaceae	*Microtis* sp.							T				✓	✓	✓
Orchidaceae	*Orthoceras strictum*	Horned Orchid											✓	
Orchidaceae	*Pterostylis concinna*	Trim Greenhood											✓	✓
Orchidaceae	*Thelymitra carnea*	Pink Sun Orchid											✓	
Orchidaceae	*Thelymitra pauciflora*	Slender Sun Orchid											✓	✓
Phormiaceae	*Dianella brevicaulis**												✓	✓
Phormiaceae	*Dianella caerulea var product*	Blue Flax Lily	T					T	T			✓	✓	✓
Phormiaceae	*Dianella longifolia*	Blue Flax Lily	T					T					✓	✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Phormiaceae	*Dianella revoluta*	Blue Flax Lily						T				✓	✓	✓
Poaceae	*Andropogon virginicus**	Whisky Grass	TB								✓	✓	✓	✓
Poaceae	*Aristida ramosa*	Purple Wiregrass	TB					T	T			✓	✓	✓
Poaceae	*Aristida vagans*	Three-awned Spear Grass	TB					T	T			✓	✓	✓
Poaceae	*Aristida warburgii*							T	T					✓
Poaceae	*Austrodanthonia bipartita* O	Wallaby Grass Syn: *Danthonia linkii*	B					T				✓	✓	✓
Poaceae	*Austrodanthonia pilosa*												✓	✓
Poaceae	*Austrodanthonia setacea*												✓	✓
Poaceae	*Austrodanthonia tenuior*	Wallaby Grass	TB					T				✓	✓	✓
Poaceae	*Austrostipa pubescens*	Spear Grass	T					T	T			✓	✓	✓
Poaceae	*Austrostipa rudis ssp. rudis*	Spear Grass											✓	✓
Poaceae	*Austrostipa ramosissima*	Spear Grass	T					T	T			✓	✓	✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Poaceae	*Austrostipa scabra ssp. falcata*												✓	✓
Poaceae	*Avena* sp.*	Wild Oats									✓	✓	✓	✓
Poaceae	*Axonopus affinis**	Carpet Grass	TB			H						✓	✓	✓
Poaceae	*Bothriochloa macra* ○	Redleg Grass	W TB	✓								✓	✓	✓
Poaceae	*Briza maxima**	Quaking Grass		✓						W	✓	✓	✓	✓
Poaceae	*Briza minor**	Shivery Grass						W	W		✓		✓	✓
Poaceae	*Briza subaristata**	Shivery Grass	B								✓	✓	✓	✓
Poaceae	*Bromus catharticus**	Prairie Grass								T	✓	✓	✓	✓
Poaceae	*Capillipedium parviflorum*	Scented-top Grass											✓	✓
Poaceae	*Chloris gayana**	Rhodes Grass	B								✓		✓	✓
Poaceae	*Chloris ventricosa*	Windmill Grass												✓
Poaceae	*Cymbopogon refractus*	Barbed Wire Grass	TB					T				✓	✓	✓
Poaceae	*Cynodon dactylon**	Couch	W TB			SH		T		WT	✓	✓	✓	✓
Poaceae	*Dichelachne micrantha*	Shorthair Plume Grass	TB								✓	✓	✓	✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Poaceae	*Digitaria ciliaris**	Summer Grass												✓
Poaceae	*Digitaria diffusa*	Open Summer Grass												✓
Poaceae	*Digitaria ramularis*													✓
Poaceae	*Echinopogon caespitosus*	Hedgehog Grass	TB					T	T			✓	✓	✓
Poaceae	*Ehrharta erecta**	Panic Veldt Grass	B									✓	✓	✓
Poaceae	*Ehrharta longifolia**	Annual Veldtgrass												✓
Poaceae	*Elymus scaber* O *Syn. Agropyron scabrum*									T		✓	✓	✓
Poaceae	*Entolasia marginata*	Bordered Panic	T					T				✓	✓	✓
Poaceae	*Entolasia stricta*	Wiry Panic	TB					T	T			✓	✓	✓
Poaceae	*Eragrostis benthamii* O	Lovegrass	T					T					✓	✓
Poaceae	*Eragrostis brownii*	Brown's Lovegrass	T					T	T				✓	✓
Poaceae	*Eragrostis curvula**	African Lovegrass		✓								✓	✓	✓
Poaceae	*Eragrostis leptostachya*	Lovegrass						T				✓	✓	✓
Poaceae	*Eriochloa pseudoacrotricha*	Early Spring Grass												✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Poaceae	*Festuca elatior**	Tall Fescue		✓							✓		✓	✓
Poaceae	*Imperata cylindrica* var *major*	Blady Grass	T					T	T			✓	✓	✓
Poaceae	*Lachnagrostis filliformis* *Syn. Agrostis avenacea*	Blown Grass									✓	✓	✓	✓
Poaceae	*Melinis repens**	Red Natal Grass	B	✓									✓	✓
Poaceae	*Microlaena stipoides* var. *stipoides*	Weeping Meadow Grass	TB					T	T			✓	✓	✓
Poaceae	*Oplismenus aemulus*	Basket Grass	T										✓	✓
Poaceae	*Oplismenus imbecillis*	Basket Grass											✓	✓
Poaceae	*Panicum pygmaeum*	Pygmy Panic												✓
Poaceae	*Panicum simile*	Two Colour Panic	T					T	T			✓	✓	✓
Poaceae	*Paspalidium criniforme* ○												✓	✓
Poaceae	*Paspalidium distans*	Paspalidium	TB									✓	✓	✓
Poaceae	*Paspalum dilatatum**	Paspalum	W TB								✓	✓	✓	✓
Poaceae	*Pennisetum clandestinum**	Kikuyu	W TB			SEH G					✓	✓	✓	✓

FAMILY	SPECIES	COMMON NAME	1	2	3	4	4a	4b	4c	4d	5	6	7	8
Poaceae	*Poa labillardieri* ○	Tussock Grass						T					✓	
Poaceae	*Setaria gracilis**	Slender Pigeon Grass	W TB								✓	✓	✓	✓
Poaceae	*Themeda australis*	Kangaroo Grass	TB			E		T	T			✓	✓	✓
Smilacaceae	*Smilax australis*	Native Sarsaparilla						T	T				✓	
Smilacaceae	*Smilax glyciphylla*	Sarsaparilla										✓	✓	✓

Best practice management and wise use of the wetlands at Sydney Olympic Park

Swapan Paul
Sydney Olympic Park Authority

Sydney Olympic Park is home for the largest cluster of estuarine wetlands in the Sydney Harbour system. These wetlands are now the jewel in the crown of the Parramatta River estuary, thanks to the reconstruction and restoration tasks undertaken over the past three decades. Leading to the Sydney 2000 Olympics, the then degraded and putrid wetlands were thoroughly restored. In addition, many new wetlands were constructed and some half-functioning wetlands were re-constructed. The monetary and other investments have been returning the dividends by a long way, as these wetlands now host high abundance and diversity of waterbirds and migratory shore birds, act as the sponge or kidney of the estuarine system by filtering much of the stormwater before it enters the River, play a pivotal role in the ongoing wetland education and tour program, a handy research site for academia, and most importantly, a magnificent cluster of functioning wetlands that not only thrive well but also act as model wetlands for others to manage theirs. The most useful aspect of the Authority's experience in managing these estuarine wetlands has been the ability to 'balance' the challenging management of the wetlands on the face of ever-increasing pressure from urbanisation, visitation, climate change and sea level rise. This presentation will highlight some of the values, vulnerability and volatility in managing estuarine wetlands at this site.

Introduction

Sydney Olympic Park (S 33° 50' 56.0872", E 151° 4' 3.7884") is situated in the greater Homebush Bay area and it is bounded by Homebush Bay itself on the eastern side, the Parramatta River on the north, the M4 Motorway on the west and Homebush Bay Drive on the south-east (Figure 1). It contains the largest coverage of wetlands in the Sydney Harbour-Parramatta River system. These wetlands are so invaluable that they are considered as the jewel in the crown of the Parramatta River system. These wetlands are listed on the national Directory of Important Wetlands in Australia as regionally significant (CoA 2020a).

The current diversity, extent and functionalities of these wetlands used to be quite different in the recent past (prior to the Sydney 2000 Olympics) and even in the longer past (prior to the establishment of the industrial estates in the mid-nineties) (OCA 1995). The presently existing wetlands are a heritage of the pre-European settlement, a legacy of the European settlement and a gift of the recent development activities particularly the Sydney 2000 Olympics. The transformations, modifications, moderations, rehabilitation, restoration and/or rejuvenation – every single episode have had made significant contributions towards what they are today: the make up of the collective presence, look, feel, functions, services, values, contributions and existence. Apart from their biodiversity and nature-serving functions these wetlands have been celebrated by Sydney-siders and beyond as places of connectivity, spirituality, culture, tradition, recreation, trade, commerce, science, education, research, refuge and many more. The extent of estuarine wetlands include Swamp Oak Floodplain Forest (8.64ha), coastal saltmarsh (28.5ha), mudflat (4.31ha), mangrove (69.56ha), estuarine lagoon (13.55) and estuarine creek (16.19ha). The Park does not have any substantial coverage of seagrass, except the presence of a few remnant plants in the NNR Wetland. Together, the estuarine wetlands makeup a total of approximately 140.75ha in the 205.0ha total wetlands in the Park. Figure 2 shows the diversity and spread of these wetland ecosystems. The ecological zonation of the estuarine ecosystems are in the same order of sequence mentioned earlier; with the estuarine creek at the lower-most elevation. The sheer diversity of these many ecosystems and the kind of ecotones that connect them are a rare occurrence in such a highly urban city.

Pre-Olympic Coverage and Conditions

There had been many wetlands in the area even prior to the Sydney 2000 Olympics. Figure 3 shows major transformational changes that the wetlands have had undergone over the millennia. These are also depicted sequentially listed in Tables 1 & 2.

The major activities that are listed in Table 1 and Table 2 have altered the physical character of the entire Homebush Bay area to such an extent that in most cases the landscape attributes are almost unrecognisable. Most noticeable changes meant a number of remarkable alternations and modifications, however, with a view to improving the functional and economic activities on the area. Some of the changes are listed below.

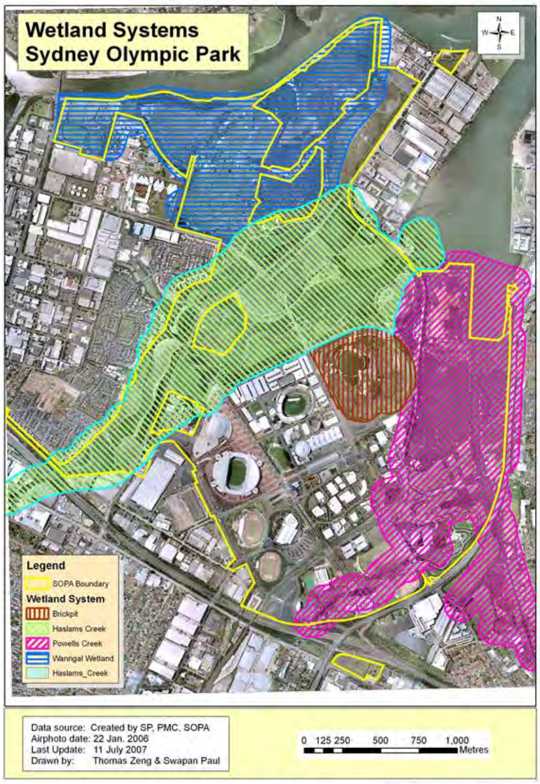

Figure 1. Estuarine Wetland Systems in Sydney Olympic Park

Figure 2. Spatial Distribution of Estuarine Wetlands.

- Massive pollution of the water, mudflats and sediment (OCA 1995);
- Up to 70% of the estuarine habitats, particularly coastal saltmarsh, were lost to development through land reclamation (Saintilan and Williams 2000);
- Fragmentation of ecosystems and habitats (OCA 1995);
- Displacement of fauna and flora (O'Meara and Darcovich 2014);
- Loss of biodiversity (Straw 2013);
- Introduction of pest and weed species, especially Mosquito Fish (*Gambusia* sp) (O'Meara and Darcovich 2014);
- Sedimentation and infilling of the natural water courses (McLoughlin 2000); and
- Obvious hardening of natural landscapes and alterations of the natural water courses.

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Table 1. Homebush Bay area Major Development Activities since 1788*

[Based primarily on literature review, other publications and examinations of aerial photos as well as site knowledge].

Period	Major events, structures and activities that have influenced mangrove, saltmarsh and other estuarine ecosystems within the greater Homebush Bay area
1788-1800s	No major activities other than traditional farming
	Initial Settlement Period
1810-1907	Homebush Estate formed and operated
1807-1860	Newington Estate formed and operated
1882-1996	RANAD (Royal Australian Naval Armament Depot (RANAD) established and operated.
1891-1960	Seawall construction in filling. This also involved conversion of the once mudflats and saltmarsh in to unexploded ordinance disposal site, which is now the Newington Nature Reserve Wetland
1907-1988	State Abattoirs operated, which used to discharge waste directly in to watercourse
1911-1988	State Brickpit operated, which required using Haslams Creek for transportation
1900-1930	Jetties formed and operated
1930-1940	Straightening of Powells Creek for stormwater discharge and sediment removals
1950-1970	Newington area landfilling for warehouse and Naval facilities
1960-1980	Landfilling of Bicentennial Park for waste disposal on waterways
	Industrial Era
1939-1970	Industrial establishments on Rhodes Peninsula and nearby areas and disposal of wastes in to the Bay
1950-1970	Reclamation of Wentworth Bay and banks of Haslams Creek through massive modifications
1919-1988	Industrial operations and chemical industries on Rhodes Peninsula, including discharge of toxic waste
1983-1988	Construction and establishment of Bicentennial Park as an environmental education facility
1995-1996	Various sporting venues were constructed
1988-today	Lidcombe Liquid Treatment Plant established and operated
1995-1998	Royal Ester Showground moved from Moore Park to the area, requiring hardening of the land surface
	Olympic Era
1995-2001	OCA formed and operated to stage the Sydney 2000 Olympics
1995-2000	OCA has undertook major clean-up and rehabilitation works, including wetland restoration and creation
	Post-Olympic Developments
2010-2012	Dioxin Clean-up from Homebush Bay bottom
2015-2016	Wentworth Bridge constructed over Homebush Bay and official opening on 22 May 2016
2000-today	Development for the Sydney 2000 Olympics and subsequently residential and commercial developments in the Olympic Peninsula and Sydney Olympic Park and Carter Street Precinct,

- Re-created after Cooper (2003) and based on site knowledge.

Table 2. Badu Mangrove Major Changes since 1930.
[Based primarily on examinations of aerial photos available from 1930 and site knowledge].

Year of Aerial Photo	Major events, structures and activities that have influenced mangrove, saltmarsh and other estuarine ecosystems within Powells Creek System
1930	Tramline present, which used to carry bricks from the Brickpit to the City of Sydney. Very small coverage of mangroves in the south; Bennelong Pond had no mangroves
1942	Some new stormwater channels visible; Powells Ck was still had its natural course
1943	Powells Ck straightened by excavations and a main drainage channel formed inside the present Badu Mangrove area. Excavated materials placed in Badu Mangrove area
1951	Mangrove colonising and area expanding to the north towards Badu Saltmarsh
1955	Mangrove areas further expanding slowly
1961	New bunds everywhere; WBR, Badu west & east showing bunds. Pipes that were used for transferring sediment by dredging Homebush Bay has been visible, laid from Homebush Bay to the flats in Badu Saltmarsh. Mangroves expanding and colonising in Bennelong Pond
1970	Badu Mangrove disconnected from Bicentennial Park by east-west pathway. East-west pathway visible from 1965) D onwards and dredging ceased possibly after 1961. Mangroves expanding; more in Bennelong Pond; massive dieback in the former course of Powells Creek, which is now Billabong
1978	Bennelong Parkway formed but with dirt; possibly from the Brickpit operations. Lots of mangroves expanding in Badu but also dieback in the area in front of the Education Centre; other areas were also struggling but expanding in Bennelong Pond. Park's workshop and compound area still not built.
1982	Colour photos available and 2SM Radio Tower in Badu Saltmarsh being built. Mangroves slowly recovering from dieback across the site but new dieback in Bennelong Pond
1986	More fill materials in the present Forebay Area in Bennelong Pond and further dieback in Bennelong Pond as the BiPark compound being built by infilling
1993	Boardwalk visible in the mangrove
1995	Mangroves closing in the ponded area left of the Tower; rest of mangroves looking ok and Forebay area colonised with Typha
2000	Mangroves in Badu east, west edge of Badu west and the area west of middle bund look poor; mangroves in Bennelong Pond sprouting and flourishing. Newly constructed channels in Badu west visible in the south-west corner and the Mangrove Classroom built in 1998 is also visible
2010	West of middle bund doing very well; isolated dieback areas recovering; Badu east showing some recovery and WBR looking better due to the automated SlipGate installed in 2006
2012	Ares closer to Benn Parkway, around the Boardwalk alignment and Badu east looking poor; area west of middle bund looking improved; Benn Pond trees looking ok; another pocket of small dieback on Badu east, perhaps from lightening
2014	Extensive area of new dieback at the upper end of Badu west; Benn Pond trees look stressed; Badu east looks poorer
2015	Parkview Precinct on the upper catchment has been developed and stormwater management system altered, that overflow through mangroves downstream
2016	Section of Badu Pathway and the bridge were raised by 600mm to avoid periodic tidal inundations due to the rising sea level
2017	A sedimentation basin was constructed inside Bennelong Pond to intercept sediment flowing from Parkview Precinct.
2020	A bypass channel was constructed in Badu Mangrove to alleviate the dieback that was caused in 2014

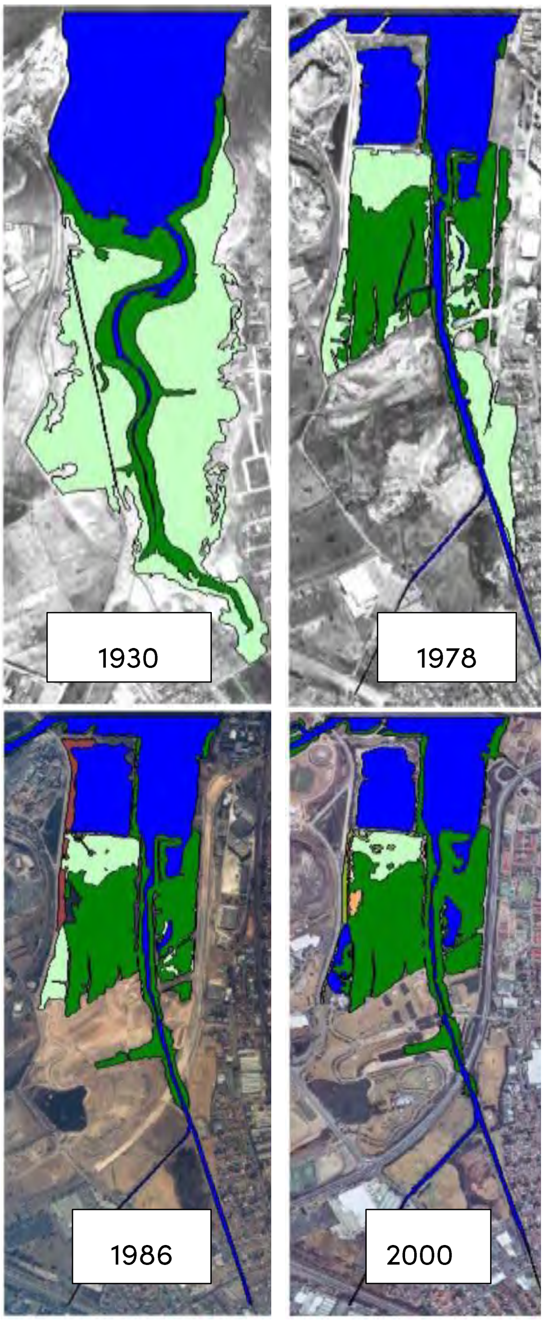

Figure 3. Noticeable changes in portion of Homebush Bay area (after Rogers 2004)

Figure 4. Major changes in the condition of the area that is now Newington Nature Reserve Wetland

Despite those changes some habitats and biodiversity thrived in the area due to the sheer resilience and natural ability to re-bounce. The ecological surveys that were undertaken immediately prior to the Sydney 2000 Olympics provides a comprehensive picture of the state of the ecology of Homebush Bay area (OCA 1995). Thanks to the Sydney 2000 Olympics that happened to be the single largest development activities in Australia in recent memory, which has also made remarkable contributions to the protection and conservation of wetlands, particularly estuarine wetlands, in the Homebush Bay area and Sydney Olympic Park. It can be claimed that if the Sydney 2000 Olympics did not take place and the size of the development activities were not undertaken, perhaps the degraded and derelict wetlands would have still remained a liability to the Sydney-siders and the nation as a whole. Some of these are illustrated below.

Wetland Reconstruction and Rehabilitation Efforts Leading to the Olympics

The most remarkable of all reconstruction activities that were undertaken leading to the Sydney 2000 Olympics (apart from the sporting venues and facilities) were the remediation of the heavily polluted site and reconstruction of the area. The remediation of past domestic, commercial and industrial waste sites at Sydney Olympic Park was the largest project of its kind in Australia and is one of the most significant environmental legacies of the Sydney 2000 Olympic and Paralympic Games. Approximately 160-hectares of the site was identified as containing wastes including power station ash, demolition rubble, asbestos, industrial hydrocarbons, domestic garbage, and dredging material from the Parramatta River. Between 1992 and 2000, the NSW Government spent $137 million for remedial action to clean up polluted areas (Pym 2001). The remediation policy at the time was to safely contain and where possible treat, waste on site, rather than relocating it to other places. Remedial action varied according to the type and location of the waste and local hydrological and soil conditions, and included the recovery, consolidation and containment of about 9.0 million cubic metres of waste. Approximately 400 tonnes of soil contaminated with hydrocarbons and classified under environmental legislation as 'scheduled chemical waste' was treated in a two-stage thermal desorption process. The majority of the buried waste was removed and relocated to designated waste containment mounds. These areas were capped, landscaped and turned into parkland. Leachate collection and transfer systems were built to prevent leachate from escaping into the environment.

Since every single one of the main waste dumping sites (landfills) and industrial polluted sites were in or near the waterways, which were developed by infilling former estuarine wetlands, as well by discharging polluted waste into watercourse, the largest beneficiary of the pollution containment and remediation was the ground water and the waterways by intercepting leachate from seeping in to wetlands and waterways. Below are brief examples of presently functioning wetlands that came about from repair, new creations, restoration, rehabilitation and or modification from the development works related to the Sydney 2000 Olympics.

a. Newington Nature Reserve (NNR) Wetland and River Walk

This wetland was reconnected to the adjacent Parramatta River after over 150 years of separation (Table 1). The new connectivity was established in 1997 and 2001 through construction of drainage and tidal flushing corridors (Figure 4). This has augmented drainage of the once stagnant water and facilitated tidal exchange. Because of the sudden drainage of the once stagnant water through the new corridors; those caused some abrupt changes in the wetland in the forms of acid sulfate release, stress on Swamp Oak Floodplain Forest (SOFF), change in the texture of the mud in the extensive mudflats that used to be heavily used as feeding grounds by migratory shorebirds, rapid expansion of coastal saltmarsh, salinity loss by the planted saltwater tolerant rare and threatened species on the upper marsh in the nursery area and stress on mangroves. Over time, those ecosystems have been undergoing fast adaptations and slowly but surely turning in to significantly beneficial habitats.

Also, the Riverwalk and the Sea Wall linear corridor was progressively restored by protecting the eroding sections of the river bank mainly due to the running of the River Cat ferry service.

b. Wilson Park and Kronos Hill remediation

These areas were two of the most polluted in the entire Homebush Bay area. These required most innovative and difficult remediation ever undertaken in Australia. In fact, it is perhaps the first attempt of remediation in the world by applying this technique. The toxic hydrocarbon, specifically tar (a polycyclic aromatic hydrocarbon compound), was buried underground from the gas conversion works in the early nineties. Tar would otherwise leach into Parramatta River and pollute the entire downstream-upstream course of the tidal river. A remediation technique was innovated, which involved containing the tar-contaminated leachate and then pumping to a mat populated with a specific type of bacteria. These bacteria would then breakdown the tar in to water and carbondioxide gas. As a result the river was no longer receiving polluted seep containing tar. Similarly, previously contaminated lands along Haslams Creek, particularly in Kronos Hill area, were contained, upgraded and landfills created. Together, these are now saving the estuarine waterways from leachate flows and pollution.

c. Haslams Creek enhancement

The entire upper section of Haslams Creek was completely reconstructed from vastly widening a previously existed concrete stormwater channel to a fully functional natural creek system. The widening has provided the much needed stormwater detention capacity to avoid flooding upstream. The works have constructed NSW's first ever large-scale creation of coastal saltmarsh. As a result, some 2.5ha of coastal saltmarsh was totally newly constructed on both edges of the Creek. The elevation was carefully maintained between 0.7mAHD and 1.1mAHD – a range that suits coastal saltmarsh in tidally open flats. Likewise, further lower section of the creek-line (Haslams Reach precinct) was also improved by undertaking various rehabilitation works. The Nuwi Wetland area was also upgraded by widening the stormwater-tidal exchange corridor and as well as created a small saltmarsh pocket (Pym 2001).

In this creek system also exists the Narawang Wetland cluster. This cluster of 22 freshwater ponds and three stormwater detention reservoirs were created to handle stormwater but most importantly, as replacement habitats for Green and Golden Bell Frog and Latham's Snipe (Pym 2001). These ponds are separate from the Creek but at extremely high tides associated with storm events, the estuarine water can intrude in this wetland corridor.

Two other wetlands – Northern Water Feature and Eastern Water Quality Control Pond were also constructed to handle stormwater but to mainly provide stormwater storage and later used as interchanging capacity for the Australia's first ever large scale Water Recycling and Reclamation Scheme (WRAMS) for water commercial recycling and reuse.

d. Powells and Badu Mangrove area enhancement

Fortunately, much of the wetland areas that were once degraded and left derelict from the reclamation activities for landfill and industrial establishments in the early 1990s, many were already rectified and restored between 1983 and 1988 prior to the opening of the Bicentennial Park for environmental education and recreation. However, a few additional but minor rehabilitation works were undertaken during the Olympic development period, which primarily included widening the lower section of Boundary Creek, installation of a Fishway (Fish Passage) in this section and also elimination of water-logging and mosquito breeding habitats in a section of the Badu Mangrove precinct by constructing earthen channels.

Recent Initiatives and Present State of the Estuarine Wetlands

The present state is largely the result of the above-mentioned restoration and rehabilitation works undertaken leading to the Sydney 2000 Olympics. However, many new initiatives were also undertaken to complement some of the previous works and attend to new issues. As a result, the estuarine wetlands in the Park are generally overcoming any impacts from past changes, modifications and/or rehabilitation activities that were undertaken in relatively recent past; especially past two or so decades that were mainly linked to the Sydney 2000 Olympics. Since ecosystem restoration takes time and for a wetland to restore its full function as well as establish the complex network of overlapping and mutually connected functions take many years, it is relatively premature to expect major improvements in the wetland conditions. Nevertheless, the estuarine wetlands are fast adapting to the relatively stable habitat conditions and they are generally in a good state. A brief account of these wetland types are provided below.

a. Estuarine Creeks

Estuarine Creeks are significant corridors for flood mitigation through stormwater discharge and tidal exchange. The Creeks are also wonderful natural corridors for marine life as breeding, shelter, nursery, migration, (limited) emergency navigation and landmark features. Distinct Creeks that exist in the Park are Haslams Creek, Powells Creek (including the lower section of Boundary Creek) and Louise-Savage Creek. By far, the former two creeks play vital roles, as mentioned above.

Over time, the conditions of these creeks have fluctuated due to a variety of reasons. These include:

i. bank erosion from high intensity stormwater flows from extreme rain events induced by Climate Change;

ii. structures and utilities in the creek corridor;

iii. sewer overflows;

iv. flow of litter and sediment from upper catchments;

v. flow and settlement of water-borne weeds; and

vi. impacts of legacy modifications and changes.

One biggest physical change in the recent decades has been the widening of former Haslams Creek, from its concrete drainage channel structure to a many-time more natural creek, including construction of saltmarsh beds on the upper elevation of the creek line. This was undertaken immediately prior to the Sydney 2000 Olympics. On the other hand bank erosion and collapse has been a problem lately from two aspects: one, with the collapsing of the shores mangrove and saltmarsh also disappear with the collapse; two, the loss of sediment that has been so age-old, which trapped so much of organic carbon, have all but emitted to the atmosphere. In addition, if the shores keep collapsing at a greater rate then the integrity of some adjacent landfills may be under threat.

b. Estuarine Lagoons

There are four noticeable estuarine lagoons in the Park. These are the Waterbird Refuge (WBR), the Main Lagoon in the NNR Wetland, the Nuwi Wetland and Saltwater Billabong. These distinctly different habitats are characterised by direct links to the estuary and on receding tides they retain some tidal water in them. Because of their wetting-drying-retaining features, they attract a high diversity of birdlife and estuarine fauna and flora. They serve a variety of purposes including refuge, shelter, feeding, roosting, breeding, nursery and relaxing by many waterbirds and shorebirds; some of which travel from as far as the northern hemisphere (Straw 2013). Among these the WBR and the Main Lagoon in NNR Wetland are prominent. Marine life also uses them for many purposes.

The WBR used to be a 'black hole'; a dead and putrid water body for decades when it was disconnected from the nearby Homebush Bay in mid-1990s. Since it was re-connected in 2006 to the Bay with the help of construction of an innovative tidal weir (SmartGate), it has become a biodiversity hotspot. Migratory shorebirds, local waterbirds, marine life and coastal saltmarsh – all are now teeming with saturation and satisfaction. More details of these are seen in other chapters in this eBook.

Likewise, ever since the Main Lagoon in NNR Wetland was opened up to the nearby River in 1997 and 2000, the lagoon has slowly transformed from an algae-infested and mosquito-ridden waterbody into a highly interactive and diverse habitat. Various migratory shorebirds have recently started visiting the lagoon. Other two lagoons, Nuwi Wetland and Saltwater Billabong, are also slowly improving as useful habitats for marine life as well as waterbirds and local shorebirds.

c. Mangrove

The Park has only two out of some 78 species of mangroves that are globally available out of 41 species that are available in Australia (Duke 2006). These two species are Grey Mangrove (*Avicennia marina*) and River Mangrove (*Aegiceras corniculatum*). Since Grey Mangrove is the most dominating in the Park and River Mangrove has only a few trees scattered across the Park, 'mangroves' implies only Grey Mangrove. Mangroves reside at a specific elevation band in this part of the

Box 1. Tidal restoration in the WBR.

In the past, the Refuge was largely isolated from tidal exchange with the Parramatta estuary, which resulted in the wetland becoming stagnant; bird diversity and abundance declined, and algal blooms became common. A small pipe installed through the bund in the early 1990s allowed some tidal exchange, but conditions did not change for the better until a 2m wide automated, solar-powered tidal gate and weir was installed in 2007, allowing daily exchange of tides. Water flow can be adjusted seasonally and daily to account for tidal cycles and habitat needs. High tides flushed the wetlands of algae as well as discouraged new algal growths. The number and diversity of benthic invertebrate, an important component of migratory shorebirds' diet, increased. With no delays, a huge number of Bar-tailed Godwit made a comeback after decades of absence.

Box 2. Recent restoration of Badu Mangrove dieback area.

Grey Mangrove trees died in an area of approximately 7,000m2 within Badu Mangroves precinct during 2012 and 2013. Several investigations confirmed that the most likely cause was long-term water-logging. Following careful planning a bypass corridor was constructed by placing a box culvert and excavating two linking channels. The construction of the by-pass corridor has instantly removed the water-logging. Mangrove trees that were earlier stressed made a comeback and new seedlings are colonising. A scientific monitoring program has been in place to track the temporal changes.

east coast of Australia, with the most suitable band being 0.5mAHD to 0.9m AHD. Mangroves are a Protected Marine Vegetation under the NSW Fisheries Management Act 1994.

According to the condition assessment (included in Field 2013) undertaken over the period 2014 through 2019, approximately 48-61% of the overall coverage of the mangroves in the Park were in good condition, 22-44% in fair condition and 5-20% in poor condition. The relative scores of the condition changed from time to time due to various factors. The major contributing factors include:

i. sudden dieback of pockets of mangroves due to water logging (2013-14) and/or lightening (various years);

ii. mangrove canopy impacted by leaf-eating moth larvae (in 2003-04);

iii. slow dieback due to elevation changes from past landfilling works (continuous);

iv. slow dieback due to increased stormwater flows and resultant water-logging (2016-17) as well as sea level rise (recent);

v. deaths of trees from shore collapse due to stormwater and tidal flows from extreme rainfall events (recent years);

vi. canopy and trunk breakdown from overgrowth and loss of balance across creek-lines (various locations);

vii. establishment of boardwalk and other utility structures in the Park over a period of time;

viii. stormwater litter and debris settling on mangrove beds, especially along the creek-lines;

ix. stress and suppression from extreme weather events such as sudden rise in extreme ambient heat (2019) and shocks from sudden extreme cold (recent years);

x. shadow impacts from structures as bridges (1998) and buildings (1999);

xi. hydrocarbon (2002) and other pollution events in the past (various decades) that have caused genetic defects (Veldkornet *et al.* 2020) and other abnormalities (continuous); and

xii. stress and death of individual tree from undetected reasons, which could be linked to past pollution events.

Although the above-listed factors do impact on the health and condition of the mangroves in the Park, the sheer resilience and adaptation ability of the mangroves make them still stand out as one of the most thriving and flourishing ecosystems in the area. Actually, even though the mangroves have been undergoing various pressures in the recent decades, as listed above, due to other type of human-induced activities such as rise in the sediment bed from landfilling and upstream catchment earthworks that had been undertaken in the long past, mangroves have rapidly expanded in Homebush Bay area; compared to what existed prior to the industrial era (McLoughlin 2000, Saintilan and Williams 2000). This is purely because mangroves quickly colonise where conditions and habitats suit them.

Recent initiatives have improved the overall conditions of mangroves in the Park. A most recent example has been the installation of a bypass corridor to allow drainage of a waterlogged area and allow a natural regime of tidal exchange. Box 2 provides some more insights.

d. Estuarine Mudflats

Estuarine mudflats are spread across many wetlands in the Park. Some are exposed to daily tidal wetting-drying regime yet others are inundated by either spring tides or stormwater discharge. These habitats are generally in excellent condition, therefore, attracting a relatively high diversity and abundance of migratory shorebirds, local shorebirds and resident waterbirds. Their conditions have been continually improving due to the improvements in the stormwater and tidal water qualities from lesser pollution. Estuarine life such as crabs, gastropod molluscs, polychaete and similar worms, algal films, seaweed as well as small fish and shrimp have been making these mudflats rich feeding grounds. As results of some carefully chosen improvement works, the texture and composition of the mudflats are gradually becoming more suitable for shorebirds and other creatures such as mud-dwellers, which are reflected by the increasing diversity and relative abundance.

e. Coastal Saltmarsh

Coastal saltmarsh resides mainly at the further higher tidal elevation than the mangroves. Coastal Saltmarsh is actually an ecological community, consisting of a number of signature plant species that are highly salt-tolerant and also other estuarine and semi-terrestrial biota. Coastal Saltmarsh is an Endangered Ecological Community in NSW under the *NSW Biodiversity Conservation Act 2016*. When referred to Coastal Saltmarsh, the assemblages of halophilic species that are represented include *Sarcocornia quinqueflora*, *Suaeda australis, Triglochin striata, Sporobolus virginicus*, and *Juncus kraussii*. It also has three other species that were introduced and by now these have been naturalised. These are *Wilsonia backhousei, Lamprathus tegens* and *Tecticornia pergranulata*. Among these, because of its rarity and special features, *Wilsonia backhousei* has been protected in NSW under the *NSW Biodiversity Conservation Act 2016* as a vulnerable species.

Like the mangrove conditions in the Park, condition assessment (Pacific Wetlands 2019) was also undertaken for Coastal Saltmarsh in the Park over the period 2008 through 2019. Approximately 51-66% of the overall coverage of the coastal saltmarsh in the Park was in good condition, 17-32% in fair condition and 13-17% in poor condition. The relative scores of the condition changed from time to time due to various factors. These factors include:

i. a decline in the extent of *Wilsonia backhousei* since 2014, most likely due to the overshadowing by trees and shrubs along the margin of the wetlands;

ii. terrestrial weeds expanding into the Saltmarsh Nursery area of NNR Wetland;

iii. stormwater litter and debris settling on saltmarsh beds, especially along the creek-lines;

iv. mangrove incursion due to sea level rise and bed slumping;

v. slow dieback due to elevation changes from past landfilling works (continuous);

vi. slow dieback due to increased stormwater flows and resultant water-logging (2016-17) as well as sea level rise (recent);

vii. losses of pockets from shore collapse due to stormwater and tidal flows from extreme rainfall events (recent years);

viii. establishment of boardwalk and other utility structures in the Park over a period of time;

ix. stress and suppression from extreme weather events such as sudden rise in extreme ambient heat (2003 and recent years);

x. shadow impacts from structures as bridges (1998) and buildings (1999);

xi. stress and death of small pockets from undetected reasons, which could be linked to past pollution events.

It has been widely claimed that over 70 per cent of coastal saltmarsh had been lost from Homebush Bay between 1930 and 1980 (Saintilan and Williams 2000). Losses have been also reported elsewhere along the Parramatta River (McLoughlin 2000). However, as an attempt to regain some of the lost saltmarshes, vast areas of the saltmarsh were reconstructed as part of the Sydney 2000 Olympic development and rehabilitation of wetlands. As a result, coastal saltmarsh area has more than doubled since late 1990s, mainly due to the creation of Haslams Creek Flats, additional saltmarsh in NNR Wetland and in the Waterbird Refuge. Not only the total area has been increased, the very quality of the saltmarsh areas has been also enhanced significantly by removing weedy plants and other measures, as below:

i. complete removal of Spiny Rush (*Juncus acutus*), a declared weed, from more than 7.0ha area of saltmarsh by employing a combination of techniques, including one that was developed through scientific trails (Paul and Young 2006; Paul *et al* 2007; Paul *et al* 2012);

ii. annual removal of Grey Mangrove seedlings from dedicated coastal saltmarsh areas under a permit from NSW Fisheries;

iii. continuous capture of stormwater-borne litter with the help of floating traps and booms, and hand-removals of litter from coastal saltmarsh beds by volunteers and SOPA staff; and

iv. careful handling and management of the tidal waters with the help of manually or automated weirs;

some of which measures are described later in this chapter.

The Authority's management approach and the successful conservation of the coastal saltmarsh have been used as demonstration examples by the NSW State Government.

f. SOFF (Swamp Oak Floodplain Forest)

SOFF (Swamp Oak Floodplain Forest), represented by *Casuarina glauca*, is an Endangered Ecological Community under the *NSW Biodiversity Conservation Act 2016*. The Authority's coverage of this community has been in three main precincts: NNR Wetland, Badu Mangrove and Badu Saltmarsh. According to the scientific monitoring conducted every two years since 2015, the condition of the NNR Wetland has been improving since it has had a setback from a dieback soon after the tidal modification in 2000 whereas other areas have been generally maintaining their conditions. So, in general, SOFF has been well protected and conserved in the Park.

g. Mosquito management

Mosquitoes, particularly those that use estuarine habitats as their primary breeding grounds, have been an integral feature of estuarine wetlands in the Park. Although their presence is a natural occurrence in habitats that suit them; their excessive populations are an indication of degrading conditions of wetlands and have been a nuisance and health issue for the Park visitors, residents and businesses. Pest mosquitoes, particularly *Aedes vigilax* (aka Vigilax mosquito), has been an estuarine specialist with coastal saltmarsh areas having semi-permanent tidal and/or rainwater impoundments being the most productive habitats for breeding of this species. But the trouble is that they breed, shelter and feed in more

Box 3. Saltmarsh reconstruction and rehabilitation in Haslams Flats.

Sydney Olympic Park has a long history of active management of saltmarsh. Remediation works in the 1990s included several major estuary restoration projects. Remnant coastal saltmarsh was conserved and a nursery established to provide local provenance seed and cuttings used in replanting programs. The concrete-lined channel of Haslams Creek was replaced with a new creek-bed and newly-built tidal mudflats were planted with saltmarsh. This was further rehabilitated in 2007.

than one habitat types – coastal saltmarsh, broken mangrove areas, water-pooled mudflats, drainage channels and crevices along creek-lines.

Therefore, any control measures often expanse across more than just coastal saltmarsh habitat or one particular estuarine habitat type.

A brief outline of the Authority's mosquito management program is illustrated in Box 4 & 5 below. However, the main approach to the mosquito problem has been two-fold: habitat enhancement measures so to eliminate actual and potential habitats for mosquito breeding, and, where this is not possible for technical, financial or other reasons, in those habitats a bacterial spore of the bacterium, Bti (*Bacillus thuringiensis* subspecies *israelensis*) is sprayed by helicopter and/or backpack spray kit (Webb 2013).

Principles of managing estuarine wetlands

Management of the complex mosaic of the estuarine wetlands has been a challenging task. In most cases the challenges have been unique, therefore, requiring innovative and creative interventions. The challenges arise from many directions and many of which were mentioned in the above sections. A summary of these include:

i. legal bindings and compliance;

ii. physical spread of the wetlands across various sub-catchments;

iii. wetlands that were attempted to be restored in the past but still taking their own time in the healing process;

iv. continued pollution from stormwater, particularly road runoff, litter, sediment and weed;

v. public usage of the site and increasing interest and presence of public with a sense of 'love to death'; and

vi. public events with potential disturbances to wildlife and habitats;

viii. development pressure, particularly light spill, noise and other pollutants; and

ix. climate change and sea level rise.

Box 4. A complex matrix, showing adaptive management of the NNR Wetland in managing the Authority Mosquito Program.

The wetland underwent many changes over the decades. The changes that were undertaken during 1993 to 2001 were aiming at fulfilling many management objectives. These include mosquito reduction, migratory shorebird optimisation, saltmarsh enhancement, mangrove protection but not encroaching in saltmarsh areas, less frequent algal growth and improved water quality.

After several iterative attempts a matrix was worked out by considering various abiotic, biotic and eco-hydrological factors that are known to have been playing direct roles in determining the success of the above objectives. Based on those factors a relative scoring was allocated, which was represented in colour codes. It is clear from the matrix that the most negative scoring (depicted by the greater concentration of red and orange colouration) was during two bands of periods. Those are periods when mosquito treatments are required. This matrix has helped determining the timing and magnitude of the efforts and at the same time to focus on managing the ecology of the wetland. As a result, by adjusting weir setting to 1.55m tide level, mosquito treatment events could be avoided during the less intense months of October and March (with less Red). However, this is possible only if there is not an associated rain event.

Adaptive Management principle helps in achieving this goal, which is primarily based on remaining focus on firm objectives but be flexible in reaching the objectives, however, based on good science. Consequently, the Authority's mosquito management program has been extremely effective, with a massive cost-saving when compared with the early days of this program.

Scenario- 1 (O–M)

Scenario-2 (N–F)

Parameter	J	A	S	O	N	D	J	F	M	A	M	J	Remarks
Mangrove Propagules	1	5	10	35	24	10	10	3	2	0	0	0	% seed drops
Saltmarsh status	4	1	5	10	17	17	17	1	1	5	17	5	% growth along ponds
Ambient Temp	6	7	8	9	9	10	11	10	10	9	7	6	% monthly distribution
Total Rainfall over 50mm	0	0	0	0	33.3	6.66	6.66	20	6.66	0	26.7	0	% highest occurrence in a week
Tides 1.7-1.8m	10.7	6.25	6.25	6.25	6.25	11.6	6.25	5.35	5.35	11.6	10.7	13.4	% monthly distribution
Tides 1.8-1.9m	10.3	8.62	8.62	0	3.44	12.1	10.3	10.3	6.8	1.7	12.1	15.5	% monthly distribution
Tides > 1.9m	18.2	13.6	0	0	0	0	18.2	18.2	9.1	0	4.54	18.2	% monthly distribution
Migratory Shorebirds[1]	0	2.3	2.87	16.1	41.9	7	3.44	4.02	4.02	15.5	2.88	0	% highest visitation in that month
Ae. Vigilax [2,3]	0	0	0.65	1.36	2.07	20	35.6	30.7	7.51	1.3	0.76	0	% highest count in that week
Colour Code		2	3	4	5								
Colour Hierarchy	Bad	2	3	4	Good								

[Prepared by- Swapan Paul]
1. Mr Phil Straw, Avifauna Research & Services
2. Dr Cameron Webb & Prof. Richard Russell, ICPMR
3. Field observations of 12 & 19 August 2002 and at later dates, incl. 1st Apr 2004

Management Scenarios Adopted:

1. **Scenario-1** (1 Oct - 31 Mar): Full mosquito period.
2. **Scenario-2** (1 Nov - 28 Feb): Most active mosquito period.

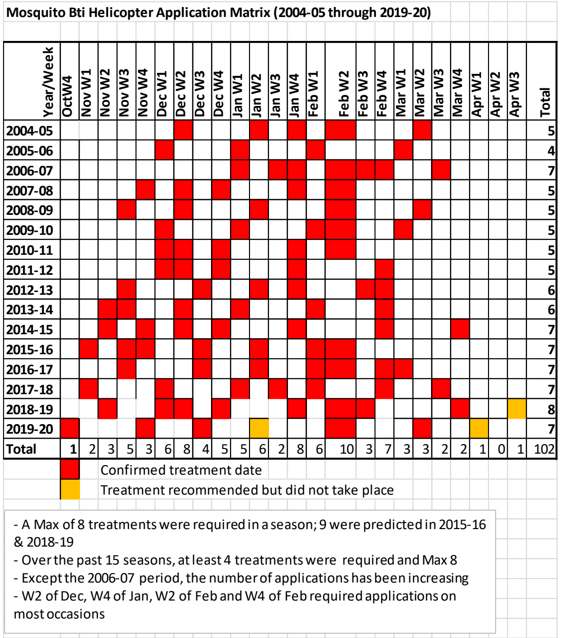

Figure 5. Mosquito helicopter treatment matrix in NNR Wetland.

So, to mitigate, manage, avoid and handle the challenges, the Authority has been undertaking many measures. The core principle of the measures and the management of the wetlands in the Park is Wise Use principle of Ramsar that the Australian Government follows (CoA 2020b). Wise Use advocates for four key pillars of wetland management: using an ecosystem approach, balancing uses, understanding and implementing sustainable use and using the best available information.

Since the values of these wetlands are in the end judged by humans – the ultimate users of these wetlands outside the wildlife and the nature - it is critical that a successful and lasting marriage takes place between human uses and sustainable functioning of these wetlands. That way nature conservation and human expectations are being balanced out on a regular basis (Paul 2018). The way the Authority fulfils the Wise Use guidelines are briefly outlined below.

a. Compliance and Due Diligence

The *Sydney Olympic Park Authority Act 2001*, (commonwealth) *Environment Protection and Biodiversity Conservation Act 1999*, *NSW Biodiversity Conservation Act 2016*, *NSW Fisheries Management Act 1994* and *NSW National Parks and Wildlife Act 1974* are the five main regulatory instruments that guide the conservation and management of the estuarine wetlands in the Park. To better manage, the Parklands Plan of Management (PoM), Biodiversity Management Plan (BMP) and Wetlands Operational Action Plan (WOAP) have been developed as guiding documents. To help undertake day-to-day activities and help maintain the site as well as undertake repair, renovation and restoration of the estuarine wetlands and ancillary lands and service structures, several other policies, procedures and protocols have been adopted. The Authority's various teams implement these procedures and guidelines, which help undertaking even a huge number of works simultaneously.

The other aspect of a balancing act has been development proposal that could otherwise influence and/or impact estuarine wetlands. This is looked at mainly under the direction of *NSW Environmental Planning and Assessment Act 1979* and the (commonwealth) *Environment Protection and Biodiversity Conservation Act 1999*. Whilst the need for more development activities in the precinct and in closer proximity to estuarine wetlands is well understood it is also given utmost priority to not encourage such developments at the expense of the ecological integrity of the wetlands. In fact, over the recent decades, the Authority has been able to strike that balance and by now it has been an exemplar in balanced urban development, as outlined above (Paul 2018).

b. Adaptive Management Framework

Realising that the natural systems have been continually evolving and so are the demands and aspirations of the Park users as well as the entire natural system is exposed to the influences of climate change and sea level rise, the Authority's management approach does have Adaptive Management principles well embedded. Accordingly, on one hand it remains firm in its conservation goals yet on the other it continually remains agile in making adjustments to its projects and programs so that ecosystems have the chance to adapt to changes. Figure 6 below shows an outline of the Adaptive Management framework.

Key steps that are always followed in the Adaptive Management are:

i. defining a management issue and drawing hypothesis that are based on scientific investigations and monitoring;

ii. undertaking risk analysis;

iii. setting management goals;

iv. undergoing genuine consultations with relevant stakeholders;

v. undertaking impact assessments and setting management actions;

vi. monitoring outcomes of management actions;

vii. evaluating the outcomes and re-setting goals (if needed);

viii. undertaking research and following the management loop.

In the above mix of steps, proper monitoring is critical to the success in achieving the conservation goals. Monitoring also helps identifying new issues and those are further challenged by employing hard science.

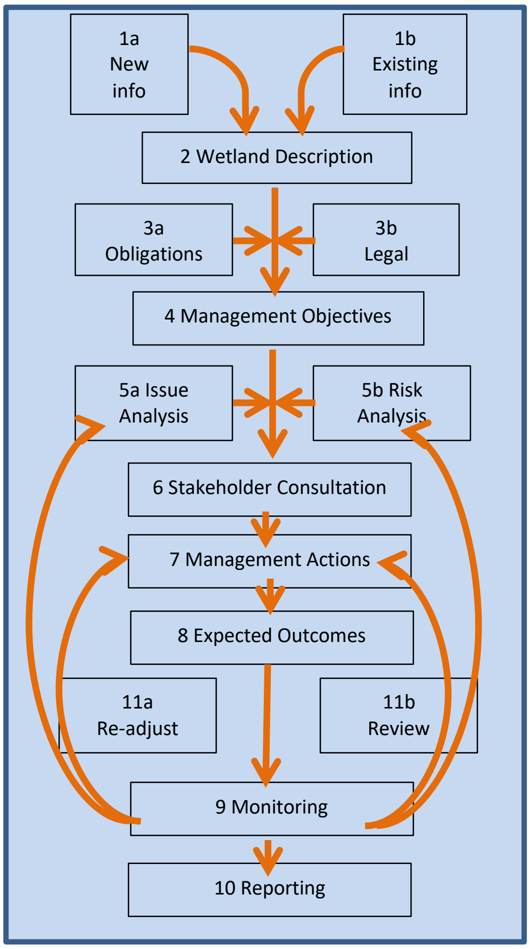

Figure 6. Adaptive Management Framework (re-constructed after SOPA 2006).

c. Innovation and Sustainability

Considering the limits in resources and funding as well as the time available for realising outcomes, it is always at the forefront of management ethos that innovative pursuit is always given the priority. In fact, by remaining open to new ideas and always challenging our own theories and hypotheses, the Authority has been able to develop numerous innovative management tools and prescriptions that are eventually replicable. Similarly, measures that will help reduce generation of wastes; reuse of materials as much as possible within the site so to reduce burden on transportation and disposal costs; recycle as much possible and use recycled materials in as many cases as possible – these have been the Authority's core practices. As a result, the Authority has recently acclaimed as a world class sustainable operator and has been one of the few public sector agencies in NSW that is a Six-star Green Star Awardee.

As examples of innovation and sustainability practices, below is a list of tools and techniques that have been successfully developed and applied in the Park. These have now been widely applied by wetland managers across Australia and beyond. These include:

i. environmentally friendly control of *Juncus acutus* from the sensitive coastal saltmarsh areas;

ii. cost-effective and self-regeneration of coastal saltmarsh vegetation in Haslams Flats that saved a huge amount of cost from other options;

iii. development of a technique of undertaking contour maps of tidal exposure in mangrove and saltmarsh habitats;

iv. development of the concept and undertaking of channel construction in Badu Mangrove for alleviating perennial mosquito problem and improving mangrove health;

v. development of the concept and installation of a solar operated and fully automated tidal gate (SmartGate) in WBR;

vi. reuse of any mulch in estuarine areas that is generated from fallen or removed mangrove trees;

vii. any organic wastes generated from mangrove and saltmarsh areas are reused on site as much practicable;

viii. operations of automated tidal gauge and communication device with solar power;

ix. complete refurbishment and replacement of a 600m long boardwalk in the mangroves that used only recycled materials; and

x. replacement of bridges and structures in estuarine areas with recycled materials as a preferred choice.

d. Partnership and Collaboration

Partnership and collaboration have been two major drivers of seeking external support and engaging interested stakeholders in not only managing these wetlands but also offering the place for the partners and collaborators to make use of. Best examples of these are the Citizen Science volunteers, student researchers, higher degree research projects, industry research, international collaboration studies, and public agency and local government reference studies. As a result several dozens of studies have been undertaken in the estuarine wetlands, which help guiding the management of these wetlands. These also help other wetland managers to extract the information and make their wetlands good. Likewise, over the decades, more than a dozen of volunteer and philanthropic groups have also benefitted from and contributed to these wetlands.

The Cumberland Bird Observers Club provides dozens of volunteers every year for undertaking seasonal bird census, including birds using the estuarine wetlands.

Another big form of our collaborations and partnerships has been the running of the Wetland Education and Training (WET) Program. This program relies largely on the volunteered contributions from over a hundred of wetland professionals and academia, who give scholarly talks and field tutorials for wetland professionals. This program has been running since 2002 and in this period of time several thousands of hours of volunteer hours were donated by these trainers and advisors to make this program successful. A large part of the program involves demonstration of tools and techniques that were successfully innovated and/or adopted in managing these wetlands. However, in running the program the estuarine wetlands also greatly benefit from the knowledge gained from the program.

Climate Change and Sea Level Rise

In the quest for innovation and sustainability and with a view to succeeding in Wise Use of wetlands, the Authority strives for up-to-date understanding in and looking out to projecting likely impacts of climate change and sea level rise on the estuarine wetlands.

The Authority's own studies, which are based on the data gathered by the NSW Manly Hydraulics Laboratory's tidal data from this site, have concluded that more than 7.00mm of average annual sea level rise in this site over the past 14 years, starting from 2002-03. This corroborates to that concluded in another independent study included in this eBook. In fact, in some years the rise was many-times higher and particularly in 2016-17 period, it rose by 55.0mm (Figure 7). The above rises mean that the estuarine wetlands are under tremendous pressure from the rising sea level. According to this trend line, the level in 2022 will reach 140mm above the 2002-03 level.

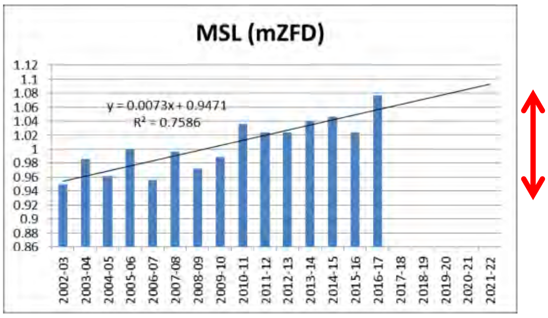

Figure 7. MSL and trend line in Sea Level Rise in Sydney Olympic Park.

To assesses the potential risks, vulnerability and adaptability, a study was undertaken in 2010 (Finlayson and Spiers 2011). According to the study, all estuarine wetlands within Sydney Olympic Park contained vulnerable components, based on an assessment of existing threats and risks and thence vulnerability to specific climate change and sea level rise impacts. However, some wetlands had more vulnerability than the others. The study suggested that the Authority's response to the changes in scenarios due to sea level rise and/or climate change would need to be reasonable, prompt and in most cases, pre-emptive. Proactive steps will help undertaking adaptation measures so to sustain conservation initiatives. Table 3 provides a summary of the outlook.

Other likely impacts of climate change (other than the sea level rise) on the estuarine wetlands are also being noticed heavily. A summary of the observations are listed below, many of which will require further detail studies. The observations include:

Table 3: Summary of major changes arising from sea level rise that are expected in main estuarine wetlands in Sydney Olympic Park.

1.075m AHD (average of high tides in 2000)	1.475m AHD (future average of high tides in 2050)	1.975m AHD (future average of high tides in 2100)
Parramatta River System: Newington Nature Reserve Wetland		
Under current tidal restrictions the entire mangrove area will be fully inundated; parts of the saltmarsh area in the Nursery section will remain un-inundated; the freshwater Wharf Pond will be partly inundated; the Swamp Oak will be partly inundated.	Under the same tidal restrictions the entire mangrove area will be fully inundated; only a very small part of the saltmarsh area in the Nursery section will be un-inundated; the freshwater Wharf Pond will be mostly inundated; the Swamp Oak will be mostly inundated; the Armory Creek will be flooded.	Under the same tidal restrictions the entire mangrove area will be more heavily inundated; all parts of the saltmarsh area including the Nursery section will be inundated; the freshwater Wharf Pond will be totally inundated; the Swamp Oak will be totally inundated; the Armory Creek will be completely flooded; many sections of pathways in the River Walk and the Armory will be flooded.
Powells Creek System: Badu Mangrove and Lake Belvedere		
With full tidal restrictions the WBR will be unaffected; Badu Saltmarsh ponds will be inundated; mangrove areas will be favourably inundated; the freshwater Bennelong Pond will not be inundated; pathways and walkways will not be flooded; freshwater Lake Belvedere will not be inundated.	With full tidal restrictions the WBR will be partly affected by water seepage through the bunds; Badu Saltmarsh and the ponds will be fully inundated; mangrove areas will be deeply inundated; the boardwalks will be more unstable; the freshwater Bennelong Pond will be inundated; most pathways and walkways will be flooded; freshwater Lake Belvedere will be fully inundated; pathways around the Lake will be flooded; leachate system may be infiltrated; portion of Oulton Ave pathway will be flooded.	Even with full tidal restrictions the WBR will be fully affected by flooding of the bunds; saltwater will infiltrate through WBR to the freshwater Triangle Pond; Badu Saltmarsh and the ponds will be fully inundated; mangrove areas will be deeply inundated; the boardwalks will be more unstable and unworkable; the freshwater Bennelong Pond will be fully inundated; all the pathways and walkways will be flooded; Lake Belvedere will be fully inundated; pathways around the Lake will be flooded; leachate system will be infiltrated and the Leachate Evaporative Pond will be infiltrated; Bennelong Parkway and the exit pathway of Bicentennial Park will be flooded; most sections of the Oulton Ave pathway will be fully flooded.
Haslams Creek System: Haslams Reach & Haslams Flats		
Tides will inundate all areas of mangroves and most areas of saltmarsh; Nuwi Wetland will be normally inundated by tides; the freshwater Northern Water Feature	Tides will inundate all areas of mangroves and all areas of saltmarsh; Nuwi Wetland will be more inundated by tides and if associated with storm events it will infiltrate the freshwater Narawang	Tides will inundate all areas of mangroves and all areas of saltmarsh; Nuwi Wetland will be more inundated by tides and even without associated storm events it will infiltrate the freshwater Narawang Wetland; the freshwater

and EWQCP will not receive tidal water; GGBF Ponds will not be inundated. Tides will inundate most areas of saltmarsh on Haslams Flats; the freshwater Teal Pond will not receive tidal water; GGBF Ponds will not be inundated.	Wetland; the freshwater Northern Water Feature will not receive tidal water but EWQCP will; GGBF Ponds will not be inundated. Tides will inundate all areas of saltmarsh on Haslams Flats; the freshwater Teal Pond will not receive tidal water; GGBF Ponds will not be inundated.	Northern Water Feature will not receive tidal water but EWQCP will be fully inundated; GGBF Ponds will not be inundated. Tides will inundate all areas of saltmarsh on Haslams Flats; the freshwater Teal Pond will receive tidal water; paths and walkways will be flooded; freshwater Narawang Wetland will be inundated by tides and GGBF Ponds will be severely affected.
Haslams Creek System: Narawang Wetland		
Freshwater Narawang Wetland will remain un-inundated.	Freshwater Narawang Wetland will remain un-inundated but if the tide heights rise due to associated storm events, the Wetland will receive tidal water.	Freshwater Narawang Wetland will be inundated with tides reaching above 1.475m AHD; internal pathways and walkways will be flooded.

i. droughts in 2003, 2013 and 2019 have burnt out mangrove canopy at places, burnt out mangrove seedlings in open pockets and burnt out saltmarsh vegetation, particularly *Wilsonia backhousei*;

ii. sudden extreme heat and rapid cold-shock are believed to have been causing failures in natural propagation success of Grey Mangrove;

iii. high intensity rain events associated with spring tides cause unprecedented flooding of estuarine and nearby public utility areas;

iv. high intensity rain events associated with spring tides create extreme flow events that naturalised estuarine creeks are unable to handle and cause bank erosions, mangrove falls and saltmarsh collapse;

v. unseasonal outbreak of filamentous algal blooms in estuarine lagoons;

vi. unexpectedly higher outbreaks of mosquito populations emanating from estuarine wetlands; and

vii. many more, which often go un-noticed.

Either in isolation and/or a combination or simultaneous effects of one or more of the above may mean that the task of managing the estuarine wetlands in the Park are likely to be much harder and more costly. To avoid remaining a helpless and silent observer of the damages taking place due to climate change and sea level rise, the Authority has been pro-active. It has prepared a Climate Change Adaptation Plan, developed in 2019 (SOPA 2019). But because of the lack of technically sound options to combat likely damage from impacts of climate change and and/or absence of timely and adequate resources, the adaptation abatement may become even more challenging.

Conclusions

The estuarine wetlands have enormous values. There have been legal imperatives; environmental and biodiversity conservation obligations; educational, recreational, aesthetic, spiritual and tourism demands; and international, regional and local drivers for which these wetlands require protection, enhancement and conservation. Over and above their usual ecosystem demands for protection and conservation, the sheer presence of these wetlands in a business hub that enjoys a high-profile economic significance, an extremely busy sporting precinct and an intensely urbanised city – the challenges in their effective management are enormous. Often these wetlands are loved to death; therefore often arise volatile situations that require urgent but thoughtful interventions. If left unattended, together those circumstances can leave the wetlands highly vulnerable to rapid, extensive and perhaps irreversible degradation and damage. It is pleasing that the Authority, with its continuous vigilance, presence of effective procedures and guidelines, and proactive interventions associated with the dedication of staff make the wetlands surviving and potentially sustaining into the future.

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Nature on the brink: The importance of urban ecology

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One of the considerable challenges in the development of the Homebush Bay industrial area and associated precincts in preparation for the Sydney Olympics was the protection and restoration of habitats that for several historic reasons had been isolated and provided a refuge in the heart of the Sydney metropolitan area for numerous threatened species and ecological communities. One species that occurred at the site was the threatened green and golden bell frog, but in a perverse way this species occupied disused industrial habitats. Most developments at the site were in the degraded industrial lands, and a program was necessary to create and restore habitats for the frog in the proposed parklands. While this objective was achieved by the time the Olympics occurred it became apparent that the long-term security of the population was uncertain. The largest issue was that many created wetlands were initially successful but gradually not used by the frogs, and others not used at all. Studies were undertaken to investigate the ecological reasons and threats to the population. Studies of the structure of the population found that there was a low number of adult females, and thus low reproduction. Thus investigations focused on the cause of low female survival and means to mitigate the impact of habitat loss by additional habitat construction.

These studies, undertaken on one threatened species, are considered in the context of the role and importance of urban ecology in providing a link between the broader human population and the challenges facing most natural systems and species.

Urban ecology and species adapted to human modified environments

Wildlife in the city, or urban wildlife as it is most commonly called, is the subject of numerous ecological studies, not least because ecologists are keen to understand the adaptations and behaviours that enable some animals to survive and thrive in the human dominated landscapes, where so many others cannot. There is a great deal to be learnt about the pace of natural selection and adaptations that these successful native survivors or invaders have made. A primary question is whether they were pre-adapted, with natural physical features and behaviours that enabled them to fit right in with human habitats, or whether rapid selection enabled them to survive. There are also some cases where fauna persist in small remnants with natural habitats within urban landscapes, and there is no particular adaptation to human impacts. This is contrasted with the inability of many native species to make this transition and which rapidly disappear as human habitats expand. There are also the in-between species, those that can survive in the back yards and gardens of the suburbs but gradually succumb to more intensive human habitation.

There are common links between the study of urban ecology and invasive species biology, whereby one great interest is in trying to address what are the biological features that enable some animals to occur almost everywhere man is. Among these animals are those that are commensal with man, the domestic pigeon, the black rat, the house mouse, the Indian myna, feral cats and foxes, the honey bee and of course the brown cockroach, and many more. Also there are those invaders that do not need human constructed habitats, such as the cane toad, carp, rabbits and pigs. What do all these animals have in common that make them successful invaders? These are representatives from the major groups of vertebrates and invertebrates, and of course this list is not comprehensive. For an Australian, a trip to urban habitats in the northern hemisphere will usually delight us with the sight of squirrels going about their daily lives in urban parks and gardens. Undoubtedly they are cute, however, thank heavens they were not successfully introduced to our shores. I presume foreign visitors to Australia are equally delighted to see brush tailed possums and magpies in Hyde Park Sydney, or water dragons at Roma Street in Brisbane.

There are several answers to the question of reasons for success. Among them must be the capacity of individuals to find suitable food and habitats to shelter, in this regard they can be described as generalists, capable of obtaining nutrition from a variety of sources, being able to seek out the novel sources (bread crumbs and chips!). As a group their behaviour can be described as alert and wary. They can avoid the obvious physical disasters such as vehicles and roads. Typically, they have a high reproductive capacity. Most importantly, and often not considered, is that when introduced, they escaped their natural predators, parasites and diseases. They are living in a new world without the enemies they had co-evolved with and that in many cases kept their populations in check.

Urban habitats are displacing natural habitats

Sydney Olympic Park and the bell frog

What has all this to do with Sydney Olympic Park? For over two decades I have been involved in one way or another with efforts to ensure that the local population of the native green and golden bell frog (*Litoria aurea*) continues to thrive. The irony is that this frog survived in a post-industrial landscape in the middle of the metropolis of Sydney, yet it had declined from many country areas with open grasslands and wetlands. Here we have one of our most beautiful frogs living in the heart of a great metropolis. Whether by accident, good luck or specific features of the local landscape, the population survived in habitats at Sydney Olympic Park and this history has been presented in the past (Darcovich and O'Meara 2008). This history is important when considering how to maintain that animal-habitat connection, and is part of the considerable challenge to provide for on-going persistence. I could discuss a swag of reasons as to why it is important to protect such populations, and there are books devoted to the philosophical arguments (Ehrlich 1988, Wilson 1988, Wilson 2016), however I will consider only two here. First there is the scientific value that comes from investigating urban wildlife, and second how these animals and habitats provide a unique opportunity for humans whose life is concentrated around urban landscapes. Surprisingly these two very disparate activities go hand in hand since these habitats are places where urban dwellers can gain some sense of nature, its beauty and fragility, while the scientific study seeks to understand the biological answers as to how these remnant populations survive amidst the intense pressures of human activities. It is possible that these habitats and animals will be the only direct exposure that many urbanites have to the greatest dilemma that faces our planet – the wave of species extinction that is occurring almost everywhere.

In 1988 one of the greatest conservation writers of our time E O Wilson wrote: "The one process now going on that will take millions of years to correct is the loss of genetic and species diversity by the destruction of natural habitats. This is the folly our descendants are least likely to forgive us." Like those that warned of climate change and its economic impacts and environmental consequences, there are those, like Wilson, who have been pointing out for decades that we are on a trajectory to disaster as we destroy the natural systems and species of our planet.

Green and golden bell frog

Perhaps the bell frog is the only frog that a child and adult of the urban landscape can see and marvel at. It is not through the glass at a zoo, or on a lavishly filmed documentary, it is there in the reeds, basking in the sun, just next to the boardwalk. On a warm summer night it can be heard singing - well that is a bit of an exaggeration, a bit more like a moaning dirge. Can this be the beginning of a greater appreciation and understanding of nature, an appreciation that may change how individual by individual we approach the broader dilemma of preserving life itself? Hopefully it will it stimulate some to go

CASE STUDY 1: Creating and restoring habitat for the threatened green and golden bell frog

The use of habitat offsets to mitigate the impact of development on threatened species is an approach adopted by planning agencies. However, this policy is contentious with most ecologists warning that creation of habitat is complex and restoration may take many years. Despite a plethora of theoretical work on the requirements of habitat offset to achieve no net loss, there are very few examples of successful habitat offset programs and monitoring regimes to detect success. The concept of no net loss is itself controversial since in most cases it is a mathematical impossibility to provide habitat for one species that is not habitat for others. There is always a loser. The objective is to restore land that has been degraded or not useful for natural purposes. The example of restoration of disused industrial land, such as occurred at Homebush Bay, is one such case.

Our study was one of the few to provide empirical evidence of the efficacy of applying no-net loss in conservation planning situations.

The problem of habitat loss

Loss and alteration of habitat has resulted in the reduction of species at the local, national and global scale and these factors are listed as the most common cause of species decline. Though the large-scale clearing of natural habitat for agriculture has recently declined in many developed countries, industrial and urban development continues to endanger many species and habitats over a wide geographical area.

The effectiveness of habitat offset has been widely debated, as the quality and extent of offset and level of monitoring and review are often insufficient to ensure that successful offset has been achieved. The creation of habitat is made difficult by the level of uncertainty in the eventual outcome of the program. Though created habitat can resemble the composition of existing habitat, certain ecological processes can be difficult to restore, possibly reducing the compatibility for the target species or community. A time lag is also expected between the creation of habitat and habitation by the target species, as resources require later-stage succession. This can result in some developments proceeding before the offset habitat has the capacity to achieve no net loss. This time lag is pronounced in certain habitat such as woodlands and some grassland, but can be rapid in highly dynamic or transient systems, such as mudflats, salt marshes and freshwater wetlands. The uncertainty of success for the development of offset habitat has resulted in some broad recommendations for its implementation.

Restoration principles applied in no net loss

Two of the major recommendations concern the size and location of habitat offset projects as a means of increasing the probability of creating the ecological processes required for success. A high offset ratio, where more habitat is created than lost, is recommended for species with a risk of failure. Under this circumstance, a small proportion of success within created habitat may still achieve no net loss as a large quantity of habitat is created. The second recommendation is to build offset at a close proximity to the lost habitat in an attempt to maintain the original composition, increase the probability of colonisation and to incorporate localised habitat characteristics or ecological processes. The third recommendation is to delay development so as to allow succession of offset habitat to achieve no net loss. However, the slow succession of some environments and the economic value of some developments to society mean that many developments proceed before this is achieved, and therefore management of the offset habitat is often neglected.

Theoretical solution

The intention of habitat offset is to achieve 'no net loss' or ideally lead to a 'net gain' in the conservation value of an area impacted by development. For habitat offset concerning a single threatened species, this usually means no loss in population size or viability through the actions of a development.

Case study at Sydney Olympic Park

We examined the population of the threatened green and golden bell frog (*Litoria aurea*) at Sydney Olympic Park which was impacted by development through the removal of nine ponds. Development was concurrent with habitat offset and construction of a large number of ponds which resulted in a 19-fold increase in available pond area.

Our findings

Through the use of demographic surveys, the population size was determined pre- and post-development. Despite the creation of ponds in the immediate vicinity of the development there was a decrease in the pond area and a measured decline in the population located within the area where the development occurred. However, the overall pond construction program also involved the addition of considerable habitat away from the immediate vicinity of the development which resulted in a 19-fold increase in pond area and an approximate 1.2–3.5-fold increase in population size. No net loss in population size to 95% confidence was achieved only when including all pond construction. This study demonstrated that to achieve no net loss for a habitat offset program can require extensive levels of habitat creation with intensive monitoring to detect it.

Conclusions

Our study showed that habitat offsetting was successful in achieving no net loss through the creation of large areas of habitat. This could be successfully evaluated with the use of long-term data that was collected for the target populations prior to and after a development that resulted in the loss of habitat. This case study highlights the complexity of dealing with habitat offsets for a species which is perceived to be 'straightforward' based on its biology and habitat requirements, and demonstrates that the level of effort required to successfully construct and monitor habitat offset may be drastically underestimated for most infrastructure projects.

Habitat offset projects have the capacity to contribute to conservation efforts when successfully implemented if they achieve net gain. However, habitat offset aimed at achieving and detecting no net loss can only be successful where the offset ratio is large, monitoring is long-term, robust and precise and funding is available to substantially increase the amount of habitat if monitoring indicates that this is necessary.

This is the major short-fall of most offset programs, and this study illustrates that even for species that are perceivably ideal for habitat offset, a large amount of effort is required for successful outcomes.

For more detail see:

Evan Pickett, Michelle Stockwell, Deborah Bower, James Garnham, Carla Pollard, John Clulow, and Michael Mahony. (2013). Achieving no net loss in habitat offset of a threatened frog required high offset ratio and intensive monitoring. *Conservation Biology* 157:156-162.

further, to delve into the deeper consequences of extinction and become advocates for a greater appreciation?

There is nothing that makes the bell frog more or less important than any other frog, just like there is nothing that makes the koala more or less important than a small marsupial mouse. Their survival is equally important. However, the koala stands as an icon, a flagship, a visible sign of what is happening to our natural forest ecosystem. It is an animal we can relate to and one that represents all the small and unseen creatures that share the trees, hiding in hollows, under the bark, and eating the foliage. For every koala there are perhaps a hundred beetles, ants and spiders of maybe ten or twenty species that share the tree. Similarly, the bell frog is a flagship for all our native frogs (perhaps more importantly a flagship for coastal wetlands), fortuitously coloured green and golden, relatively large and visible by day to those with sharp and enquiring eyes. If we cannot conserve a frog, what are our chances of saving nature, and who will be the champions for nature? Hopefully it will be those experiences that for young and old begins or sustains a life-long journey of discovery of the amazement and peace that comes from spending time in nature away from the urban hubbub. And hopefully, this appreciation builds a constituency that will require more to be done to protect it.

The sixth extinction

As Wilson (2016) and many others have pointed out life on earth is in the midst of the sixth extinction event (Kolbert 2014). What makes this one different to the others that are known from the fossil record, is that it is us, humankind, that is the driving force, and not a major geological or astronomical event. If ever we needed evidence of this, the summer of 2019-2020 in south and eastern Australia, brought it to our doorstep. Our land experienced a drought and heat wave conditions that broke all previous weather records (BoM 2020), and resulted in wild fires the extent and severity of which we had not previously imagined possible. The most used media word was "unprecedented", as if that enabled us to wash our hands of responsibility. That way we could blame nature, and not our own collective long-term neglect. Greater than 80 % (853,977 hectares) of the Greater Blue Mountain World Heritage Area, and 53% (196,000 hectares) of the Gondwanan Rainforest of Australian World Heritage Area burnt. These are landscapes that we as Australians protect and manage on behalf of all humanity, not just our own community (UNESCO World Heritage Charter 1972). Several estimates of the number of animals killed in the fire have been made, and there is general acceptance that over 1 billion perished. What of the survivors, will there be sufficient unburnt habitat to enable a recovery and over what time period will that occur? While our government devotes funds to recovery efforts ($25m for animal welfare recovery efforts and about the same for on-ground mitigation effort. Department of Agriculture, Water and Environment (DAWE)), we devote $50b to building a fleet of submarines, and globally billions to find if there was ever evidence of life on Mars, while the biodiversity of the planet where 99.99% of us will live and die, is threatened by our wilful negligence and greed. Or is it blind ignorance? How do we change the ignorance, where is the beginning of appreciation and love of nature?

The status of threatened species – life on the brink

It appears that even legislating to redress species declines and extinctions is a forlorn task. For over two decades we have had national and state legislation to protect threatened species. An outcome of our ratification of the United Nations Convention on Biological Diversity (United Nations, 1993). Is it a sign of failure of our legislation or a lack of biological understanding of the real issues that sees the threatened species list grow annually, with only rare occasions where a species is removed as being secured? In New South Wales, after being considered ineffective, the *Threatened Species Conservation Act* (1991, 1995) has been replaced by the *Biodiversity Conservation Act* (2016), and the mechanisms to protect and recover threatened species have been changed. New thresholds for species survival are set and can be traded as in a market place. One can only ask, by setting new thresholds, are we just moving the goal posts, and kicking the can of species persistence further down the road. As a clear example of the extent of the current status, it is valuable to look at recent catastrophic events. After the summer fires, the federal Department of Agriculture, Water and the Environment published a list of priority species, developed from a multi-trait ranking process that included over 90 vertebrates, and 20 ecological communities, considered to be likely impacted by the wildfires. The majority of these species were already listed on national and state threatened species lists. All of a sudden in one season a large proportion of the lands set aside to protect our natural heritage along the eastern slopes of the Great Dividing Range in southern Queensland, NSW and Victoria were destroyed. On Kangaroo Island in South Australia, our largest offshore island and one of the few large terrestrial environments free of foxes, almost half of the native vegetated habitats were burnt. It is not with a feeling of justification that many conservation biologists could say, the warnings were made and ignored. It is with feelings of great sadness and distress. My observation is that most conservationists are optimists, they have to be in the face of such rapid change and the destruction of nature, otherwise they would move into depression. They continually question how to deliver a message of doom and at the same time provide a solution. One of our solutions was to have about 15% of habitats protected in reserves, and in the summer of 2019-20 we observed that even that could be destroyed in a matter of weeks.

Bell frogs and understanding frog survival

So where does this leave urban ecology and the bell frogs? In the past two decades, studies of the bell frog at Sydney Olympic Park have provided significant insights on how to establish habitats in which frogs can survive in restored habitat deep within an urban landscape and beyond (Case Study 1). Methods to manage the impact of a widespread invasive disease (a fungal invader not listed above, now cosmopolitan, and estimated to have caused the extinction of about 120 amphibian species worldwide) (Skerratt et al. 2007), were developed and the theoretical concepts to minimise the impact of the pathogen that can be applied to many other frogs. Thus studies of the population at Sydney Olympic Park have proven influential in addressing broader issues of conservation biology for amphibians. These studies could have been possible on populations away from urban landscapes, however it was the urban landscape that enabled the studies to be undertaken. The dilemma of survival of the bell frog population was at Sydney Olympic Park.

In the early 1990s when work commenced in earnest to prepare the Sydney Olympic Park site for the Sydney Olympic Games in 2000, one of the promises was to deliver the 'Green Games', and this meant everything from sustainable building materials, water and waste management, to the ecological legacy of the Olympic parklands. An opportunity to redevelop and revitalise a part of Sydney that had a chequered industrial past. What better for the Green Games than to have a threatened frog at the site with the common name the 'green and golden bell frog' (fortuitously the Australian national colours). History tells that the passage was not an easy one (Darcovich and O'Meara 2008), but the games were delivered and with many years work from many dedicated people the bell frog continues to persists twenty years on.

At the time the first conservation actions were to be taken for the bell frog population at Homebush, there was wide debate among amphibian biologists as to the cause of observed worldwide declines in amphibian populations. It is widely accepted that the first international consensus on this situation among those who study amphibians was at the World Congress of Herpetology held in England in 1989, and by 1993, when the second congress was held, there were several contending hypotheses from the impact of exposure to ultra-violet radiation caused by the hole in the ozone, to environmental contamination of hormone by-products, to widespread habitat destruction, or to a disease. While the scientific debate progressed, the green and golden bell frog had been listed as threatened on the NSW *Endangered Fauna (Interim Protection) Act* (1991), since this once common and widespread frog had declined from a vast area of its former

Ponds built for the green and golden bell Frog at Sydney Olympic Park

distribution. Surprisingly, and perhaps ironically, it persisted in some unusual situations such as in old industrial landscapes, such as those at the pre-development Sydney Olympic Park site, and in a few other notable locations.

In the absence of a full understanding of the causal agent of amphibian declines, the challenge was to maintain a viable local population of the green and golden bell frog at Sydney Olympic Park. From a biological perspective, the principles behind managing a threatened species require that the cause of decline be identified and then mitigated (Caughley 1994). Why had this population survived when many others, some in relatively benign habitats such as grazing lands on the Southern and Central Tablelands, had disappeared? And how to mitigate the cause when there was active debate among specialists as to the underlying cause? And what if there was no mitigation possible? What can one do to mitigate the effects of a hole in the ozone in the short-term? In the hurly burly of the preparations for the Olympics there was little time to undertake research into the cause of bell frog declines. As areas where the frog occurred were earmarked for construction of a stadium, road or car park, the approach taken was to construct new wetlands within the parklands precincts based on the features of the ones that the frogs were using. This approach was successful initially, but it was not long before there was an observed decline in the distribution and abundance of the population. Biologists and managers alike were frustrated with patterns that made little sense. New wetlands were constructed to a well-defined habitat model, and the frogs moved in and often bred within a season or two. But over time the frogs deserted some of these wetlands and breeding ceased.

Research to improve persistence of the bell frog population

After the Olympics had been completed, a five-year research program on the green and golden bell frog population at Sydney Olympic Park was undertaken by the University of Newcastle with the support of the Sydney Olympic Park Authority and the Australian Research Council. The primary aim of the investigations was to ensure the persistence of the population of the green and golden bell frog at the site. Investigations focused on the cause(s) of decline and if possible, how to mitigate it. By this time there was a firming of the postulated cause of amphibian declines and studies undertaken in Australia had shown that a disease was the most likely agent (Berger and Speare 1998, Scheele et al. 2017). The pathogen had been described (chytrid fungus) and the disease it causes named chytridiomycosis (Berger & Speare 1998). Studies revealed that it arrived in Australia in the 1970s (Berger and Speare 1998). With this in mind a population viability analysis (PVA) was undertaken for the Sydney Olympic Park bell frog population, along with studies of the tadpole and adult stage of the life cycle, water quality, habitat associations and the prevalence of the chytrid fungus in the population. The population viability analysis showed a high mortality rate in the terrestrial stage of the life cycle (juvenile to adult frogs) such that only a small percentage of females reached sexual maturity to contribute to the next generation (Pickett et al. 2013, Pickett et al. 2014a,b,c, Pickett et al. 2016). What was causing the high mortality rates? The answer pointed mostly to the disease (Stockwell et al. 2006a, b, Stockwell and Mahony 2007, Stockwell et al. 2010, Stockwell 2011, Stockwell et al. 2012, Bower et al. 2013, Stockwell et al. 2015a,b). Our studies revealed that bell

Testing for chytrid

CASE STUDY 2:
Impact of a pandemic pathogen specific to frogs, and susceptibility of the green and golden bell Frog

The problem of wildlife disease causing population declines

Introduced pathogens are increasingly being implicated in population declines and their effects are difficult to manage. It is now documented that over 120 amphibian species have disappeared (presumed extinct) in the past three decades to a disease that emerged in the mid-1970s. In the absence of methods to eradicate pathogens acting as threatening processes, intervention before population decline is necessary. Such an intervention requires an ability to predict when population declines will occur, and therefore, an understanding of when exposure will lead to infection, disease, death, and population decline.

Determining susceptibility of a species is a key component of understanding impact and mitigation

We investigated when pathogen exposure leads to disease for the amphibian chytrid fungus *Batrachochytrium dendrobatidis*, which has been implicated as a causal agent in the global amphibian decline.

Susceptibility studies were conducted on two anuran species, the green and golden bell frog *Litoria aurea* and the striped marsh frog *Limnodynastes peronii*, when exposed to the fungus as either tadpoles or juveniles. Host species was found to significantly affect the outcome of exposure, with infection loads in *L. aurea* increasing over time and resulting in significantly lower survival rates than unexposed. By comparison, infection loads in *L. peronii* remained the same or decreased over time following the initial infection, and survival rates were no different whether exposed to chytrid or not. These outcomes were independent of the life stage at exposure.

Our findings were unexpected and changed our understanding of how disease may progress in amphibians. Individuals with higher infection loads were not found to have lower survival rates; rather, an infection load threshold was identified where individuals with infection loads that crossed this threshold had high likelihoods of showing terminal signs of chytridiomycosis.

Why are some frog species more susceptible to the pathogen?

We found that host species determined whether infection load crossed this threshold and the crossing of the threshold determined the incidence of disease and survival.

The development of disease following exposure to a pathogen requires the successful establishment of an infection and the replication of the pathogenic organism to a level that impairs biological function. *Litoria aurea* and *L. peronii* were found to be equally susceptible to infection with chytrid as all exposed tadpoles and juveniles tested positive for infection. However, the multiplication rate of chytrid differed significantly between species. Mean number of pathogen organisms were significantly higher in juvenile *L. aurea* than *L. peronii* and increased over time, whereas mean number of pathogen organisms in *L. peronii* either remained the same or decreased below the detectable limit. Given that both the environmental and exposure conditions were standardised in this experiment, these results suggest that juvenile *L. peronii* possess an innate mechanism that inhibits the replication of chytrid following an initial infection and that this mechanism is lacking in *L. aurea*.

Identification of the first step in understanding which species will be impacted by the disease pathogen

The quantification of infection load thresholds for survival, along with the time it takes to reach them, enables infection loads in wild populations to be related to the likelihood of disease and is the first step in the understanding and prediction of when exposure will result in population decline.

Understanding that disease causes the decline of a population changes significantly how ecologists consider management actions to secure a threatened and susceptible species such as the green and golden bell frog.

For more detail see:

Michelle Stockwell, John Clulow & Michael Mahony. (2010). Host species determines whether infection load increases beyond disease-causing thresholds following exposure to the amphibian chytrid fungus. *Animal Conservation* 13: 62-71

frogs were highly susceptible to this disease, especially in the cooler months of the year. Many females die before they reach maturity and breed (see Case Study 2).

Why the focus on females? Our studies showed that male bell frogs could reach maturity in one year, whereas it takes females two years. With the impact of the disease being so severe, females need to pass through two winter seasons to reach maturity, and that reduces their chances of survival (Pickett et al. 2014b). Once a female bell frog reaches maturity, they are capable of producing a large clutch of several thousand eggs, and one might expect that such a number would be sufficient to shore-up the population. Our studies showed that the high fecundity of females was of great importance to survival of the population. However, the adaptation to produce large numbers of offspring is an evolutionary response to a high mortality rate during the tadpole and juvenile stages. Tadpoles were observed to be an important source of food for many natural predators including turtles, lizards and birds at Sydney Olympic Park (Remon et al. 2016). Indeed, they may be a vital component of the food chain, and the frog is therefore an example of a keystone species. With this understanding, the adaptive research approach was to see for which part of the life cycle it was possible to intervene to increase survival rates. We asked the questions; is it possible to reduce the impact of the disease on adults and increase survival, or is it possible to reduce tadpole predation and increase the numbers that can grow to adulthood? At the time there were no examples in the world of any successful approach to controlling chytridiomycosis in wild frog populations. We tested the increased survival hypothesis by preventing death in a small cohort of female frogs by holding them in captivity over a winter and releasing them at the beginning of the next season. We tested the tadpole survival hypothesis by raising natural clutches in large aquaculture tubs that were covered with mesh to prevent predation. These studies confirmed the theoretical PVA model, and enabled management interventions to secure the population should they be required in the future (see Case Study 2). Following on from the studies at Sydney Olympic Park, and based on the knowledge developed there, we have guided the construction of large natural wetlands that passively control the impact of the disease in a world first approach to controlling the impact of the disease in nature at Kooragang Island in the Hunter River estuary.

In addition to these studies we investigated the impact of the introduced fish, the plague minnow that occurs in several of the wetlands at Sydney Olympic Park. Understanding the impact led to considerations of how to limit the distribution and occurrence of the fish (Hamer et al. 2002, Pollard et al. 2017). Investigation were undertaken on the habitats most favoured by the bell frog, and changes made to management practices. In an innovative study, the first for any Australian frog, we conducted analysis of the population structure and movement of the frogs using genetic markers (DeBoo et al. 2012).

Together these studies were possible because of the unique situation that occurred at Sydney Olympic Park. Urban ecology was able to address major questions that were occurring in the conservation management of amphibians worldwide. The lessons learnt have been applied in several other restoration projects. We did not solve all the problems and dealing with amphibian chytridiomycosis remains a major challenge to amphibian conservation. Science is often a slow and sometimes frustrating process.

Green and golden bell frog metamorph

Perhaps I should share one story of our time in the wetlands at Sydney Olympic Park. As you no doubt appreciate most frog field work occurs at night. Well in one summer the major stadium at the Park was host to the heavy metal rock band AC/DC. It was fun; fitted-out in waders with head torches on, conducting our survey in the large wetland at the end of the Olympic Boulevard, and listening to the band AC/DC pump it out, and we could hear every word. The song list was the same each night and we would wait to hear the fireworks go-off when "TNT I'm dynamite" reached the audience to great applause. Where else can you do field work and listen to AC/DC live? There was a downside however. When the crowd streamed out in the balmy summer night air, excited and still singing, some would walk out on the canter-lever walkway that extended over the edge of the wetland. And we would need to scurry away and turn-off headlamps to avoid some unrepeatable but obvious comments and behaviour.

The bell frog has been a flagship, to show that in the face of total population loss, it is possible to enable coexistence with urban development. Hopefully, it can be more than this, if its occurrence inspires a new generation to understand and appreciate nature, there is a bigger winner. Nurturing appreciation may be the best hope we have of saving nature.

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Images - Sydney Olympic Park Authority

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Made to measure – building homes for bats, parrots and possums

Tina Hsu
Sydney Olympic Park Authority

Sydney Olympic Park Authority commenced a nest and roost box program in 2010 to provide supplementary habitat to the Red-rumped Parrot, microbats and possums, installing more than 60 boxes over the past 10 years. The Red-rumped Parrot population has increased almost three-fold as the parrots use the boxes for breeding each year. The bat boxes support three bat species, including a maternity group of Southern Myotis, Australia's only fishing bat and a threatened species. The Authority conducts regular inspections, ongoing management and habitat restoration to ensure the boxes continue to provide optimum habitat to fauna of conservation focus at the Park.

Hollows - what are they and why are they important?

More than 300 native Australian vertebrate species use tree hollows for breeding or shelter, including birds, microbats, arboreal marsupials, reptiles and frogs. Hollow-dependent fauna constitute approximately 15% of Australian vertebrate fauna (15% of birds, 31% of mammals, 10% of reptiles and 13% of amphibians), a far greater proportion of hollow-dependency compared to other continents (Gibbons and Lindenmayer, 2002). In NSW, at least 174 species (46 mammals, 81 birds, 31 reptiles and 16 frogs) are dependent on tree hollows; 40 of which are listed as threatened under the *NSW Biodiversity Conservation Act* 2016 (DPIE, 2019).

Tree hollows are cavities that develop in the trunk and branches of trees through natural processes such as damage by fire, wind or disease, and consumption by fungi or invertebrates such as termites (Goldingay, 2009; O'Connell and Keppel, 2016; DPIE, 2019). Tree hollows are common in myrtaceous trees, primarily eucalypts, and four broad types can be recognised – vertical spout, hollow in dead branch, hollow in live branch, and trunk hollow (Goldingay, 2009). The formation of tree hollows through natural processes typically requires more than 100 years but can take up to 400 years depending on tree species (Ridgeway, 2015; O'Connell and Keppel, 2016). While the minimum size-class at which trees consistently contain hollows varies with species and environmental conditions, in general, large old trees provide a greater density of hollows and hollows of a larger size, with eucalypts containing large hollows rarely less than 220 years old (Gibbons and Lindenmayer, 2002; DPIE, 2019). Unlike primary hollow users that can create cavities such as woodpeckers in Europe, North and South America, Australian animals are secondary hollow users that rely on pre-existing hollows (Goldingay, 2009). The existence of large, hollow-bearing trees, both dead and alive, is therefore of critical importance to hollow-dependent fauna, particularly larger species.

Extensive clearing since European settlement has removed and fragmented native vegetation including hollow-bearing trees across large swathes of NSW; for example, 70% of native vegetation has been cleared from the NSW sheep-wheat belt, the tablelands of the Great Divide and the coastal plain (DPIE, 2019). Clearing of native vegetation and loss of hollow-bearing trees are both listed as Key Threatening Processes under the *NSW Biodiversity Conservation Act* 2016, however, clearing has continued apace in NSW. The continual loss of hollow-bearing trees to land clearing is exacerbated by other factors such as clearing for development, public safety and asset protection; tree senescence and lack of recruitment; poor health and shorter lifespan of isolated tree/s; removal of dead wood and dead trees (also a Key Threatening Process); weeds; arson, and suppression of abiotic processes such as fire that may promote natural hollow development, leading to projections of hollow shortage across urban, rural and forested landscapes in large numbers of studies (Lindenmayer and Wood, 2010; Davis et al., 2013; Saunders et al., 2014; Leary, 2015; DPIE, 2019).

As hollow-bearing trees form a critical resource for many species, including critically endangered fauna such as the Swift Parrot and Leadbeater's Possum (Commonwealth *Environment Protection and Biodiversity Conservation Act* 1999), the provision of artificial hollows has become an important interim solution to address their continual loss.

Artificial hollows as supplementary habitat

Artificial hollows are manufactured simulations of tree hollows for the purpose of providing habitat for hollow-dependent fauna; these can be made out of various materials including PVC pipe, plastic drum or salvaged hollows, however, the majority are boxes made out of hardwood, softwood or plywood (Goldingay et al., 2018).

Within Australia, published information on artificial hollows date back to the late 70s, although studies have been slow to accumulate in the following decades. A review by Goldingay and Stevens (2009) found documented information on artificial hollows for just 15 of 114 hollow-using bird species and 8 of 41 hollow-using microbat species. These early reports were small in scale and often not well documented, although some were highly valuable as they demonstrated the potential for artificial hollows to meet the ecological needs of hollow-dependent fauna. For example, bat boxes installed in Organ Pipes National Park in Victoria facilitated the establishment of bat populations within regenerating forest in the park; the number of bats increased from 15 bats per check in 1994-95 to more than 100 bats per check in 2004-05. Artificial hollows have also been used for decades as supplementary nesting habitat for the critically endangered Orange-bellied Parrot.

As artificial hollows have been identified as an interim solution to the ongoing loss of hollow-bearing trees, their use has become more prevalent over time, appearing in Council reserves, National Parks, rehabilitating mine sites, as well as suburban backyards. DIY nest and roost box manuals are feely available online from various conservation and government agencies (e.g. Greater Sydney Local Land Services, 2016). Research on this topic is growing, and findings suggest much remains to be learned about species-specific roost ecology and artificial hollow design preferences. For example, while artificial hollows have been found to be useful to a population of Carnaby's Cockatoo, providing 45% of available hollows and raising the number of breeding attempts in the study area by 112% between 2011 and 2018 (Saunders et al., 2020), Rueegger et al. (2018) reported few bat species used boxes in their study; although introduction of a new box design markedly increased box usage, some species used boxes infrequently and maternity roosting was rare.

For land managers who wish to use artificial hollows to maintain long term viable populations of hollow-dependent fauna, research on natural and artificial hollow occupancy have identified many factors for consideration. However, it is important to recognise that the hollow requirements of most species are still poorly understood and only broadly described. Continual learning of the target species' natural hollow requirements and preferences, in conjunction with a commitment to assess artificial hollow performance through regular monitoring to inform adaptive management, is critical to the development and implementation of a successful, long-term artificial habitat provision strategy (Leary, 2015).

What do hollow-dependent fauna want in a home?

Many factors influence hollow occupancy, beginning at the landscape scale. Occupancy is dependent on hollow availability, which is related to tree species, age and size and strongly influenced by land management practices past and present. For example, in agricultural and pastoral landscapes, tree hollows are often confined to isolated paddock trees, dead trees and small remnants; artificial hollows installed in such areas are likely to have a different occupancy rate compared to areas with a high abundance of natural hollows (DPIE, 2019).

Within the pool of available hollows, only a fraction are suitable. Species select hollows for multiple, specific characteristics as the use of hollows with suboptimal characteristics can adversely affect survival and reproductive success (DPIE, 2019). Characteristics that influence hollow occupancy include:

- The hollow-bearing tree's **position and spatial configuration** in the landscape, with some species preferring hollows near riparian habitat or foraging areas (DPIE, 2019).
- **Territoriality** of the species under investigation. Strongly territorial species need spacing between hollows to minimise interspecific conflict; conversely, species that nest colonially (e.g. Superb Parrots) or in clusters across the landscape need a local abundance of hollows (DPIE, 2019).
- An **entrance size close to body width** is favoured by most species to avoid predation by or competition from larger species (DPIE, 2019); Goldingay and Stevens (2009) cites one study where predation of Crimson Rosella chicks by Pied Currawongs ceased after the artificial hollow entrance was modified into a 10cm spout.
- **Safety from predation** is critical to survival, and additional measures may need to be used if exclusion is not achievable, e.g. sensor-operated nest boxes that close the door at night were deployed to protect the critically endangered Swift Parrot from predatory Sugar Gliders.
- **Adequate hollow volume** to suit specific needs. Animals that roost communally or raise large litters need hollows with small entrances but large internal dimensions (DPIE, 2019); for example, studies have found some bat species chose roost trees that are significantly larger than available trees in the area (Goldingay, 2009). Hollow requirements can also differ within species; Rueegger et al. (2012) reported female Brown Antechinuses showed strong preference for large plywood boxes compared to smaller boxes of plywood and other materials. Hollow volume and depth are known parameters for avian breeding success (Goldingay, 2009). For example, Saunders et al. (2014) found nesting attempts by Carnaby's Cockatoo in shallow hollows (<400 mm) were less successful than those in deeper hollows (>1000 mm).
- **Protection from the elements.** Flooding of vertical spouts have been implicated in nest abandonment by the Red-tailed Black Cockatoo and loss of Eclectus Parrot clutches of between 12% to 20% over 4 years (DPIE, 2019).
- **Multiple hollows** are required by some birds, microbats, reptiles and arboreal marsupials to reduce parasite load, minimise risk of predation, obtain appropriate thermal microclimates, and allow efficient access to foraging areas as a function of their home range size. For example, the Brush-tailed Phascogale has a home range of 41-106ha, and individuals have been found to use up to 38 hollows over a year (Goldingay et

al., 2018; DPIE, 2019). In a study by Goldingay et al. (2018), Phascogales were found in 9% of functional boxes over 4000ha, but another 48% of boxes contained their distinctive nests, bringing total box usage to 57%.

- **Optimal microclimate**. The thermal property of a hollow is related to hollow height, entrance size, hollow width, tree diameter, aspect, and foliage mass near hollow. Tree hollows have a high capacity to buffer extreme temperatures, which is important for many species. O'Connell and Keppel (2016) recorded lower maximum day temperatures and higher minimum night temperatures in tree hollows, and a maximum buffering of 15.1°C below ambient temperatures. In contrast, nest boxes are usually poorly insulated and less temperature stable due to thinner walls and greater area to volume ratio, which could be detrimental to its users. Studies have found even small variation in internal nest temperature can have an effect on behaviour, reproductive performance and development in birds (Larson et al., 2018), and Burcher (2015) found Eastern Pygmy Possum breeding success in salvaged timber hollows was twice as high as that in poorly insulated PVC boxes. Thermoregulation is important to bats and they may select roosts that are heated by the sun to facilitate passive rewarming from daily torpor; studies have found species-specific preferences for aspect (Goldingay, 2009), as well as seasonal differences in preference for timber box thickness and aspect for some microbat species (Leary, 2015).
- Preferred **hollow height** varied among species, however, most bird and bat species reviewed by Goldingay (2009) would use hollows within 5m from ground. Leary's study on artificial bat box use by Cumberland Plain microbats (2015) found different occupation rates with box height (3-3.5m, 6m, 9m) with lower boxes more frequently occupied, and evidence of some species-specific height preference.
- **Stability and longevity** of hollows. Natural tree hollows can provide valuable habitat to fauna for decades, even when the tree is no longer alive. For example, Musk Lorikeets and Little Lorikeets have been reported to use the same hollows for close to 3 decades (Goldingay, 2009). Artificial hollows can also provide long-term habitat if made to last. Squirrel Gliders have been found to occupy and breed in nest boxes over a 10 year period, with individuals occupying boxes for up to 7 years (Goldingay et al., 2017), and Brush-tailed Phascogale and Sugar Glider boxes can remain functional despite infrequent maintenance for 20 years, depending on attachment method and tree species (Goldingay et al., 2018)
- Since suitable hollows are difficult to come by, i**nter- and intraspecific competition** can be fierce when hollows are scarce (Davis et al., 2013); competition between hollow-nesting parrots have led to nest usurpation and direct loss of eggs and nestlings (Goldingay, 2009). Displacement by the introduced Common Myna, Common Starling and European Honeybee are well documented (Goldingay et al., 2018), with

'Competition from feral honey bees (*Apis mellifera L.*)' listed as a Key Threatening Process under the *NSW Biodiversity Conservation Act* 2016. Goldingay et al. (2018) reported infestation rates from 9% to 57%; however, bees may depart after 1-2 years and management may not be required where large numbers of boxes are installed and infestation rate is low.

For artificial hollows to approximate the habitat value of suitable tree hollows, the abovementioned factors and the target species' ecological requirements need to be addressed and reflected in the design, material, placement (height and orientation), location and number of artificial hollows.

It is also important to recognise management success is not measured by hollow occupancy alone. In order to enable the persistence of viable populations over the long term, indicators of success should include the proportion of target fauna groups benefited by artificial hollows, evidence of reproductive success such as females with young, and increase in population over time (Leary, 2015).

These are discussed in greater detail in the Sydney Olympic Park Nest and Roost Box Project case study.

Fighting the housing shortage - a history of Sydney Olympic Park's nest and roost box project

Background

Nationally, 83 mammalian species are hollow-dependent; 46 occur in NSW, 14 of which have been recorded in Sydney Olympic Park (the Park). 114 Australian bird species are hollow-dependent; 81 occur in NSW, 19 of which have been recorded in the Park (Table 1). Some of these species or groups have been identified in the Sydney Olympic Park Authority's *Biodiversity Management Plan 2019* as priority species or groups for conservation focus due to ongoing, landscape-scale declines. These groups are microbats, woodland birds, and the Red-rumped Parrot in particular, as this species is at the eastern limit of its range at Sydney Olympic Park.

Table 1. Hollow-dependent species recorded in Sydney Olympic Park since 2000. Species with confirmed breeding records are denoted with *; threatened species are denoted with ^.

Mammalian hollow users – microbats	Avian hollow users
Chocolate Wattled Bat	Australian King Parrot
Eastern Bent-wing Bat^	Australian Owlet-Nightjar
Eastern Broad-nosed Bat	Barn Owl
Eastern False Pipistrelle	Crimson Rosella
Gould's Wattled Bat	Dollarbird*
Greater Broad-nosed Bat^	Eastern Rosella
Large Forest Bat	Galah*
Lesser Long-eared Bat*	Laughing Kookaburra*
Little Bent-wing Bat^	Little Corella*
Ride's Free-tailed Bat	Little Lorikeet
Southern Myotis*^	Long-billed Corella
White-striped Free-tail Bat*	Musk Lorikeet
Mammalian hollow users – arboreal marsupials	Powerful Owl^
Common Ring-tailed Possum*	Rainbow Lorikeet*
Common Brush-tailed Possum*	Red-rumped Parrot*
	Sacred Kingfisher*
	Scaly-breasted Lorikeet
	Southern Boobook*
	Sulphur-crested Cockatoo*

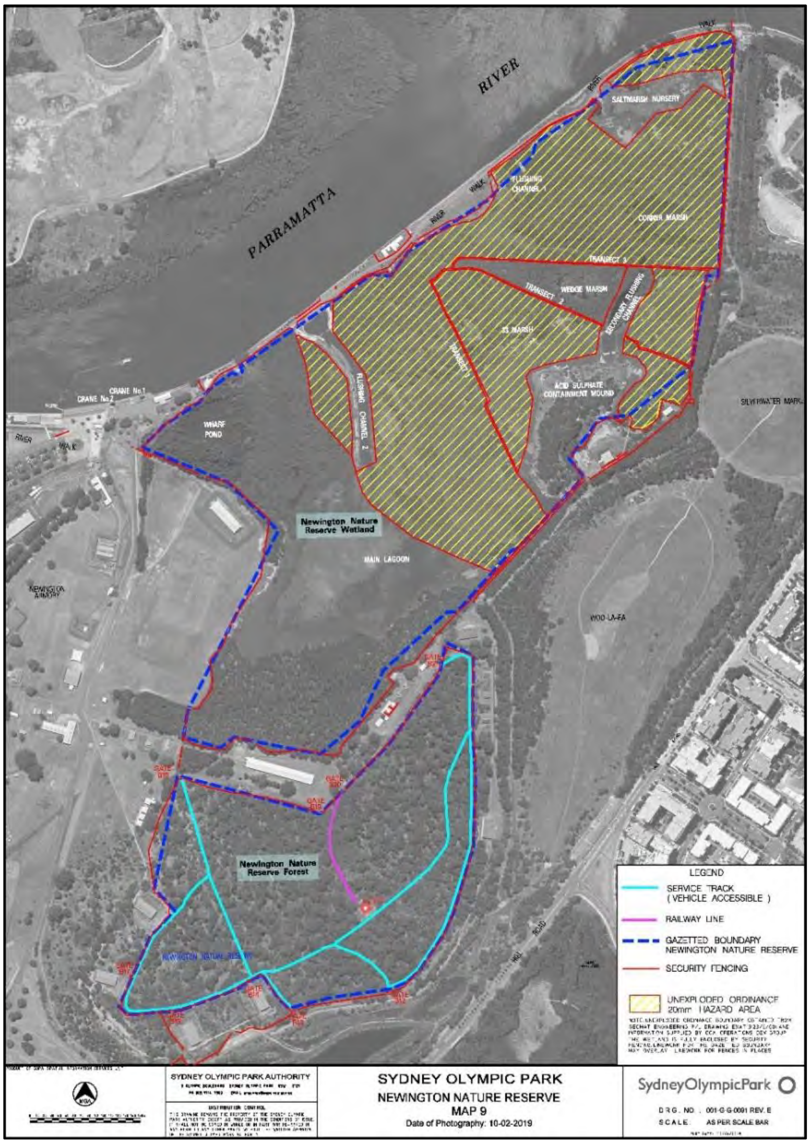

Figure 1. Newington Nature Reserve in Sydney Olympic Park contains a 13ha remnant of Sydney Turpentine Ironbark Forest with many large hollow-bearing trees

Figure 2. (left) Newington Nature Reserve forest contains large mature trees of the critically endangered Sydney Turpentine Ironbark Forest community; (right) Eucalypts planted across the Park for the 2000 Olympic and Paralympic Games are too young to have hollows

The majority of hollow-dependent animals live in Newington Nature Reserve forest (the Reserve, Figure 1), which contains a 13 hectare remnant of Sydney Turpentine Ironbark Forest, a critically endangered ecological community. The forest and surrounding lands were formerly part of the Royal Australian Navy Armament Depot, Newington. Military use excluded public access and exploitation of the forest for more than 100 years, allowing trees to grow and develop a multitude of hollows (Figure 2).

Since Sydney Olympic Park was constructed for the 2000 Olympic and Paralympic Games, trees planted for the Games are too young to have formed natural hollows. As hollows are a limited resource isolated to the Reserve, the need for supplementary habitat was recognised early. The first nest and roost box project ran for three years from 2003 to 2006; 53 boxes were installed – 20 for birds made from marine ply, 30 for bats made from hardwood and 3 for possums made from marine ply. Only the possum boxes were successful in attracting the target species; Common Mynas, Common Starlings and feral honey bees occupied many boxes. By 2009, most boxes were not functional, being in disrepair, fallen from the tree or missing (Figure 3). Less than one-third of boxes – and only those made from hardwood - were in reasonable condition for reuse.

The first project, though unsuccessful, taught us the importance of box material, design and installation method. Learnings from this project include:

- Hardwood boxes were more durable than boxes made from marine ply
- Waterproofing is required to increase box longevity
- Trial different box heights (boxes were mounted to 3-4m due to safety concerns and for ease of inspection)
- Stable attachments that go around the tree trunk and allow for tree growth are essential. Attaching boxes by nailing mounting strips to the sides of trees and looping wire over small branches were inadequate
- Entrances should be clear. Branches and growing shrubs obscured some box entrances which may have contributed to lack of success
- Anti-myna baffles did not deter Common Mynas on all occasions but this may be due to the positioning of a perch at some entrances, allowing Common Mynas to land there.

Figure 3. Common problems with artificial hollows from the Authority's first nest and roost box project; a) bat box entrance obscured by branches; b) bat box attached to a small branch, with lid missing; c) marine ply possum box with poor attachment and in disrepair; d) marine ply bird box with missing panels; attachment does not allow for tree growth

Current project – an overview

Armed with past lessons and increasing industry knowledge of nest box design, and in consultation with an experienced fauna ecologist licenced to work at heights, the current nest and roost box project commenced in October 2010 with 25 boxes installed around Newington Nature Reserve and in forest grids in Bicentennial Park. These are:

- 10 possum boxes
- 5 natural salvaged branch hollow for parrots
- 5 microbat boxes modified from the first project
- 5 new open-bottom microbat boxes, followed by
- 3 large microbat boxes customised for the threatened Southern Myotis, installed in bridge culverts over a wetland in June 2011

All of these original boxes were designed by Narawan Williams and made from hardwood (SOPA, 2020), and installed at approximately 5-6m from the ground. Regular half-yearly inspections began in October 2011, to determine if the boxes were being used by target fauna and to conduct box maintenance and repairs as required. Inspections are scheduled annually for October to determine box usage and breeding activity in spring, and April to determine box usage as the weather cools.

Inspections are done from a ladder with the aid of an inspection camera, and a torch with red light when inspecting microbat boxes; inspections of Red-rumped Parrot boxes are done through side hatches incorporated into the box design to access the back of the box while minimising distress to the animal.

The project is continually informed by new information, from Ecological Consultants Association conferences, published literature, expert advice as well as in-house research. For example, the Authority observed hollow competition between parrots in Newington Nature Reserve and conducted a study on hollow usage over 2011 and 2012; the study found intense competition for hollows and constant displacement of the smaller Red-rumped Parrot by Rainbow Lorikeets. Despite the large number of unused hollows available in the Reserve, two pairs of Red-rumped Parrots were found nesting nearby in Homebush Bay, in the posts of a disused wharf surrounded by open water (Figure 4). As the species' population was declining in the Park, likely due in part to hollow competition, customised boxes of different material and dimensions were made specifically for the Red-rumped Parrot to provide them with more suitable nesting sites and arrest population decline.

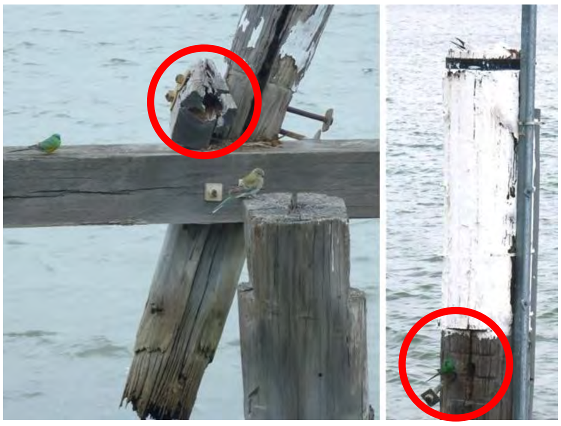

Figure 4. Two pairs of Red-rumped Parrot nesting in disused wharf posts in Homebush Bay; nest hollows are marked with red circles

Just as the plight of the Red-rumped Parrot was identified by Authority staff through observations in the field, observations by Park users have also informed the provision of supplementary habitat for other species. For example, the Authority have responded to reports of Brush-tailed Possums in heritage buildings by installing possum boxes to support relocated possums, as possums must not be released more than 150m from point of capture due to potentially lethal territorial disputes. Similarly, possum boxes have been installed in response to community reports of Brush-tailed Possums in unsuitable locations; three of the Park's possum boxes were donated to the Authority by concerned public and a wildlife rehabilitation group to provide habitat for the Brush-tailed Possum. In the case of microbats, direct observations are rare; the Authority uses data from four-yearly population studies conducted with ANABAT detectors to inform bat box placement.

Regular inspections have facilitated adaptive management in response to hollow occupancy. From 2013, boxes that were unsuccessful in attracting target species for more than 2-3 years were modified and/or relocated almost annually based on expert advice and in-house research. Regular inspections have also allowed relocation of boxes from unstable and potentially unsafe trees, e.g. due to termite activity, to safer locations. Inspections to date have found all boxes continue to be in excellent condition, only requiring infrequent minor repairs and wire adjustments in response to tree growth. Box placement has not included the use of nails or screws in live wood to prevent damage to tree tissue, but has successfully relied on careful site selection where branches are used to support boxes up to 35kg.

The original boxes have been successful with occupancy by target species. However, the Authority continues to trial new artificial hollow designs and new methods to increase the rate of occupancy, and to support ecological needs not supported by existing boxes. For example, microbats roost in groups of varying sizes; following the success of small-chambered microbat boxes, the Authority installed the 'Bat Mansion' in 2014 to provide roosting habitat for larger groups and/or multiple species (Figure 5). In June 2015, the Authority engaged arborists to create hollows inside live trees, to assess whether or not these would be favoured by microbats and birds. In November 2019, the Authority collaborated with the conservation arm of the Avicultural Society of NSW (ASNSW) to provide nest boxes for Red-rumped Parrots along the Parramatta River; to date, 16 Red-rumped Parrot boxes from ASNSW have been installed in Sydney Olympic Park, and Red-rumped Parrots have been observed inspecting these boxes (Figure 6).

Figure 5. The 'Bat Mansion' has much greater internal volume than original boxes and was installed to provide habitat for larger groups or multiple species of microbats. A heavy box like this should be installed with 3-5mm wire rope threaded through rubber hose for tree protection

Figure 6. A Red-rumped Parrot box donated by the Avicultural Society of NSW to support the species along the Parramatta River © Ivan Cindric

As at 2020, the Authority currently has a total of 66 artificial hollows, comprised of:

- 25 microbat roost boxes or logs
- 17 possum boxes, including 3 donated by the community
- 24 Red-rumped Parrot boxes, including 16 donated by the Avicultural Society of NSW

Salient findings from half-yearly inspections over the past 10 years are presented below.

10 years of artificial hollow monitoring

Microbat boxes

Microbat boxes compose the largest proportion of artificial hollows in the Park, and are more varied in design compared to hollows made for other species. The changes in microbat boxes over time illustrate adaptive response through informed experimentation with box design and placement.

The ten original microbat boxes installed near the Reserve in October 2010 are comprised of two designs (Figure 7). Half of the boxes were taken from the 2003-2006 project and modified to include the addition of naturalistic entries through a short length of hollowed branch (spout) and small slits at the side of the box.

Figure 7. The two main bat box designs are (left) closed bottom bat boxes modified from the first nest and roost box project, and (right) open bottom microbat boxes, later modified to emulate the more successful closed bottom design

Large chambers were split into several smaller chambers to suit bats of different sizes and in different numbers, and a cover was installed at the cavity base to help maintain a stable microclimate; this cover can be opened to allow for inspection without disturbing bats which usually cluster at the top of the cavity. Microbat boxes are approximately 50x20x10cm in size and mounted to different aspects (N, NE, NW, S and W) although there appears to be no difference in results. Leary's study on 150 bat boxes (2015) found seasonal differences in preference for aspect of closed bottom boxes for some bat species. The number of boxes at the Park may simply be too small for any species-specific preferences to be evident. All boxes have been used by microbats at one time (either Gould's Wattled Bat and/or Lesser Long-eared Bat), starting from six months to two years after the first inspection.

The other five boxes were a new design of multiple chambers with an open bottom, approximately 33x35x30cm in size. Only one was successful in attracting the Gould's Wattled Bat 1.5 years after the first inspection. Three boxes were taken down and modified in 2013 to emulate the initial design, i.e. adding attractive entries through a spout and slits at the box's side, partially covering the bottom of the box, and drilling a hole between two chambers at the far end from the entrance so bats can move between chambers. All three were taken up by bats after 1.5-2.5 years.

Inspections offer a snapshot in time, and occupancy is often based on the presence of fur and scats, not the actual animal. As droppings accumulate over the six-month period between inspections, it is difficult to determine whether season or aspect play a role in bat occupancy. However, one microbat box facing south consistently housed

Gould's Wattled Bat in April for five years (consecutive for 3 years, followed by a gap then another 2 years). Other boxes did not exhibit such a clear pattern.

Box designs known to be successful elsewhere were adopted for use, including the 'Inverse U' box designed by Narawan Williams for National Parks and Wildlife Service, with an internal volume approximately 4-5 times greater than common microbat boxes, able to support multiple species and large numbers (~157) of breeding microbats (Leary, 2015). The aptly named 'Bat Mansion' is a very large and heavy structure (~35kg), comprised of a horizontal section with two wings, each containing an internal box, allowing bats to move between sections and chambers of different width based on their thermal needs. It only took 1 year to be used by a Gould's Wattled Bat and a Lesser Long-eared Bat at the same time, and thereafter, by larger groups of Gould's Wattled Bat (~20), including the first sighting of a hairless juvenile in October 2017. It is the only box type to support female Gould's Wattled Bats with young in Leary's study of artificial hollow use by bats on the Cumberland Plain (Leary, 2015). At the October 2019 inspection, calls from adult and young Gould's Wattled Bats were heard in two small boxes of different designs, indicating this common species is benefiting from multiple boxes of different designs.

At any one inspection, about 3-4 boxes would contain live bats. However, unlike studies conducted in remnant forest reserves where up to seven species of microbats have been recorded in bat boxes (Leary, 2015), only the Gould's Wattled Bat and Lesser Long-eared Bat have been recorded in boxes installed near Newington Nature Reserve in the past 10 years. Evidence of breeding have been observed in both species.

Key findings and recommendations:

- It may take some years before boxes are occupied by the target species
- Occupancy may be improved by emulating successful designs
- There may be preferences for specific aspects by different species. Install boxes facing different aspects to facilitate roost selection
- Install boxes with larger internal dimensions to accommodate larger groups including maternity groups, an important component of microbat populations
- The boxes provided have not augmented habitat for species other than the common Gould's Wattled Bat and Lesser Long-eared Bat, and may have increased the relative abundance of these common species. Going forward, the abundance, distribution and hollow requirements of other microbat species in the vicinity needs to be investigated.

Australia's only fishing bat – the Southern Myotis

In June 2011, three large, multi-chamber, open bottom microbat boxes were placed in culverts over the freshwater Narawang Wetland to attract microbat species that prefer to roost in caves, tunnels and under bridges. Each box is approximately 80x40x30-40cm. The numerous vertical chambers of varying width were divided by timber ~ 15-25mm thick to create different microclimate. There are also two chambers above some of the vertical slots (Figure 8).

a) b) c)

Figure 8. a) Bat boxes installed in culverts over a wetland have been successful in attracting the Southern Myotis, a microbat species listed as vulnerable in NSW; b) the box is large with many chambers to accommodate different group sizes; c) the vertical chambers of varying width are flanked by timber of varying thickness

It took 1.5 years for microbat droppings to appear, and almost four years for the first group (6) of Southern Myotis to be recorded. The Southern Myotis is Australia's only fishing bat, and is listed as vulnerable under the *Biodiversity Conservation Act* 2016. The species' natural roost preferences are tree hollows and caves near water or directly over water if roosts are available. They also roost in tunnels and culverts, and under bridges and piers; bat boxes targeting the Southern Myotis have been successful in replacing roost sites lost during bridge upgrade (N. Williams, pers. comm.). The species has been found to select for cavities with smaller entrances compared to available, unused cavities in the area (Campbell, 2009).

After the first Southern Myotis sighting, adult Southern Myotis with young appeared in the same box six months later (October 2015); thereafter, the population began growing in number and has expanded to use other boxes. Juveniles were observed again in November 2019 and October 2020. At the time of writing, this is the only known maternity roost on the Parramatta River. Abundance continued to rise over time. The April 2020 count of 28 individuals across two boxes is the highest number recorded at this roost site.

Myotis were found to roost in the open bottom vertical chambers as well as the larger, horizontal cavities above these vertical chambers. The open vertical chambers are of different width, and are made by timber planks of different lengths and thickness. Based on the presence of Myotis and their scats, there may be a preference for the 'shorter' chambers, where the timber does not protrude too far from the side walls. Myotis scats are found in multiple chambers in each of the three boxes, indicating the bats visit more chambers than they are observed to roost in. One chamber has been continually used since the first Southern Myotis was observed, and this may continue to be the maternity chamber into the future.

In 2018, a round branch hollow with an open bottom was attached to one of the boxes to test their preference for naturalistic hollows that can accommodate larger groups; so far there has been no sign of microbats visiting or roosting in this hollow.

Key findings and recommendations:

- Understand the species' ecology and install boxes in appropriate locations
- It may take many years for the target species to be observed using the artificial roost
- Provide different microclimate by making chambers of different width and wall thickness, as well as open bottom chambers and closed cavities; record details to facilitate replication if a preference is identified.

Other microbat boxes

Following the success of the Myotis boxes in Narawang Wetland, the Authority installed Myotis boxes in the Brickpit, as ANABAT records suggest the Southern Myotis forage over the many large ephemeral and permanent freshwater ponds in the precinct. Three large, round timber hollow sections were selected to provide for communal roosting; a large metal sheet was placed over the top of these hollows to protect the bats from rats and other predators. Two other general microbat boxes were also installed in the Brickpit. Surprisingly, there has been no sign of usage such as scats since installation in October 2015. The precinct may contain sufficient numbers of suitable natural roost sites for microbats, or the positioning of the roost boxes was just not favourable. These boxes are being progressively relocated to new trial locations, selected based on the presence of suitable microbat foraging habitat but potentially lacking in suitable roosting habitat.

Key findings and recommendations:

- Hollow occupancy may not occur even if the target species is confirmed to be present and foraging ground is nearby
- Regular monitoring allows inactive hollows to be identified and relocated to other areas sooner, with potentially better results.

Red-rumped Parrots

In May 2012, eight boxes were custom made for this species, two from PVC, and six from hardwood. Two were installed near Newington Nature Reserve and six on timber posts at the Archery Centre, near a confirmed nesting site at an old wharf and also near a large expanse of turf where the birds were known to feed (Figure 9).

Figure 9. Red-rumped Parrot boxes installed on timber posts at the Archery Centre

The boxes have a landing platform with a ladder for climbing, internal ladder for young to climb out, a small entrance (45 to 60mm) to exclude non-target parrots, anti-myna baffle, peat moss for nesting, and a side hatch or removable lid for inspection. They were mounted at a height of 5 metres or above with the entrance facing north-east or east. Two of the hardwood boxes were 'vertical' i.e. 45cm in height (internal volume approx. 23x23x35cm) and four 'horizontal' i.e. 45cm in length (2 internal chambers each 12x15x20cm); two of the latter were mounted at 45 degrees. Only the nest boxes installed at the Archery Centre have been successful. The two boxes at the Reserve were relocated to another location adjacent to the parrot's known feeding ground in October 2015, before being relocated to the Archery Centre in April 2017 due to lack of occupancy.

The parrots inspected and used the boxes for breeding in the season following installation, and they used every box type, with eggs or fledglings found in each, i.e. PVC, hardwood horizontal, hardwood horizontal mounted at 45 degrees, and hardwood vertical. The same three hardwood boxes were used in the following seasons, with chicks successfully raised to fledging (Figure 10).

Successful recruitment has boosted the Red-rumped Parrot population; the annual Red-rumped Parrot surveys across the Park detected an increase from just over 30 birds in 2013 to more than 80 birds in 2018.

Unlike the hardwood boxes, the PVC box presented problems from the start – four unhatched eggs were found in the season following installation (April 2013). While a fledgling was seen in the box in October 2013, and another breeding attempt was made as suggested by egg shells and a chick skull seen in April 2015, the parrots stopped using the box. Lack of breeding success in the PVC box may be related to temperature, as the box presumably gets hotter than the hardwood boxes, particularly as the boxes are completely exposed to solar radiation. To test this theory, the other PVC box was taken down, covered in insulation material and returned to the same post as the uninsulated PVC box in April 2018. So far, the only bird attracted to the box was the Common Starling, which used it in the spring 2019 breeding season, suggesting a preference for the insulated PVC box to the uninsulated PVC box right above it. Since nest box installation in April 2012, this is the only non-target species to use the nest boxes, with one previous attempt in 2013.

To better understand the role of temperature on breeding success, 11 temperature and humidity loggers called I-buttons were installed in June 2019 on the inside of used and unused nest boxes,

Figure 10. (left) A pair of Red-rumped Parrots at a horizontal hardwood nest box mounted to 45 degrees; note the dampcourse over lid, anti-myna baffle and parrot ladder at the front, and a side hatch to facilitate inspection; (right) three Red-rumped Parrot chicks in a vertical hardwood box; note the grooves carved into the inside of the box to assist the young to climb out

and on the posts on which they sit (Figure 11). These temperature and humidity loggers will record data for one year before they are removed for data analysis.

Figure 11. An I-button temperature and humidity logger attached to the inside of a horizontal hardwood Red-rumped Parrot nest box

Key findings and recommendations:

- Inform installation location with field observations and known ecology of the species; locate boxes close to known foraging grounds
- Customise boxes to the target species; trial different materials, aspect and design where possible
- Temperature may have adverse impacts on reproductive success; locate boxes across different thermal gradients to allow choice, and use materials that provide greater insulation qualities.

Natural branch hollows for parrots

The Authority's study on hollow usage in Newington Nature Reserve identified a concentrated area of breeding activity by the Rainbow Lorikeet, Galah, Sulphur-crested Cockatoo, and Red-rumped Parrot. Available hollows are present outside this hotspot but not used. Five natural branch hollows for birds were installed in October 2010 in the perimeter area just outside the Reserve. Despite the proximity, these were never used by the target species. Instead, three of the five hollows were regularly used by rats.

After 3.5 years the hollows were removed, modified, and re-installed at Archery Centre (Figure 12). The expanse of turf at the edge of the Archery Centre shooting range provide excellent foraging grounds for the Red-rumped Parrot, and nest boxes installed here in 2012 for the species were quickly used to raise young successfully. It was thought that the natural hollows may provide additional nesting habitat, and also inform management of the species' preference in hollow type and structure. The salvaged hollows were capped at one end, and dampcourse was applied where water ingress may occur. As the hollows were installed on tall timber posts, metal strips and nails were used in addition to PVC-coated wire for attachment, as there was no concern of sap corroding the nails or the attachment harming the tree.

Since their installation in April 2014, all hollows have been used by microbats periodically based on the presence of bat scats, with up to two Gould's Wattled Bats seen in three hollows and a Lesser Long-eared Bat in another. No Red-rumped Parrots have used the capped natural hollows. The internal volume of the hollows may be more suited to microbats. Also, by this time, the Red-rumped Parrots have already shown a preference for a subset of the available hardwood nest boxes. These natural hollows have now been classified as bat roosts.

Figure 12. A salvaged branch hollow modified to provide nesting habitat for the Red-rumped Parrot was used by microbats instead

Key findings and recommendations:

- Artificial hollows need to be installed in known active breeding area of the target species
- Hollows of different types should be installed at the same time to test for preference

Possum boxes

Possum boxes are simple in design. The ten original hardwood boxes installed in 2010 are approximately 45x30x35cm with an entrance of 12x13cm; subsequent boxes are similar in size, but come with improvements such as a climbing stick near the entrance, and dampcourse to waterproof the lid (Figure 13).

Lack of a climbing stick in the original boxes did not hamper occupancy, as most boxes were occupied in the first inspection one year after installation, and have been occupied on a regular basis since; females with joeys have been seen in all but three of the original boxes. In the original design (Figure 13a), the front wall is comprised of two panels, and the small gap between the panels was not

a)

b)

c)

d)

Figure 13. a) original hardwood possum box installed in 2010; lack of climbing stick does not appear to affect uptake; b) Men's shed possum box donated by WIRES in 2016; c) Men's shed possum box with additional dampcourse on lid, installed in 2017; d) hardwood possum box with dampcourse on lid installed in 2018

considered a concern. However, in October 2017, an Australian Wood Duck nesting in one of the possum boxes died after its foot became stuck in the gap between the panels. The gap had become larger over time as the timber panels expanded and contracted in response to humidity and temperature. Subsequently, all the gaps were plugged to prevent similar incidents from occurring in the future, and design changes such as single-panel walls will be used in future boxes.

The time between box installation and occupancy differed with location, not with box design. Boxes installed near Newington Nature Reserve and in the forest grids of Bicentennial Park were occupied shortly after installation; however, it took six years for a box with the same design installed in Kronos Hill to be used, even though the box was installed in response to possum sightings, including a possum sleeping in a garbage bin, indicating lack of suitable shelter. Kronos Hill was planted with thick stands of eucalypts for the Games, with a sparse understorey dominated by the invasive grass kikuyu. Staged replacement of weeds with native shrub plantings commenced in the precinct in 2014. The development of a habitat with greater floristic and structural diversity may have created adequate food resources for the Brush-tailed Possum in what was once a movement corridor for the species.

Distance between boxes, as short as 10-50m in the case of the six possum boxes in Bicentennial Park, did not appear to affect occupancy or the condition of the occupants. At most inspections, five, or sometimes all six boxes would be occupied, with dependent young in some boxes. All animals have appeared to be in good condition to date.

Possums are adapted to the urban environment and will roost in roof spaces and other human structures. At Blaxland Riverside Park, a possum moved into a playground climbing tower, roosting underneath a protruding section of the structure about 15 metres off the ground (Figure 14). The sleeping possum could be seen from inside the climbing tower, and prompted numerous enquiries from concerned community members. Two boxes were donated by WIRES and installed near the tower in 2016 (Figure 13b). These were not occupied until one year after installation, and the possum in the climbing tower continued to roost there.

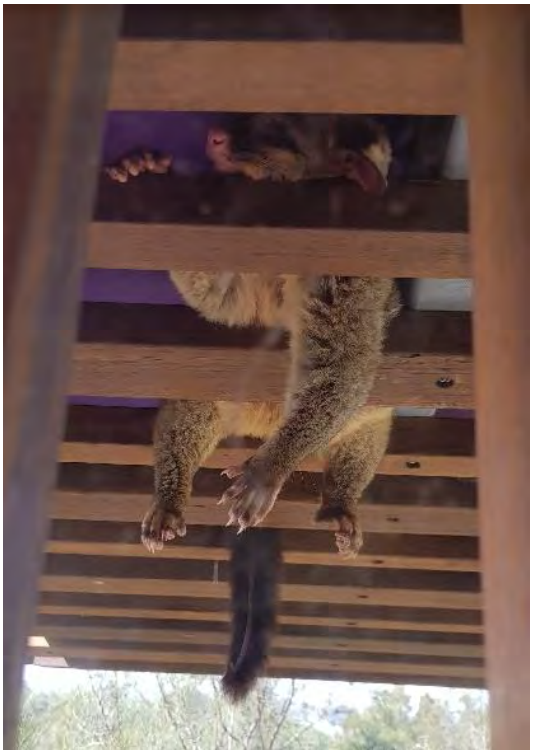

Figure 14. Brush-tailed Possum roosting in the climbing tower

The area encompassed by Newington Nature Reserve, Newington Armory and Blaxland Riverside Park appears to have a high possum population. Fights between possums, presumably over territory, have been observed, and Authority staff once rescued an injured possum sheltering in a skip bin. In response, two more possum boxes were installed in the area in 2018, and these were occupied within six months. Again, the possum in the climbing tower has not relinquished its roost; it was there at the April 2020 inspection, even though two of the possum boxes in the vicinity were unoccupied on the day.

Similarly, two possum boxes in Narawang Wetland were installed in January 2017 following public concern over a young Brush-tailed Possum being harassed by birds. Despite the lack of tree hollows in the area, and what appear to be abundant food resources, it took almost two years for one of the boxes to be occupied, and by a Common Ring-tailed Possum rather than a Brush-tailed Possum.

Apart from the Common Ring-tailed Possum, which has been found in three possum boxes to date, the Australian Wood Duck is the only other native fauna and the only avian species to use a possum box. Feral European honey bees have infested three possum boxes to date. Interestingly, feral honey bees have only been found in possum boxes, and not in boxes designed for other species. Unlike microbat boxes which have narrow internal cavities, the large internal cavity size of possum boxes appears to suit feral honey bees in establishing hives. The Red-rumped Parrot boxes, although of suitable cavity size, may be in a location that is not favourable for feral honey bees (N. Williams, pers. comm.).

Some studies suggest the bees are likely to move away on their own; however, the Authority actively manages this Key Threatening Process to prevent the bees from taking over natural hollows in the Reserve. Covering the entrance is one method to exterminate the bees without the use of chemicals, and has been used successfully. However, in light of the positive value of honey bees to the beekeeping industry, the Authority has since approached a licenced beekeeper to assist with bee removal, and one of the infested boxes was taken down and the bee colony relocated. The percentage of boxes affected is ~18% to date. Due to ongoing management, bee infestation has not occurred in more than one box at one time, so the infestation rate remains low at ~6% per inspection.

Key findings and recommendations:

- Have gap-free panels to avoid risk of injury or death to fauna
- Possum boxes located in high density areas may not be used if the animal already has preferred roosts
- Boxes may be installed in close proximity to each other without adverse effects
- Native and introduced fauna may occupy the box; devise management options for feral honey bees.

Habitat trees

At the Hollows as Habitat forum co-hosted by the Authority and Greater Sydney Local Land Services in May 2015, arborists demonstrated how to create hollows in trees with chainsaws. A faceplate is first taken off the tree, and the desired internal volume removed section by section; the faceplate is returned and secured, and an entrance hole of the desired diameter drilled into the faceplate. This method creates an approximation of a hollow made by natural processes, with the advantage of providing a hollow that is natural in looks and also potentially more favourable in terms of insulation properties.

This technique was subsequently trialled at the Park in 2015. Four trees were chosen for this trial, two *Corymbia* and two *Eucalyptus* trees, and each had two bird hollows and one bat hollow carved into the tree. The first inspection in

December 2015 found no activity and identified improvements, i.e. hollow should be smaller than faceplate, so that light doesn't penetrate after the faceplate shrinks, and that the bird hollows were too narrow and shallow for birds. A subsequent inspection in October 2017 found one *Corymbia* too unstable to inspect. A couple of bird hollows in the *Eucalyptus* trees may have been inspected by wildlife, based on the presence of unidentified scat in one hollow, and the other hollow having been scraped clear. Entrances to the bat hollows have become too small or sealed over.

Key findings and recommendations:

- It may be better to trial hollow creation on dead or senescing trees so that wounds don't seal over as is likely to happen in live trees
- Trial different cutting technique into live trees
- Account for faceplate shrinkage to ensure the cavity is adequately protected from light
- Provide sufficient internal volume for target species
- Use arborists experienced in this technique, or arborists guided by ecologist on fauna requirements.

Conclusion

Sydney Olympic Park Authority's nest and roost box project has provided supplementary habitat to the Common Brush-tailed and Ring-tailed Possum, Red-rumped Parrot, and microbats including the Southern Myotis, Gould's Wattled Bat and Lesser Long-eared Bat.

The effect of supplementary habitat on the Red-rumped Parrot has been the most clear and most successful. This species took up the customised nest boxes soon after installation and has raised young annually, increasing the population from a low of just over 30 birds across the Park in 2013 to a high of 87 birds in 2018. The successful boxes were positioned on the south east side of the posts, but box orientation did not matter. While other customisation likely assisted in increasing box uptake, the lack of success of the same boxes in two other areas suggest installation location is important. As the boxes are completely open to the elements, they are subject to predicted increase in temperature and extreme weather events due to climate change. As artificial hollows are less insulated compared to tree hollows due to thinner walls and larger surface area to volume ratio, future reproductive success or offspring development is likely to be negatively affected (Larson et al., 2018). Data from the temperature and humidity loggers will inform if there is temperature variation in used and unused boxes in close proximity to each other, and assist with future placement of nest boxes. Studies are being conducted on insulation products or methods to buffer artificial hollows from extreme temperatures, such as foil batts and paint (Griffiths et al., 2017; Larson et al., 2018); boxes with different thermal properties may need to be installed across different levels of canopy cover and aspect to provide suitable habitat to a range of species.

Although the Authority's trial with chainsaw hollows was not successful, research in this area is continuing apace. Mechanically created hollows have been used by birds, microbats and arboreal marsupials (Rueegger, 2017). Other research has found internal decay can occur in trees before access is developed e.g. though limb breakage, and it may be possible to add artificial entrances to developing voids to increase hollow availability in the landscape (Ellis, 2018). The Authority will keep abreast of developments in this field, as it has the potential to substantially increase the number of tree hollows with the insulation property of live trees across the Park.

The outcome of microbat boxes is equivocal. Studies have found microbat boxes can increase bat populations, but favour common species disproportionately (Leary, 2015), as has happened at the Park with bat boxes outside Newington Nature Reserve providing habitat to two common microbat species. In contrast, bat boxes installed above freshwater wetlands for the Southern Myotis have been a success. The boxes were located within the species' foraging ground, and were used for both roosting and breeding, suggesting the species' ecological needs were met. This is of significance as the species is listed as vulnerable in NSW and few maternity colonies are known. The box design may be replicated elsewhere to provide habitat for the Southern Myotis. Investigation into the habitat and ecological needs of other uncommon microbat species in the Park, particularly threatened species, and how to deliver supplementary habitat at a scale that is helpful, is the next task to address.

Based on reduced observations of Brush-tailed Possums roosting in inappropriate locations (roof spaces and bins), the provision of roost boxes may have contributed to easing the pressure of housing shortage. Without possum boxes, these possums may be roosting in roof spaces, or experience increased territorial disputes.

Tree hollows are a critical resource that cannot be easily replicated or replaced by artificial hollows. Much remains unknown about the attributes that hollow-dependent species rely on for their survival; many species do not use artificial hollows, and those who do may be lured into an ecological trap if the artificial hollows – installed for the purpose of attracting fauna to a resource that they become dependent on – are not made, maintained and monitored adequately into the long term. Ultimately, processes causing the continual loss of hollow-bearing trees need to be slowed, and halted where possible, and artificial hollow provision should be part of a holistic habitat restoration practice alongside replacement tree plantings, with the aim of providing suitable, long-term habitat for a full assemblage of fauna to ensure their continued survival.

Acknowledgements

Sydney Olympic Park Authority acknowledges Narawan Williams, fauna ecologist, for his expert advice and high quality boxes that has contributed to the success of the nest and roost box project; and the Avicultural Society of NSW for the donation and installation of Red-rumped Parrot boxes. Multiple SOPA staff participated in field inspections.

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Quality and longevity in artificial hollows - how to design and install long-lasting boxes

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There has been concern over the longevity and quality of nest boxes that are being installed especially where there is no long-term monitoring and maintenance inspections set in place. Average life of nest boxes can range from 2 to 15 years depending on multiple factors such as material used, construction design and how the box is attached onto the tree. There are also uncontrollable factors which can affect nest box longevity such as weather conditions, termite infestation and chewing of the box by species such as Cockatoos.

The aim of any nest box installation is to provide habitat refuge for hollow-using fauna species, so it is important that we use nest boxes that are high quality, of suitable design and will stay in position on the tree. A good quality box will often cost more to purchase however if it lasts 5 times longer with no maintenance required then there is cost benefit to the manager and to the fauna that use them.

Identifying weak points in the structural design of a nest box and improving those features will make a difference to box longevity. Important features include: a good durable protective lid, suitably positioned hinge, durable material with minimum thickness of 18mm, sealed cut edges, non-rusting screws and a zig zag wire expandable attachment to allow for tree growth. Annual maintenance inspections are useful in identifying attachment failures or box condition decline, and allow for timely repairs.

Introduction

There may be a misperception that making a nest box is easy and cheap. It can be if you don't want your nest box to last very long. There are a number of factors that have to be considered.

I have been making, installing and inspecting artificial hollows including nest boxes, capped hollows and augmented chainsaw hollows for over 18 years. These have been targeting mostly a diverse range of nocturnal mammals including microbats along with both diurnal and nocturnal bird species in a variety of habitats. In most part artificial habitat has been installed as replacement for lost hollows, to provide temporary fauna refuge directly after clearing works, and for habitat improvement in hollow depauperate sites such as Council reserves and offset sites.

Early on in my career I was installing form ply nest boxes with metal strapping and roofing screws. I was not satisfied with this method of attachment and was disappointed with the limited life span of many plywood boxes, especially when they were meant to be replacing lost natural hollows. Nest box structural designs had not changed much over the years and plywood was one of the most commonly used materials. I started to observe what were the common features that were failing and causing the box to deteriorate or to fall off the tree. The two most common factors of nest box failure were the lid falling off, and using a non-expanding attachment method. I then looked at ways to alter the design to increase longevity of the box; and rather than using plywood I made boxes from seasoned hardwood timber. My first hardwood box has been up for almost 15 years without requiring any repairs and has a family of sugar gliders regularly observed using it. The wire zig zags on the attachment are still expanding. None of the hardwood boxes have failed structurally apart from one incidence which required a lid replacement. As most people make nest boxes out of plywood, I also looked specifically at how a plywood box could be constructed to last longer. Some of the important factors are the type of plywood used, minimum thickness, cut edges in particular have to be sealed well, and the hinge positioned appropriately or sealed strongly so the lid does not fall off due to decay.

Key to long-lasting artificial hollows

Experience has shown that box material type, attachment method, structural and species-specific design and placement are important for box uptake and longevity. Observations have shown:

- thin plywood boxes fail faster than thicker well sealed plywood or hardwood
- long-lasting screws hold boxes better than staples or nails (Figure 1)

Figure 1. A staple (shown here) and nails do not hold as well as good quality screws

- it is essential to account for tree growth or both the box and the tree will be impacted. Hardwood boxes have been in place for 10 to 15 years without requiring maintenance or replacement with the zig zag Habisure attachment method continuing to expand out. In contrast, tree growth can push boxes with non-expanding attachment off the tree, or start crushing the back plate, and/or push the lid off (Figure 2)

- one of the most important parts of the box is the lid as this helps protect the rest of the box from decaying and makes a dark and safer cavity for the species that rely on the box
- lids that are not much wider than the top of the box allows water to more easily reach the end grain of the ply walls or enter inside the box
- metal edging on the lid and around the entry hole can protect plywood from being chewed by animals, maintaining the entry hole size for target species
- hinges screwed into the cut end grain of the lid without being very well sealed is a common failure and will result in decay around the screws, followed by lid falling off (Figure 3). Brushtail possums, Ringtail possums, Rosellas and other species will use boxes without lids however the box will decay faster, and the young may drown in heavy rain
- nest boxes will often be used by non-target species with entry-hole size being the factor to exclude larger non-target species
- when targeting specific species, having an understanding of the species' breeding or shelter requirements can assist. E.g. Red-rumped Parrots were regularly observed feeding in an area that lacked nesting hollows. However, exposed wooden posts were available to install boxes on. As

Figure 2. A box with a crushed back plate and lid pushed off by tree

Figure 3. Decay around hinge screws will result in the lid falling off

Figure 4. Successful hardwood Red-rumped Parrot box

the species nest in spring and summer, hardwood boxes were placed on the south-east side of posts to give some protection from the hottest parts of the day. The entry hole size was made just adequate for this species to enter, excluding larger species. This has been successful with Red-rumped Parrots raising young in the boxes (Figure 4).

There are many hollow-dwelling species we have not been able to provide habitat for and this is something that needs to be acknowledged when installing nest boxes as a mitigation measure. More trials are required to create appropriate habitat for a greater number of species, including targeted habitat for amphibians and reptiles, which on occasion will use standard nest boxes to shelter in.

Design recommendations

I have tended to preference using 20 to 25mm thick hardwood timber to make nest boxes (Figure 5) for many reasons, such as:

- good durability
- very little chemical product required (e.g. coating lid with timber seal oil or end grain with long lasting paint)
- better insulation properties
- easier to cut climbing ladders into the inside and outside of the box
- more natural in appearance.

The few downsides are that it is heavier than other materials and may not be able to be sourced as easily or sustainably. However, there are plenty of trees being cut down for other reasons that could be salvaged to make nest boxes.

For a lighter weight design, a combination of hardwood and durable ply with minimum thickness of 18mm can be used, however consideration needs be taken to get the longest life out of it.

Some suggestions of how to do this from my experimenting are:

- a good durable protective lid
- suitably positioned hinge under lid edge rather than into end grain of ply (Figure 6)
- durable ply with cut edges sealed well using oil based outdoor paint or other long lasting oil based product
- durable non-rusting screws to hold the box together
- base plate inset within side walls (Figure 7)
- a good zig zag wire expandable attachment to allow for tree growth (Figure 8)
- use wire knots inside box to stop the wire from pulling out. When the box eventually falls apart the wire will not be left siting all the way around the tree thereby reducing risk of harm to tree. Check no sharp edges of wire are protruding (Figure 9)
- avoid using metal mesh ladder as these often have lots of sharp edges when cut. Hardwood timber ladders allow for some chewing by parrots however is not harmful to the bill
- a strip of hose makes a good latch to hold the lid in place and stops larger animals lifting it (Figure 10).

Figure 5. A durable hardwood box with 20-25mm thick timber

Figure 8. Expanding zig zag Habisure attachment

Figure 6. Hinge screwed into side and up under lid using good quality screws

Figure 9. Wire knots inside box stops the wire from pulling out

Figure 7. Inset base plate and include some drainage holes or small gaps

Figure 10. A strip of hose makes a good latch

The attachment is a key feature that can determine the useful life of a nest box. Expanding zig zag Habisure attachments are proving to be successful along with large galvanised nails to hang box onto (Figure 11). Another method is the use of long galvanised coach screws with metal spacers, allowing the tree to grow over the spacer rather than pushing directly against the box (Figure 12).

Figure 11. The zig zag Habisure attachment method used in conjunction with a wire loop over long galvanised nail

Figure 12. The spacer attachment method

Having a combination of two attachments for a box allows for one attachment failure. The box remains in the tree until the failed attachment can be rectified or remains until the box falls apart. Annual maintenance inspections from the ground can identify attachment failures or box structure condition decline.

What to consider before you install

If you wish to purchase or make your own nest box, first consider the benefit of installing it. How will it help the species you are considering providing habitat for?

There are nest box designs on the internet however are they built for longevity, with good structural design and an appropriate expanding attachment, along with meeting the needs of your target species? Don't be afraid to contact the supplier/designer and ask questions.

If you are not sure of where or how to position your box you could do your own search on the target species to find out information, such as do they breed in summer or winter or anytime of the year, is there abundant food sources available nearby or linking vegetation corridor which allows your target species to travel into the installation area. There are many factors to consider with box placement however generally avoid the entry hole facing coldest winds (south, south west) and avoid hottest side of tree (often hottest on north round to west depending on canopy cover). Alternatively employ an experienced person to install it for you. Contact local Environmental Consultants, Local Land Services and Council Environmental Officers to recommend quality nest box suppliers and installers.

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About the author

Narawan has had the pleasure of being involved with native wildlife all his life. He has been a Fauna Ecologist for over 20 years. Part of his work and passion has been creating fauna habitat which has included installation, monitoring, and construction of nest boxes, capping salvaged hollows to reinstall, monitoring and advising on augmented hollow designs and educating community on the importance of habitat for wildlife. Concerns over the short life span of many nest boxes led him to look at different ways to increase longevity, with the long-term aim to share and discuss designs with others to encourage longer-lasting nest boxes.

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Nest box failure: most common reasons

1. **Poor quality materials and construction**
   - Inappropriate ply or timber
   - Plywood/timber too thin, i.e. under 18mm
   - Cut edges not sealed adequately, particularly for ply
   - Poor quality screws and staples, i.e. rust and too short
   - Lid with inadequate overhang

2. **Lid failure**
   - Hinge not protected from weather: ply/timber deterioration around screws causing them to loosen
   - Tree pushing lid off box
   - Lid hinge screws often fail due to being screwed into cut edge of ply and not sealed well. See below.

3. **Failure of hanging attachment**
   - Attachment does not allow for tree growth and forces failure of box or strapping
   - Sap of tree corrodes screws and metal strapping. Some species more corrosive than others. E.g. *Corymbia gummifera* and *Angophora costata*

4. **Base plate falls out**
   - Moisture entering box causes rot in base
   - Inadequate drainage holes or gaps in base plate
   - Base plate not inset into base of box

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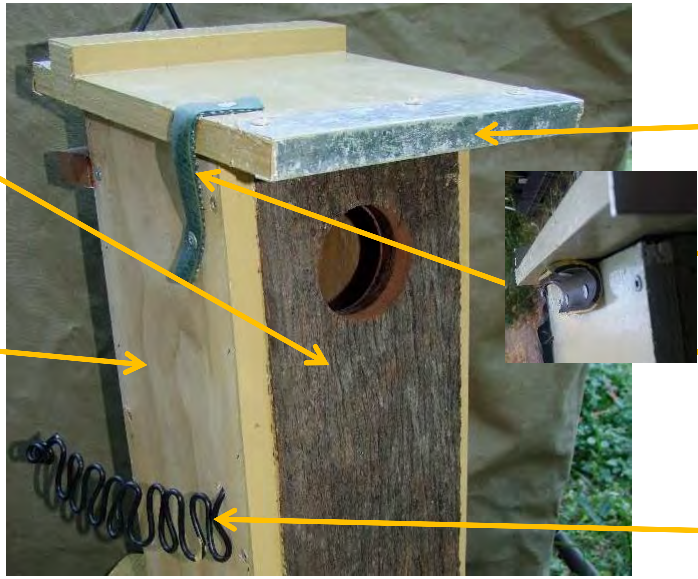
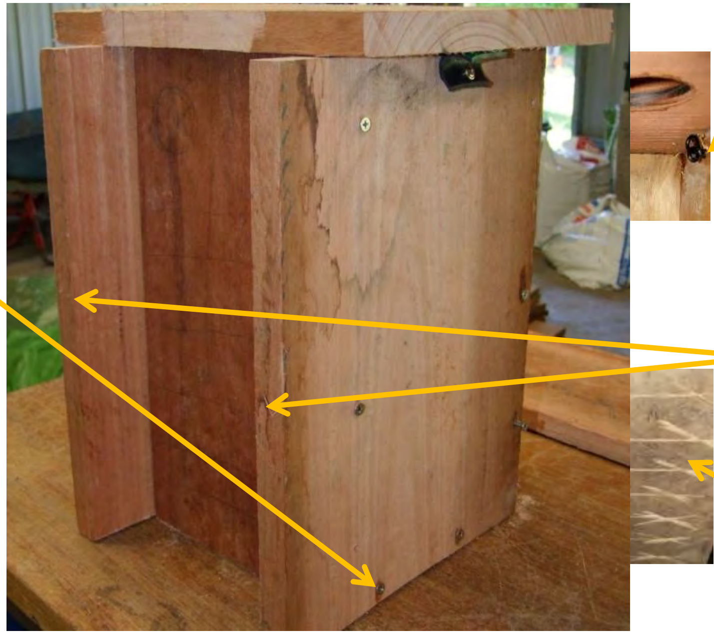
Recommendations to increase nest box life

1. Good quality materials and construction

- Made of seasoned hardwood timber or a combination of hardwood timber and ply. Suggest entry panel made of hardwood with climbing grooves. 3 sides plywood (well sealed ply lid or double layer of ply for extra life)
- Seasoned hardwood 20 to 25mm thick.
- For lighter weight box make 3 sides and lid from birch, marine or another external outdoor ply
- No ply thinner than 18mm
- Seal cut end grains and lid surface
- Use appropriate sealer to stop ply splitting in weather e.g. exterior oil based paint or marine based treatments
- For hardwood and ply surface you can use oil-based product such as Cutek (organic vegetable oil based product)
- Use stainless steel or outdoor decking screws 40 to 50mm long
- Pre-drill to avoid splitting timber
- Hinges can be made from thick rubber hose attached with galvanised flat head screws or non-rusting metal hinges
- Base plate inset into side panels with 4 to 5 drainage holes (5 to 6mm wide) or gaps (no more than 4mm wide)





2. Lid

- Lid overhang minimum 20-30mm
- Use metal plate on front and back edge of lid to prevent animals chewing. Fix with screws and sealant
- Fit hinges under edge of lid to protect from weather
- Two layers of ply will further increase longevity
- Secure lid in place with a latch to maintain alignment and closure

3. Attachment

- Use zig zagged wire for attachment to allow tree growth. Make spring form if heavier box
- Use 3.15mm wire, PVC coated
- Knot wire inside box wall to secure. Avoid sharp points
- Use 3 to 5mm wire rope threaded through rubber hose to install larger/heavier boxes

4. Design

- Include side flanges to stabilise box against tree
- Entry hole can go on front, back or side of box depending on target species
- Cut climbing grooves on inside of hardwood entry plate. A couple of grooves on front below entry hole

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How Sydney Olympic Park's mangroves are responding to climate change

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The Badu Mangroves precinct within Sydney Olympic Park supports the largest remnant mangrove forest in the Sydney Harbour-Parramatta River estuary. The forest has been continuously monitored using the Surface Elevation Table-Marker Horizon technique for nearly 20 years, providing insights into the response of mangroves to two decades of sea-level rise. Surface elevation gain in the wetland has been strongly linear over the time period and corresponds to approximately 6cm of vertical accretion comprising mineral and organic matter accumulation. Mangrove root material is contributing to over 40 tonnes of carbon sequestration per year within the wetland, contributing to vertical adjustment of the wetland surface. Sea-level rise over the period has been higher than the rate of mangrove vertical adjustment, though is more variable. Mangrove dieback within the wetland is consistent with a ponding of water during the spring tide cycle and has been ameliorated by the cutting of a direct channel from the dieback zone to the main creek channel. The long-term fate of mangroves within the parklands will be determined by emissions pathways over the coming decades and local decisions concerning land use, coastal protection and floodgate operation.

Introduction

Sydney Olympic Park supports some of the largest mangrove forest within Sydney Harbour, with forests located in each of the precincts of Badu Mangroves, Haslams Reach, Newington Nature Reserve and Nuwi Wetland. The mangrove is dominated by the grey mangrove *Avicennia marina*, with minor representation of the river mangrove *Aegiceras corniculatum*. The largest forest, Badu Mangroves, has been modified since the 1950s with the training of Powells Creek (initially causing extensive dieback of mangrove lining the former channel) and the deposition of dredge spoil and brick dust on the site, subsequently colonised by saltmarsh (Rogers et al. 2005). Mangroves have since expanded to cover most of the area of original saltmarsh.

The mangroves at Sydney Olympic Park, in common with mangroves across the globe, are facing the pressure of accelerating sea-level rise. Global eustatic sea-level rise has accelerated through the past century, increasing from an average rise of 2.0 ± 0.3 mm yr^{-1} in the period 1966-2009 to 3.4 ± 0.4 mm yr^{-1} in the period 1990-2009 (White et al. 2014). Sea-levels in Australia are influenced year-to-year by large-scale ocean-atmosphere drivers such as the El Nino Southern Oscillation and the Indian Ocean Dipole. When adjusted for these influences, the mean rate of sea-level has risen from 1.4 ± 0.2 mm yr^{-1} in the period 1966-2009 to 4.5 ± 1.3 mm yr^{-1} for the period 1993-2009 (White et al. 2014). Tide gauges within the Badu Mangroves suggest a similar rate of rise over the past two decades.

Sea-level rise poses challenges and opportunity for mangroves. Mangroves respond dynamically to changing inundation patterns and increases in inundation frequency can lead to increases in the rate of sedimentation and plant productivity. However, upper thresholds to these feedbacks are suggested by the palaeo-stratigraphic archive (Saintilan et al. 2020). Monitoring networks are being established to carefully explore the response of mangroves across the globe to sea-level rise. Badu Mangroves is one such wetland, and this paper presents results emerging from nearly two decades of observations of mangrove adjustment to sea-level rise.

Monitoring Elevation Gain

The surface elevation table is an elevation benchmark inserted deep into a wetland substrate, against which changes in the elevation of the wetland surface are measured. At the same time a small quadrat is covered with white feldspar powder, which serves as a marker horizon against which sediment accretion can be measured. The two techniques, when used together (referred to as the Surface Elevation Table-Marker Horizon or SET-MH method), allow both the estimation of elevation gain and the extent to which sediment accretion is contributing to surface elevation gain. If elevation gain is less than accretion over the same time period, the difference is the degree of subsidence occurring in the wetland between the surface and the base of the SET benchmark pole (Figure 1).

A network of SET-MH stations was installed in the Badu Mangroves and saltmarsh in 2000 and has been continuously monitored for 20 years. This is one of the longest SET-MH records in the world, and the unusual longevity of the buried feldspar horizons makes this the longest mangrove MH record known globally (Figure 2). The Badu Mangroves at Sydney Olympic Park are therefore providing a unique record of the

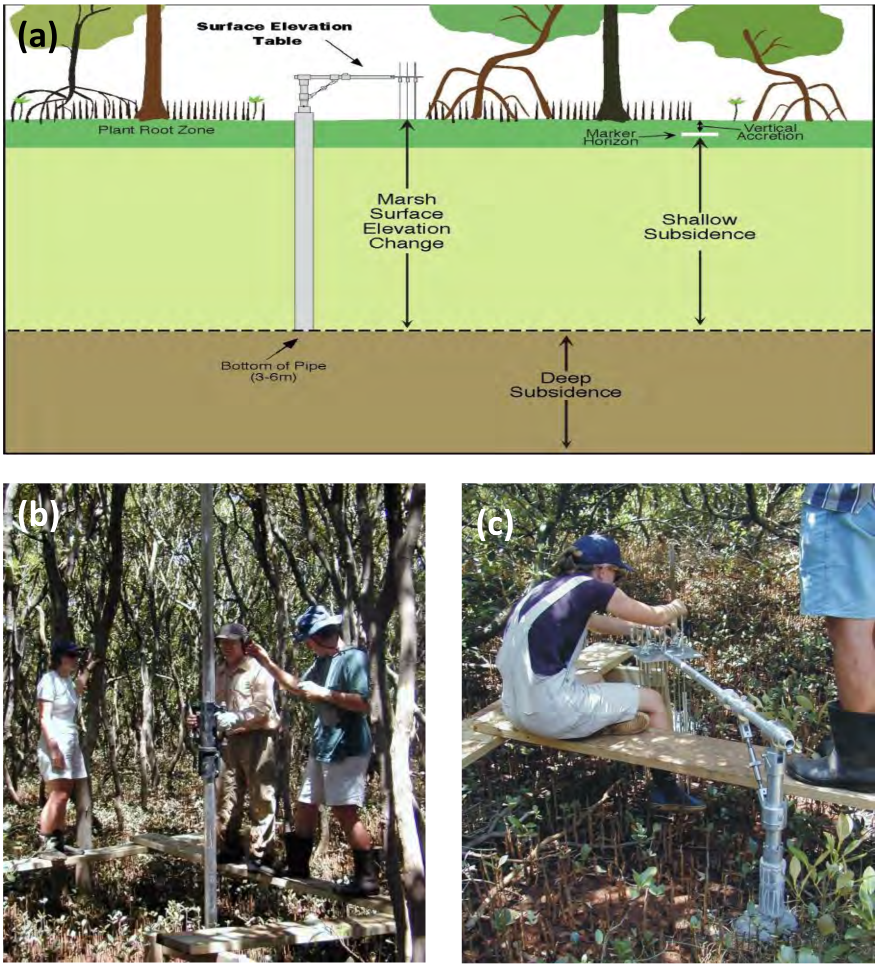

Figure 1. (a) The SET-MH monitoring station as installed in the Badu mangrove and saltmarsh. (b) Installation of the SET benchmark pole and (c) first readings in 2000

relationship between sea-level rise, wetland accretion and elevation gain. The Greater Sydney Local Land Services has produced an excellent video featuring the SET-MH method in the Badu Mangroves, accessible through this link https://vimeopro.com/littlegeckomedia/gslls-saltmarsh-and-mangrove-ecosystems/video/322132198).

At the Badu Mangroves wetland, three SET-MH stations were installed in the mangrove, three in the saltmarsh, and three in a mixed mangrove-saltmarsh zone. Each SET was accompanied by three feldspar MH plots. Badu Mangroves wetland is one of seven sites in SE Australia established at the time (the others being Tweed River, Hunter River, Hawkesbury River, Minnamurra River, Jervis Bay and Westernport Bay). Since then, SET-MH monitoring stations have been established in Queensland, the Northern Territory and Western Australia, part of an international network of SET stations in more than 20 countries (Webb et al. 2013). Pooling of data across this network has clarified the vulnerability of mangroves to sea-level rise and reductions in sediment input due to water resource developments in large river catchments (Lovelock et al. 2015).

The mangroves in the Badu Mangroves wetland have largely increased in elevation at a remarkably linear rate (r^2 = 0.97), corresponding to a linear increase in accretion (r^2 = 0.97). The rate of elevation gain in the mangroves (about 6cm over 20 years) is slightly lower than the annual rate of surface accretion, though both are approximately similar to the rate of sea-level rise as measured at a tide gauge within Powells Creek (Figure 3). As can be seen in the tide gauge data, sea level in any given year is variable, being influenced by local meteorological and oceanic conditions. For example, water levels within Powells Creek in 2016-2017 were 13cm higher on average than in 2002-2003, the year of tide gauge installation (Figure 3).

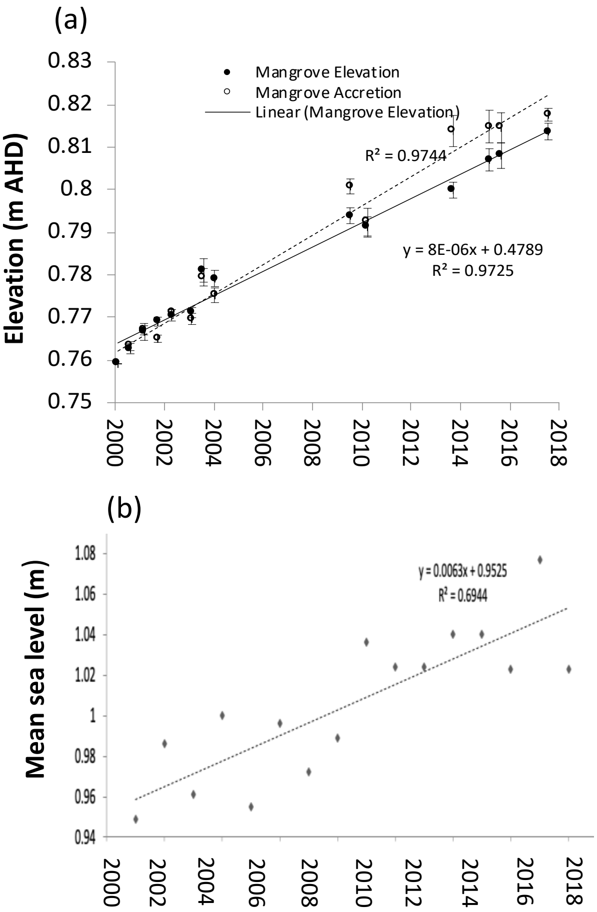

Figure 3: (a) Change in elevation 2000-2018 in the Mangrove SET-MH stations. (b) average annual mean sea level within Powells Creek 2002-03 until 2017-18

Figure 2. A Badu Mangroves feldspar marker horizon at installation (a) and soil core retrieved from the plot 17 years later, showing 7cm of organic and sediment accretion.

Carbon sequestration in the Badu Mangroves

An important component of vertical

The Badu Mangroves have a high percentage of carbon in the upper 25 cm of their soil, reflecting the strong contribution of new root material in this zone (Rogers et al. 2019b). The accumulation of new organic carbon on the surface as measured by the SET-MH stations in Badu Mangroves suggest an accumulation of organic carbon of 1.13-1.16 tonnes per hectare per year, or about 40 tonnes of carbon sequestered per year across the wetland. This is likely to be a conservative estimate. Old mangrove root material was found at a depth of 1 metre (dating to approximately 1200 years before present), but modern root material was also found at these depths (Rogers et al. 2019b), suggesting that new mangrove root material is being incorporated across the whole profile, as also observed on the Hawkesbury River (Lamont et al. 2020) and Port Stephens (Kelleway et al. 2017).

One obvious change since the SET-MH stations were installed in 2000 has been the proliferation of mangroves in the saltmarsh along the western edge of the wetland. SET plots in a 'mixed zone' of saltmarsh plus occasional mangroves in 2000 are now devoid of saltmarsh, and the saltmarsh zone has transitioned to a mixed mangrove-saltmarsh. Rogers et al. (2019b) found little increase in carbon storage as a result of this mangrove thickening, a finding corresponding to short-term encroachment studies in the United States Gulf Coastline (Osland et al. 2012; Doughty et al. 2016). It is probable that a longer time (40-50 years) is required before the influence of encroachment of mangroves is obvious in soil carbon storage (Kelleway et al. 2016).

Figure 4: Mangrove dieback in the Badu Mangroves wetland

Mangrove dieback

An area of mangrove dieback covering over 2000 m^2 was noticed in Badu Mangroves during annual inspections in 2014. Examination of aerial photography indicated that the dieback had commenced in 2013, two years after a "step-change" in average sea-level between 2010 and 2011 (Figure 3). The area was waterlogged, and poor drainage was noticed relating to impediments to flow between the dieback area and feeder channels to Powells Creek (Sydney Olympic Park Authority 2014). The area expanded to cover over 6000 m^2 by 2017 (Figure 4). Water level recordings within the dieback zone in 2016 suggested that up to 10 cm of water was ponding at the site over the duration of a spring tide cycle (Manly Hydraulics Laboratory 2016). This is a sufficient depth to inundate the aerial roots (pneumatophores) leading to anoxia and dieback of *Avicennia marina*.

The dieback of interior mangroves due to impediments to the ebbing tide is an anticipated outcome of sea-level rise (Rodriguez et al. 2017). Flat areas within wetland interiors cannot be efficiently drained, increasing the timeframe of inundation (hydroperiod) of larger tides

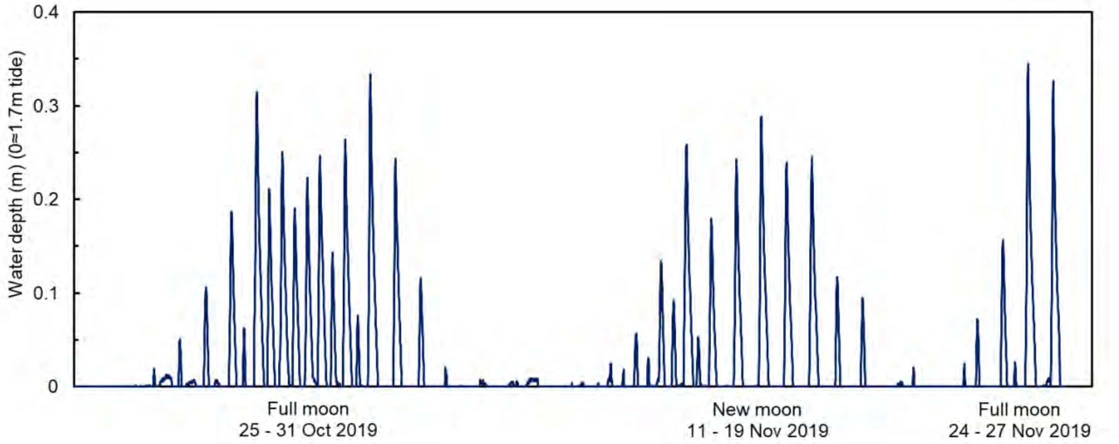

Figure 5: Water level within the Badu Mangroves dieback zone following the cutting of an auxiliary channel.

beyond that encountered at the more steeply sloping seaward edge of the wetland. This gives rise to the counter-intuitive but widely observed result that coastal wetlands break up from the inside out when under anoxic stress from sea-level rise (Rodriguez et al. 2017). The natural infilling of the Badu Mangrove surface observed since 2000 (Figure 2) has reduced elevation gradients between the seaward and landward edge of the forest, providing a further impediment to the egress of water on the ebb tide.

In 2019, a 70-metre-long channel was cut linking the dieback area directly to Powells Creek. The objective of the intervention was to improve drainage from the wetland, reducing hydroperiod during the spring tide cycle, with the aim of promoting mangrove recruitment and forest recovery at the dieback site. Water level measurements over two spring tide cycles in October-November 2019 within the dieback zone demonstrated the complete drainage of the wetland on all tides (Figure 5). Recruitment of seedlings and juveniles was observed over the 2019-2020 summer.

Conclusions

Mangroves within the Badu Mangroves wetlands are accreting vertically, offsetting the effect of recent sea-level rise. An important component of this vertical elevation gain is organic carbon, which has been stored within the wetland for over 1000 years. The Badu Mangroves fix and store over 40 tonnes of organic carbon every year. The interaction between sea-level rise, organic and mineral sediment deposition, and elevation gain suggest that simple "bath-tub" models of wetland response to sea-level rise are inappropriate and underestimate the resilience of wetlands within Sydney Olympic Park to sea-level rise.

However, the dieback of a patch of mangroves within the Badu Mangroves wetland due to hypoxic conditions demonstrates that the mangroves are not immune from the impact of sea-level rise, even under current rates. This dieback resulted from impediments to the egress of the ebb tide, continuously ponding water during spring tide cycles above the level of pneumatophores. The flattening of the wetland profile observed from a transect of Surface Elevation

Tables over 17 years (Rogers et al. 2019b) would also have contributed to resistance to ebb tide flow. The outcome has been anticipated from modelling of relative sea-level rise impacts on wetlands in the region (Rodriquez et al. 2017) and suggests that the interior of mangroves rather than the seaward edge is likely to show the first signs of deterioration under sea-level rise. Monitoring of the seaward edge of mangrove forests may be ineffective in rapid identification of stress in these situations.

The intervention of a direct channel linking the dieback zone and the main creek channel appears to have been successful in the short term and may be a useful model for interventions in other high value wetlands impacted by flooding stress. The long-term fate of the mangroves of Sydney Olympic Park will depend on decisions made concerning greenhouse gas emissions, because mangrove capacity to accrete is directly linked to the rate of relative sea-level rise (Krauss et al. 2017; Saintilan et al. 2020). Under mid- to high- emissions scenarios, mangroves will be unable to retain their current position and seek refuge in parkland areas currently above the reach of the spring tides.

Acknowledgements

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Secrets revealed: What we've learnt from EagleCAM

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BirdLife Southern NSW

EagleCAM live-streams the secret lives of a pair of White-bellied Sea-Eagles as they nest and raise their young each year. Over the twelve years that the program has been running, much has been learnt about the breeding behaviour of these magnificent birds – how they build their nest, how they incubate their eggs and raise their chicks, and how the chicks develop from hatching to fledging. The study has found that the eagle pair both contribute to nest preparation, incubation and care of the young and has indicated delayed incubation after the laying of the first egg. The program is run by BirdLife Australia Southern NSW, and has also proven to be a highly successful engagement and education tool. There have been over 5 million views by people from 194 different countries since streaming began, and research information generated by the program feeds into school and community education packages.

Introduction

The White-bellied Sea-Eagle *Haliaeetus leucogaster* is a fairly common sight along the coasts and inland rivers of Australia, as well as further afield. Along the Parramatta River of Sydney however, there is only one known pair. This pair is often seen during the day on their prominent mangrove perch, loafing or feeding on a mullet or other fish from the wetlands. They may also be seen soaring overhead on up-swept wings.

At the beginning of this project, little was known about the complete breeding cycle of Sea-Eagles from nest building to fledging. A huge nest of large sticks is commonly placed in a high tree and the nest may be used for many years in succession. Sea-Eagles are however easily disturbed at their nest sites, which are now few and far between in the Sydney area. The combination of a reduction in nesting success and the number of active nests, and increased mortality, indicates this species is declining. The Sea-Eagle is listed in NSW as 'vulnerable' under the *Biodiversity Conservation Act 2016.*

There has been a Sea-Eagle nest in Newington Nature Reserve for many years, with a succession of eagle pairs renovating a nest in the breeding season each year. The Reserve contains the critically endangered Sydney Turpentine-Ironbark Forest community, and has highly restricted access to both people and service vehicles. The only probable predators at the nest would be other large raptors.

There were few records of successful breeding in the local area however (successful fledging of one chick in 2003 is the only confirmed record of breeding prior to 2008) and in the past several adult eagles were found dead in and around the Homebush Bay area, possibly due to acute poisoning. Autopsy also

revealed bioaccumulation of organochlorides, which has been linked to reproductive failures. Life is hard in the city and several other factors may have contributed to their breeding failure over the years. Further study of breeding outcomes was recommended and led to initiation of the EagleCAM project.

Following the failed breeding of Sea-Eagles in 2004, regular observations of the eagles began in 2008 by observers stationed in a hide near the nest, and in the adjacent areas of the forest and riverside.

EagleCAM was established in 2009 to more comprehensively monitor the eagles throughout the entirety of the breeding season, whilst minimising impacts of human disturbance. EagleCAM is a live remote feed operating out of the BirdLife Discovery Centre in Newington Armory at Sydney Olympic Park. EagleCAM was started and funded by a small group of BirdLife Australia volunteers, who continue to develop and operate the technology that brings the Sea-Eagles to the screen. Each year their nest has been monitored and valuable observations made.

BirdLife Australia is a national organisation whose primary objectives are the conservation, understanding and appreciation of our native birds and their habitats. EagleCAM has proved to be one of BirdLife Australia's most celebrated awareness-raising tools, for visitors to the BirdLife Discovery Centre at Sydney Olympic Park, for on-line viewers, and in developing education programs.

EagleCAM now has three CCTV cameras installed on branches near the current nest and at a nearby roost, with remote zoom lens and focus. Infra-red provides vision at night. All power comes from the Discovery Centre and video is fed back via a cable link. This video data is recorded onto digital media and is available for detailed study. A live feed is displayed to visiting members of the public at the Discovery Centre and via YouTube live stream.

EagleCAM is operated under a BirdLife Australia Research Agreement, working in partnership with the NSW National Parks & Wildlife Service and Sydney Olympic Park Authority. Our objective is to observe and learn about White-bellied Sea-Eagle biology without interfering in their behaviour or the processes that they undergo in the natural environment. These are wild birds and it is our privilege to observe their breeding behaviour. Our Policy is for non-intervention, unless in an extreme situation.

What have we learned about the secret lives of these magnificent raptors?

Reproductive success 2008-2019

A Sea-Eagle pair has nested in the forest of Newington Nature Reserve every year since 2008 with an average of just below one young fledged per breeding attempt. Two eggs have been laid each year. Compared to other studies conducted over several years they still maintain a normal "success" rate. Records are presented at Appendix 1. Between 2008 and 2019:

- A total of 22 eggs have been laid, 18 of these have hatched successfully
- 10 young have fledged – "fledged" is defined as young that flew from the nest and eventually left the area
- The total mortality on the nest over this period is 10 ("mortality" is defined as eggs that failed to hatch or young that died in the nest). This gives a nest mortality rate of 45% (Appendix 1).

Pair Bonds

The eagles are monogamous, faithful to their partner, until something happens to one of the pair. Juveniles or unattached birds or floaters may then move in, searching for a mate or territory. When the original female "Mum" disappeared in 2016, a young female, "Lady" moved into her place within just seven weeks.

Duetting on the nest or nearby strengthens the pair bond and often stimulates mating. This continues before and during the nest renovation period and even after.

Nest building

Both adults share nest building, bringing sticks to the nest, and green leaves to line the nest bowl. Each year, nest renovation begins around March, with the eagles building up the rails of the nest, creating a bowl again, to cup the coming eggs. As the breeding season progresses, the nest is built up, until before the nestlings fledge it is almost a platform. At the beginning of each season, the nest rails are built up again until the nest is massive. The current nest is about 20m above ground. The male brings most food during the nest-building and incubation periods.

Nest building (top) and the view of the nest from the ground (bottom)

Incubation

The incubation period is around 40 days with the second chick usually hatching in a shorter time, after delayed incubation of the first egg. This gives the second hatchling a chance to "catch up".

Our study indicates that both parents incubate though usually only the female incubates at night.

Infra-red cameras enable nocturnal observation

Over all these years of observations, (though initially there was no night time footage), there seems to be a definite trend for delayed incubation between the first egg laid and the second. The time between laying of the two eggs varied from 3 to 4 days when we were able to observe the lay.

Detailed observations of delayed incubation were made in 2019 (Box 1).

Box 1: Observations of delayed incubation 2019

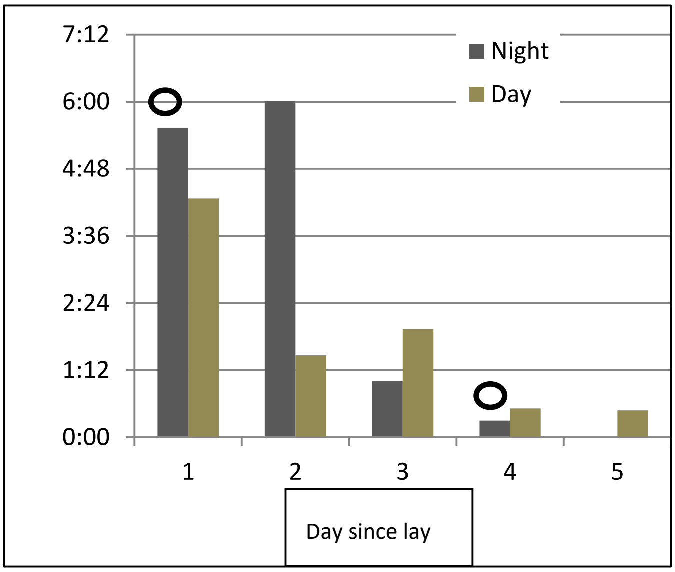
In the 2019 nesting season, two eggs were laid some 73 hours apart:

- Egg 1 SE23 was laid at 17:37 on June 16.
- Egg 2 SE24 was laid at 18:43, on June 19.

The first night after egg 1 was laid, when the weather was cold (dropping to 5 degrees overnight), the female incubated for only 5 hours, leaving the egg uncovered for 5.5 hours. As usually it is the female incubating at night, it was unusual to see that the male incubated for over 2 hours after 3:00am, possibly due to disturbance nearby.

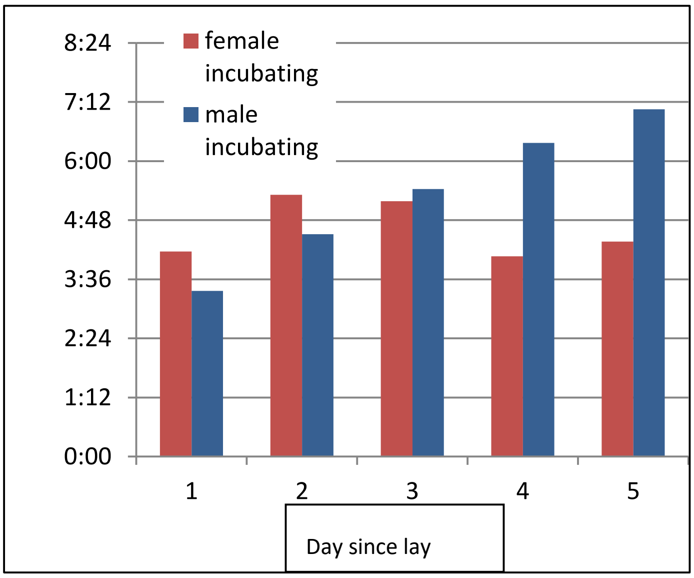
The next day, both adults shared daytime egg duty, with the egg uncovered for over 4 hours. On the second night the female again left the egg uncovered, for nearly 6 hours, despite the cold weather. Daytime incubation and care at the nest was again shared by both adults. As lay of the second egg approached, incubation time increased until the second egg was laid. Full incubation then continued, with the female on at night, assisted by the male during the day.

Graph 1 Number of hours the first egg was uncovered during Incubation before laying of egg 2



Egg 1 was uncovered nearly 13 hours total at night and nearly 9 hours by day before egg 2 was laid

Graph 2 Comparison of daytime Incubation by male and female between egg 1 and egg 2



During the day, both adults incubated, with the female a total of 23 hours and the male nearly 27 hours

Nestling Development

Sea-Eagles are devoted and caring parents, with both bringing food and feeding the young, though initially the male brings most food. Both brood the chicks during the day, with the female mainly at night. As the nestlings grow and develop strength, they learn to grab food and eventually feed themselves on the nest, with food the adults bring. After fledging, the adults continue to bring food to the young birds, though observations are harder when no longer visible on the nest cameras. This project has observed little information on their behaviour once the fledged youngsters leave their natal area and disperse, or how they learn their hunting technique. One juvenile SE21 was identified, after dispersing, in Broken Bay. Though unfortunately not banded, her injured wing feathers allowed identification.

Nestling development week-by-week is shown at Appendix 2.

As the nestlings grow, they lose their initial fluff, develop feathers and strengthen their legs and wings as they grow. Initially they are fed bill to bill by the adults, until they gradually grab food from the parents, or one another, learning to tear apart their prey. When older, they rush to grab prey from the parent making the delivery.

As they grow, the nestlings practice on the nest, jumping up and down, flapping their wings, and gradually getting enough courage to "branch" - flapping from the nest to reach a nearby branch - then back to safety. Finally, with enough strength to fledge, they take the first flight away from the nest.

Nest defence

Both adults have been observed to defend their territory against other raptors. In 2017, the newly hatched chick perished and the second egg failed to hatch when the parents left their brooding duties to defend their territory against an intruding female Sea-Eagle. Other large birds, like Australian Ravens, Magpies and Currawongs, may follow the eagles to the nest and even swoop the young. A newly fledged eagle fell to the ground last year and was threatened by a fox. The eaglet defended itself against the fox, with outstretched wings and defensive behaviour, until the fox was frightened off by a volunteer and staff. The adults were not seen to intervene at all in defending against the fox.

Sibling Rivalry

Raptors may exhibit "siblicide," in which the larger chick kills its smaller sibling. We have not observed this in our study. We have observed some sibling rivalry – mainly competition for food. Although usually there has been delayed incubation, allowing some "catch up" between the two chicks, there has been some initial competition. The bigger, first-laid chick initially always receives the first feed and may peck at its sibling often, causing it to retreat in submission. This competition has been seen early after hatching, and gradually lessens as both chicks grow. The parents do not intervene in this competition, and feed the closest begging chick.

In three seasons (2010, 2012 and 2019), two chicks hatched and both survived to fledging, despite this competition.

In 2018, the death of the smaller nestling was caused by sibling rivalry. For an unknown reason, possibly injury, the male brought no food for some days. While food was scarce, the older stronger nestling monopolised the food, causing the starvation of its sibling. The bigger chick did not actually kill its sibling, though it pecked it aggressively and pulled out feathers, leading to its submissive behaviour.

Prey

The eagles bring a wide variety of prey to the nest (Appendix 3). Most common are fish – of many species, including mullet, whiting, bream, leatherjacket, flounder, carp and eels; birds, most commonly Silver Gulls; and carrion. Their prey may cause injury, as from fish hooks, or illness from contamination or disease carried by their avian prey. Rock Doves, or feral pigeons, are of particular concern with respect to diseases. Prey, particularly fish, may be contaminated by Persistent Organic Pesticides, a legacy of past industrial use in Homebush Bay.

The bigger nestling is being fed as the weaker chick cowers in submission and received no food for several days (top and centre)

The female removing the body of the smaller nestling, which has died from lack of food (bottom)

Conditions observed to cause nest failure or risk to chicks

Close monitoring of the nest over the twelve years of the project has generated substantial knowledge of the risks to survival faced by each new generation of birds in this urbanised environment. Our observations have included:

- Possible poisoning of young chick caused by being fed a pigeon affected by the poison 'Scatterbird' – Amino Pyridine

- Extreme weather affecting a possibly already weaker chick
- Entanglement of the nestlings in fishing line with hook, brought to the nest by a parent bird in fish prey
- Trichomoniasis or Frounce– caused by a Protozoan parasite usually carried by pigeon prey, causing lesions to grow, and leading to the death of the affected bird
- Circovirus or Beak and Feather Disease. In 2015, the eaglet SE15 was seen to have deformed feathers and failed to fledge. It was diagnosed with Beak and Feather disease. His condition worsened and euthanasia was deemed necessary. This information may contribute towards the understanding of how this virus affects raptors

2012 intervention, when nestlings were tangled in fishing line and SE9 had swallowed a fish hook. Both survived to fledge and left the area.

SE15 showing damaged feathers, affected by Circovirus

- Though there are foxes in the area, the nest is high in the tree and inaccessible to foxes, cats or dogs. However, in 2019 a fox threatened the newly fledged SE24, which had fallen to the ground
- Accidental fall – SE 21 landed clumsily and fell, becoming trapped by a wing in a branch. She was taken into care and after rehabilitation, released in her natal territory
- An eagle intruder at the nest, causing the nesting pair to abandon their nestling and unhatched egg
- Starvation caused by sibling rivalry, when food was scarce and there was insufficient food for both nestlings
- Unexplained failure to thrive after fledging, with the fledgling SE23 apparently not fed by the adults
- Infertile eggs or undeveloped embryo

Community Interest and Engagement

This on-going project contributes to knowledge about the ecology and life history of the White-bellied Sea-Eagle and contributes to better management of its habitat. EagleCAM also educates the public about the Sea-Eagle and promotes the conservation and protection of the species.

EagleCAM has proved a valuable tool promoting the conservation work of BirdLife Australia and Sydney Olympic Park Authority to both local and International audiences. Many visitors to the BirdLife Discovery Centre have marvelled at the eagles and millions have watched their progress on the EagleCAM website. There have been many positive media reports over the years. BirdLife volunteers have developed education programs for school students using this footage including for activities during Science Week and the Youth Eco Summit held at Sydney Olympic Park, and have presented papers about the program at regional and national ornithological conferences.

EagleCAM-Public-Engagement-Snapshot 2020

- Facebook, Sea-EagleCAM (official FB page) 9,700 Likes, with 21,637 people reached per month as of March 2020
- Facebook, Sydney Sea Eagles Cam, (Group): 2,438 members
- Sea-EagleCAM Web page, has had: 1,603,276 total visits
- Sea-EagleCAM Web page: 194 countries have visited the web page with ~ 50% of the visitors from the USA.
- 'Ustream' Live streaming views: 4,690,745 (this service finished 19 July 2018)
- Youtube Live streaming, started in July 2018, and has had about 77,500 watched hours

There are about 200,000 views per year and at peak time the daily views to the Live Stream is up to about 16,500.

The viewers are about 70% female in the age group of 45+, most being in 50 to 60 range.

The origins of the viewers are Sea-EagleCAM.org = 67%, Facebook = 12%, and Birdlife = 2.5%.

Acknowledgements

The EagleCAM research project team acknowledges the assistance of NSW National Parks & Wildlife Service and the Sydney Olympic Park Authority in approving this research and facilitating access to Newington Nature Reserve.

We acknowledge the essential assistance from the current EagleCAM team - Judy Harrington, Geoff Hutchinson, Bob Oomen and Chris Bruce, for camera installation and maintenance and Shirley McGregor for managing the daily operations. Special thanks to Dasha, Marsha and Pat, for monitoring nesting observations and Dasha and Helen for camera operations. Additionally, we also have a wonderful team of volunteers including Facebook admins, chat moderators, ground observers and more (too many to mention here). Above all, thank you to our Supporters, for funding this project.

Visit EagleCAM at:

https://www.birdlife.org.au/visit-us/discovery-centre/eagle-cam

or

https://www.sea-eaglecam.org/video.html

APPENDIX 1

EagleCAM nest records

Year / Nest	Outcome	Delayed Incubation	Time between eggs laid	Time between hatching	Eggs hatched	Mortality on nest	Success? Fledged and left
2008 Nest 1 in historic site. Male died, replaced by current male "Dad" with female "Mum"	SE1 fledged, but died in care SE2 died on nest				2	1	
2009 Nest 1 in historic nest site	SE3 fledged SE4 died on nest				2	1	1
2010 Nest 1 in historic nest site	SE5 & SE6 both fledged	YES			2		2
2011 Old nest collapsed New nest in same tree	SE7 died on nest, possible poisoning from Scatterbird SE8 fledged	YES	72 hours	28 hours	2	1	1
2012 Nest 2 – new nest in another tree (Blackbutt)	SE9 & SE10 both fledged after intervention to remove fishing line		Un-known	48 hours est.	2		2
2013 Nest 2 in Blackbutt	SE11, SE12 – neither egg hatched		72.5 hours	NA	0	2	0
2014 Nest 2 Began Nest 3 in *E. fibrosa*. After possible disturbance returned to Nest 2 in Blackbutt	SE13 died at 30 days from Trichomoniasis		77.5 hours		1	2	0
	SE14 failed to hatch			NA			
2015 Nest 3 in *E. fibrosa*	SE15 was diagnosed with Beak and Feather Disease and euthanased SE16 fledged	YES	78 hours	14.5 hours	2		1
2016 Original female "Mum" disappeared. Female 2 "Lady" Nest 3	SE17 fledged SE18 died on the nest at 10 days, possibly from a combination of sibling rivalry, poor weather	YES	77 hours	36.5 hours	2	1	1
2017 Female 2 "Lady" Nest 3	SE19 died on the nest at 3 days from cold and no food SE20 failed to hatch Intruder disturbed breeding	YES	81 hours	NA	1	2	0
2018 Female 2 "Lady" Nest 3	SE21 fledged, was injured, in care, then left the area SE22 died on the nest at 33 days – sibling rivalry	YES	73 hours	37 hours	2	1	1
2019 Female 2 "Lady" Nest 3	SE23 fledged but died at 103 days, failed to thrive SE24 fledged and left the area	YES	73 hours	33 hours	2		1

APPENDIX 2 - Summary of development from Hatch to Fledge week by week

 **Hatch**	 **Week 01**	 **Week 02**	 **Week 03**
 **Week 04**	 **Week 05**	 **Week 06**	 **Week 07**
 **Week 08**	 **Week 09**	 **Week 10**	 **Week 11**
 **Week 12**	 **Week 13**	 **Week 14**	 **Week 15**


SE 21 branched at 11 weeks, fledged at 12 weeks

APPENDIX 3 Recorded prey species

Just another bat in the wall-observations of a microbat maternity colony

Marg Turton

The White-striped Free-tail Bat (*Austronomus australis*) is one of Australia's most common bats. Despite this, they have been rarely studied. A maternity roost of this species has been studied since 2006 using video-recording, Anabat detection, radio tracking and PIT tagging to determine roost use and composition. The seasonal use of the roost, gender composition, breeding and potential changes to roost use as a result of climate change is discussed.

Introduction

The White-striped Free-tail Bat (*Austronomus australis*) (Figure 1) is one of Australia's most common bats. They are one of the few bat species that produce echolocation sounds that can be heard by humans. Though rarely seen, except flying quickly overhead, their echolocation calls are one of the most common sounds of the night. Their body fur can vary from dark brown to almost orange above and is slightly lighter below. Wide white stripes are located on each side of the body under the wings. Ears are large and leathery. Their wingspan can reach 40 cm, body length 10 cm and their 'free' tail extends well beyond their flying membrane. They fly high above the canopy, in a fast, relatively straight path in search of high-flying insects. Due to this they are rarely trapped and little is known of their ecology.

In 2002, a colony of White-striped Free-tail bats was found within a building in the Newington Armory during a bat survey by Glenn Hoye (Turton and Hoye, 2011). This was very unusual as this species is more commonly found roosting in trees; to date this is the only known maternity colony of this species to have a maternity roost in a building. The location of this colony seemed to provide a perfect opportunity to learn more about this little-known species. This study is the only long-term monitoring of this species to be carried out, and has much potential to expand existing knowledge.

Figure 1 White-striped Free-tail Bat

Early days

I undertook monitoring of the colony in December 2005. This initial monitoring was carried out over a period of four months (December 05 – March 06), and comprised a combination of night-long video and Anabat recording on a monthly basis. This study revealed interesting bat behaviour and noted an increase in colony numbers, indicating that indeed, this was a maternity colony.

From September 2006 to August 2007, further video recording was undertaken one night per month. As with the earlier monitoring, equipment used was fairly primitive by today's standards, using a security-type camera, with Infra-Red spotlights pointing at the exit point and recorded onto video tape. One drawback with this method was that the time required to review a 10-hour tape was ....10 hours. My volunteer base rapidly dwindled after a few hours of looking at video of a brick wall waiting for a flash of activity as a bat emerged!

In addition to the video recording and bat call detection, a small 'ibutton' data logger was lowered into the roost to determine the temperature and humidity of the roost. Unfortunately, when it was retrieved after 12 months it had been infiltrated with bat urine and small brown mites and the data was unable to be retrieved.

Although the techniques in those early years were basic, we did deduce that:

- The roost was being used yearly, with bats showing a high roost fidelity to the site, and that it met the highly specific conditions required for a maternity colony;
- Bats were not recorded using the roost in the winter months of June and July;
- A better understanding of the size of the maternity colony was determined.

Figure 2 A White-striped Free-tail Bat in the hand having its forearm measured.

2008 onwards

In March 2008 we upgraded to an automatic system! A generous Queensland bat researcher (Bruce Thomson) lent me equipment to upgrade the project into the next phase using PIT tags (Passive Integrated Transponders) in the bats and an antenna at the roost entrance.

For this new system, bats were caught in a mist net as they exited the roost, examined, tagged and released (Figure 2). Once trapped, the bats are weighed, sexed, measured and, if not previously trapped and tagged, are injected with a uniquely numbered PIT tag (ISO standard 134.2khz full duplex Passive Integrated Transponder (Allflex)). When the bats enter and exit the roost, their unique tag number is picked up by an antenna located at the roost entrance and the number and time transmitted to a laptop that is running continuously. This data is then downloaded regularly and analysed (Figure 3).

This technology not only told us how many bats were using the roost, but whether the same bats were returning each night, the gender composition of the roost, how many times an individual left and re-entered, if the same adult females used the same maternity roost year after year, if their female young use the roost, and ultimately how long the bats are reproductively active and their longevity.

In our first 2008 season, we tagged a total of 27 bats over six trapping sessions. As of 2020, we have tagged a total of 98 individual bats.

```
Date,Time,Bat number
2008-03-13,20:27:49.413,009105952189
2008-03-13,20:31:55.997,009106179683
2008-03-13,20:34:30.017,009106184217
2008-03-13,20:37:48.004,009106145195
2008-03-13,20:41:36.852,009105952189
2008-03-13,20:41:54.704,009105828189
2008-03-13,20:45:14.882,009105952189
2008-03-13,20:48:35.814,009106179683
2008-03-13,20:48:46.356,009105952189
2008-03-13,20:50:03.803,009106159225
2008-03-13,20:50:58.067,009106179683
2008-03-13,20:51:10.165,009105952189
```

Figure 3 Example of the data collected from the roost

Unfortunately, the 2018-2019 and 2019-2020 maternity seasons were plagued by equipment failures and I was forced to look into a new system. Luckily, I was successful in obtaining a grant and have now set-up a brand-new Biomark IS1001 reader system and custom made antennae which should see the project continue successfully for a few more years.

Breeding

Mating, ovulation and fertilisation in the White-striped Free-tail bat occurs around late August. Most females, including young of the previous season, become pregnant each year and give birth to a single young, usually between early December and late January.

Bats start returning to the roost around October, although they may come and go for a while until numbers start to stabilise around mid-November. In March the young become mobile and start to leave the roost to forage. In April the bats may leave the roost for several days at a time and then return, this activity is at least partially explained by the radio-tracking results discussed below. By the end of April, most bats have left the roost for the winter period. It is not known where they go at this time, although it is thought that colonies disperse over winter allowing mixing of colonies and mating.

During the peak months from December to February, the majority of bats within the roost exited within an hour and a half after sunset. During the afternoon, audible social calling (chittering) can be heard in the late afternoon until the colony exits the roost.

One bat that was originally trapped and tagged in April 2008 was re-trapped in 2018, the first time she has been re-trapped. Surprisingly she was found to be lactating, showing not only longevity but a long reproductive life. She was showing some signs of aging however, with thinning fur on her back and extensive tooth wear (Figure 4).

Figure 4 As bats get older, tooth wear becomes more obvious, caused by a life-time of chewing on the hard exoskeletons of invertebrates.

Roost Fidelity

This species has high roost fidelity. Approximately one third of the PIT tagged bats have returned to the roost in subsequent maternity seasons and stayed for the entire maternity season. Naturally as the bats age, these numbers are expected to decrease over time. Many of these bats have returned to the roost every year after they were first tagged.

Gender composition of roost

As of 2019, only 21 of the 97 bats tagged have been male (21%); it is not known if this is unusual amongst bat species. The majority of the males tagged as juveniles do not return to the roost, however there have been a few exceptions to this.

Most notable is the thirteenth bat tagged whom we have named Gandalf the Gray (Gray after J.E. Gray, 1838) who first described the species. This bat was last detected in February 2019 when it would have been at least 11 years old. This male is a consistent visitor to the roost, visiting regularly but rarely staying longer than a day or two. Gandalf was re-trapped in 2018 and the photo shown in Figure 5 taken; he was going a little grey and had quite pronounced tooth wear. Now the faulty equipment has been upgraded we hope to find that Gandalf is still visiting the roost.

Figure 5 Gandalf the Gray, an 11-year-old White-striped Free-tail Bat.

Weather

Bat maternity roosts require very specific temperatures and humidity requirements and need to be fairly stable. The roost faces west, which enables the roost to warm up before the cooling of the evening.

Extremely hot weather has led to the desertion of the roost on a few occasions. Although White-striped Free-tail Bats appear to have a higher heat tolerance than many other bat species, (Lyman, 1970), it is assumed there is a limit to the temperature and humidity able to be tolerated by the adults and young. The 2016-17 summer was the warmest on record for Sydney Observatory Hill with the mean temperature 2.8°C above average (Australian Bureau of Meteorology data). Rainfall was average to below average across the city, with a dry December and January but a wetter than average February. The number of tagged bats in the roost started declining from the 23rd December with only a few tagged bats returning sporadically to the roost. Bats did not start returning to the roost in appreciable numbers until March.

Winters are also becoming warmer. The winter of 2017 had the most bats overwintering than ever before, with 14 bats present when in previous years it has been less than 5.

The potential impacts of climate change and resulting higher temperatures may mean that the suitability of the site as a maternity roost may change, and that it may move to being more of a 'hub' roost than exclusively a maternity roost. The next few maternity seasons will hopefully show the likely trends.

Rain also impacts on bat movements with decreased activity recorded on rainy nights.

Radio-tracking

To attempt to determine where the bats were going when they left the roost in April, a radio-tracking program was started. In April 2010, five White-striped Free-tail Bats were radio-collared (Holohil BD-2C 1.6 gms) and both day roosts and foraging areas were radio-tracked with Titley regal 2000 and Australis 24K receivers with Yagi 3 element antenna, over a period of eight weeks (Figure 6). Extensive movement of bats between roosts was noted, with bats moving between the main maternity roost and tree spout roosts in Scribbly Gums (*Eucalyptus haemastoma*) located in adjoining woodland.

Initial results appear to reinforce the findings of Rhodes (2007), of a network of roosts consisting of a 'communal' roost (which appears to be female dominated and is also a maternity roost in the breeding season) and associated satellite roosts. Roost fidelity of the communal roost is high during the months December to April (until the young become independent) then the satellite roosts are utilised. These satellite roosts may also be used by individual males during the breeding season.

Roost switching occurred between the four satellite roosts and also between satellite roosts and the communal roost.

After a few weeks (just before the cold and wet weather set in) the bats left the area, therefore the woodland roost trees may just represent 'stepping stones' between the main communal roost and the winter destination.

Figure 6 White-striped Free-tail Bat with a radio collar.

Summary

To date this project has monitored 11 maternity seasons. Unfortunately the 2018-19 season had equipment failures (laptop broke down while I was on an extended holiday in Western Australia). And the 2019-20 season was also plagued with equipment failures. However with the new equipment, monitoring is expected to remain trouble-free for quite a few years. This project provides a unique snapshot into the ecology of this species over time.

Acknowledgements

I would like to thank the staff of Sydney Olympic Park Environment Team for their ongoing support for this project, in particular Kerry Darcovich, Jenny O'Meara, Tina Hsu and Viveca McGhie.

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

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Sydney Olympic Park Authority

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.

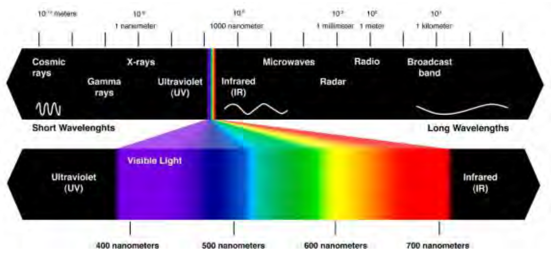

Figure 2. The electromagnetic spectrum. The 'visible light spectrum' occurs between 380-780 nm and is what the human eye can see. Reproduced from the National Light Pollution Guidelines for Wildlife 2020.

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).

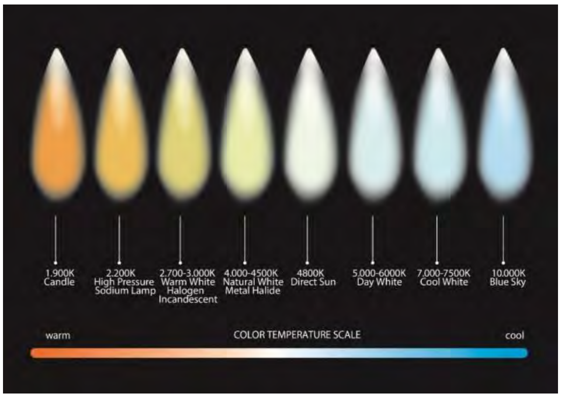

Figure 3. Pictorial representation of the Correlated Colour Temperature (CCT) of LED lights, from warm to cool. Reproduced from the National Light Pollution Guidelines for Wildlife 2020.

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).

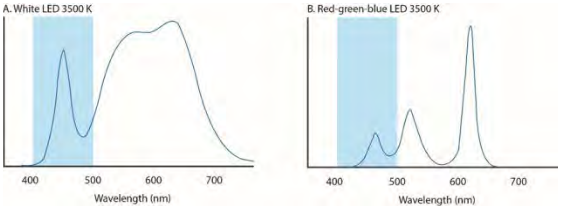

Figure 4. Spectral power distribution curves of two LED lights with the same Correlated Colour Temperature (CCT) but different blue wavelength content. The blue band shows the blue region of the visible spectrum (400-500 nm). Reproduced from the National Light Pollution Guidelines for Wildlife 2020.

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.

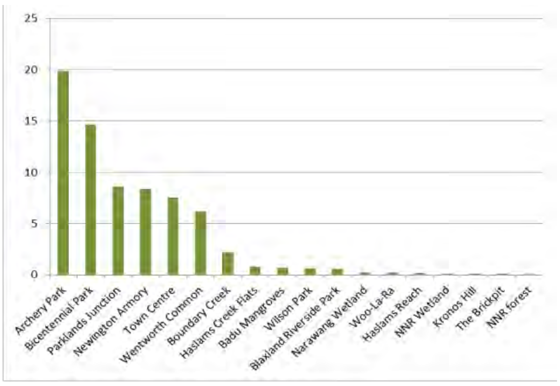

Figure 6. Average brightness (lux) of each precinct based on data collected during the 2018 and 2019 light spill surveys at Sydney Olympic Park

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).

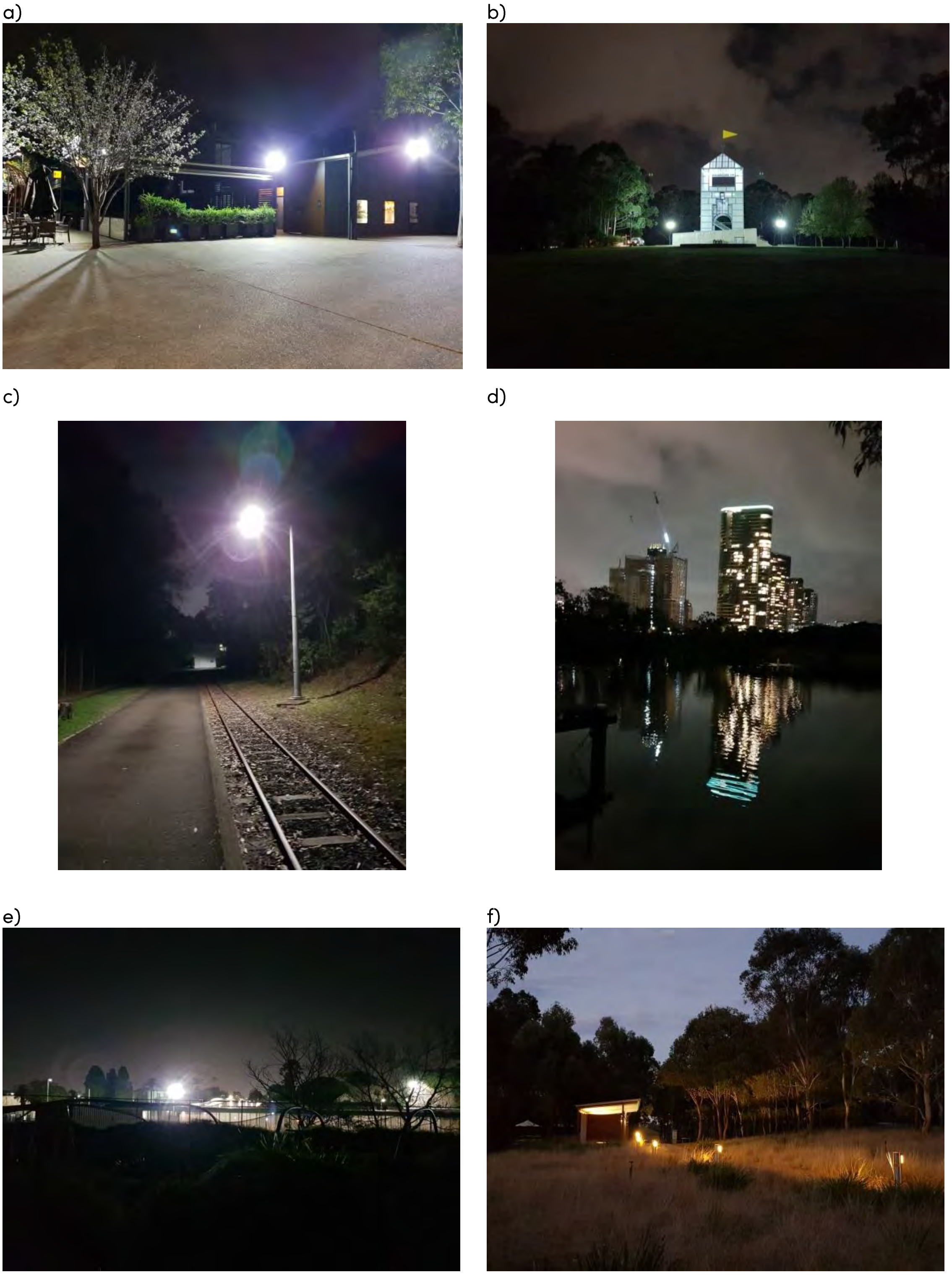

Figure 7. a) Six floodlights light up a closed function centre in Bicentennial Park; b) The Treillage Tower at Bicentennial Park lit up by upward facing floodlights; c) Lighting inside a sensitive ecological area, Newington Armory; d) Residential towers casting light into Lake Belvedere, a regionally 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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Restoring the restoration: bringing back woodland birds

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Sydney Olympic Park is a large urban park containing both remnant and constructed landscapes that underwent significant restoration in preparation for the 2000 Olympic Games. The initial landscape design and plant species selection resulted in a landscape with low structural complexity dominated by maturing canopy trees and a simple grassy understory. Woodland birds are a component of the Park's biodiversity that are sensitive to and have declined as a result of this initial landscape design as well as adjacent urban development. The results of a 2005 monitoring program focusing on woodland birds led to a change in landscaping strategies to include increased vegetative structural complexity. This study measured changes in vegetation structure and bird composition from 2003 to 2019. The study found that diversity of woodland birds was correlated with high shrub cover, low tree density and the distribution of the aggressive Noisy Miner *Manorina melanocephala.* The most recent surveys in 2019 found that increases in both woodland bird abundance and richness occurred in quadrats that were part of a shrub-planting program suggesting that suitable woodland bird habitat can be achieved in urban parks.

Background

Birds are one of the most recognised and popular elements of urban biodiversity (Fuller *et al.* 2007), but they are directly threatened by urbanisation (Watson *et al.* 2002) and populations of woodland birds in particular are declining across a range of urban environments including Sydney (Parsons *et al.* 2006). Factors contributing to this decline are generally assigned to land development (Ford 2011) resulting in fragmentation, edge effects, increased generalist species, simplified habitats, and reductions in bird diversity (Marzluff 2001). Over one-third of Australia's land birds are woodland dependent and as a consequence of these changes at least one in five of these species is now threatened (Birdlife Australia). Retaining small birds in urban landscapes is a challenge for landscape designers and land managers juggling the demands of recreation and conservation in finite urban green spaces.

Sydney Olympic Park covers approximately 640ha and forms a suburb of Sydney, Australia, located 14 km west of the central business district. The Park was developed for the 2000 Sydney Olympic Games and involved significant rehabilitation of 435ha of parkland through the remediation of contaminated land, restoration of remnant bushland areas and landscaping while accommodating a number of sporting, entertainment and leisure facilities (Darcovich and O'Meara 2008 and O'Meara and Darcovich 2014).

Remediated and landscaped areas were designed to form linear and structurally simple shapes in order to provide for both active and passive recreation (Hassel 1997). The planting design sourced mainly eucalyptus species or *Casuarina glauca* with grassy understory species selected for their fast growth, tolerance of poor soils and aesthetics. These landscaped habitats are dissected by pathways and open spaces for use by the public. A remnant bushland patch (13 ha) of critically endangered Sydney Turpentine Ironbark Forest is located in the Newington Nature Reserve. Dense areas of woody weeds dominated by Lantana *Lantana camara* and Bone Seed *Chrysanthemoides monilifera* were present in several pockets (35ha total) forming a dense shrub understorey.

Woodland birds at Sydney Olympic Park are defined as species that are dependent on woodland and forest remnants, excluding urban generalists such as Australian Raven, Magpie-lark and Willie Wagtail. Aggressive species such as the Grey Butcherbird *Cracticus torquatus* and Noisy Miner *Manorina melanocephala* whose behaviour excludes other species have also been excluded because they impact the diversity and numbers of smaller woodland birds. Sydney Olympic Park supports a high diversity and abundance of woodland birds, despite being relatively isolated from other remnant bushland habitats in surrounding suburbs. Species such as the Superb Fairy-wren *Malurus cyaneus* or Red-browed Finch *Neochmia temporalis* are resident and common; however, the Park is an important refuge for other species that occur only in comparatively small numbers or are vagrant and migratory, using the Park as a stepping stone during large landscape scale movements. Woodland birds require structurally complex habitat comprising a mix of groundcover, shrub and tree species to provide a high volume and variety of food, dense thickets for shelter and nest sites.

In recent Australian studies, the presence of Noisy Miners has been shown to be a major threat to the diversity of small woodland birds within remnant patches (Maron 2007, Robertson *et al.* 2013 and Thompson *et al.* 2015). This species exhibits 'aggressive despotic behaviour' that has shaped avian assemblages in woodlands of eastern Australia (MacNally *et al.* 2012). The changes to landscape that result in fragmentation, loss of vegetation structure, dominance of Eucalyptus and loss of species richness contribute to the formation of habitat that favours the Noisy Miner (Munro *et al.* 2007 and NSW Scientific Committee 2013). Studies have found that the presence of Noisy Miners can reduce the richness and abundance of smaller birds (less than 63g) by 50% through aggressive exclusion (Clarke and Oldland 2007, Maron and Kennedy 2007, MacNally *et al.* 2012 and Thomson *et al.* 2015). MacNally *et al.* (2012) found that densities of Noisy Miner greater than 0.8 birds per hectare had a negative correlation with the abundance of smaller birds.

The extensive plantings of eucalyptus species and casuarinas between 1998 and 2000 gradually evolved from a dense shrub layer to a developing canopy as the trees matured (Appendix 1; Figures 1a and 1b). In 2005, the Authority commissioned a study examining the relationship between bird diversity and vegetation. The bird survey component of the study collected information on the abundance, diversity and distribution of bird species and the vegetation analysis component collected important data on habitat condition to relate habitat variables to bird biodiversity. This study was to be repeated every four years and provided important information about bird distribution and abundance and the habitat requirements of birds. This then became the basis for management aimed at maintaining and enhancing bird biodiversity within the Park.

The most important outcome of the first study was a prediction that the original planting design would result in a change in distribution and density of some of the bird species with declines in woodland dependent species (Saunders 2005) and increases in aggressive species such as the Noisy Miner. In 2008, woodland birds were identified in the Authority's Biodiversity Management Plan as a focal species group. The conservation actions for this group reflected the findings and recommendations of this study. In 2009 a follow-up study reported a significant relationship between Noisy Miners and small birds where the density of smaller birds decreased with increasing density of Noisy Miners. The distribution of small birds was closely related to high shrub cover rather than to tree density (Saunders 2009).

The habitat enhancement program

Woodland birds require structurally complex and diverse habitat with functional connectivity between habitat areas. The original design intent for the Park was to create a simplistic vegetation structure of mainly eucalyptus or casuarina species with grassy understory species selected for their fast growth, tolerance of poor soils and aesthetics. These landscaped habitats were then dissected by pathways and open spaces for use by the public. This study suggested that the original plantings were not likely to support large numbers of woodland birds in the long term because of their structural simplicity, small patch size and lack of connectivity. Very few of these plantings included shrub species that would have increased habitat complexity. While planted tree saplings initially supported woodland bird species by functioning as shrub habitat, they became progressively unsuitable as they matured. Additionally, the small patch size of tree plantings, with a high edge to area ratio, favoured aggressive 'edge specialists' such as Noisy Miners and Rainbow Lorikeets that compete with and displace woodland birds.

As a result of the initial 2005 study, attention turned to improving the quality of Park habitat and management of site-specific factors to address woodland bird conservation. The Authority implemented a habitat modification program in 2006, aimed at increasing the structural diversity and complexity of key areas of the Park. The program seeks to build connectivity between key woodland bird habitats identified in the Brickpit, Narawang Wetland, Newington Nature Reserve, Kronos Hill and Woo-la-ra precincts.

Plants were sourced from local and regional provenance supported by an extensive seed collecting program from the on-site Sydney Turpentine Ironbark Forest community. The form of habitat enhancement varied depending on site characteristics and works have included:

- Enhancing the extent of remnant bushland - increasing the extent of and quality of Sydney Turpentine Ironbark Forest from 14ha to 20ha;
- Woody weed control - Since 2006, a program of long-term staged weed removal was initiated with the aim of removing the majority of dominant weeds in the Brickpit, Triangle Pond and north of the Waterbird Refuge. This program included habitat replacement with native species suitable for woodland birds. Each planting stage is required to form functional habitat before further weed removal occurs to ensure no net loss of overall habitat;
- Increasing structural complexity – the retrofitting of structural complexity under established trees:
    1. Initially the program consisted of plantings beneath the existing tree canopy but shrub growth was slow and survivorship was low;
    2. Selected areas were identified for a more active intervention program where the tree canopy was thinned to 50% or less, invasive grasses in the ground story removed and shrubs/ groundcovers retrofitted underneath. Any trees removed to reduce tree canopy cover were laid on the ground to increase coarseness within the mulch layer.

As recommended by Parsons (2007), management of small bird habitat should recognise the positive value of invasive species such as *Lantana camara.* Lantana at Sydney Olympic Park is actively restricted to current extents and new outbreaks are removed before they form habitat (greater than 1m^2). The removal of Lantana is staged over periods of approximately four years to allow woody weeds forming good bird habitat to remain until alternative replacement habitat consisting of native species of the same density can mature.

When planting, tubestock consisting of 50% shrubs and 50% groundcovers were used, supplemented by direct seeding. The species palette included both slower growing, longer lived species and short lived species so that structure is still present as plants with different life spans mature, senesce and recruit. Acacias form a high proportion due to their cover crop role in shading and fixing nitrogen – they are quick growing, generally short lived and usually result in good recruitment. Spikey plants such as Hakeas and Bursaria are also well represented due to their prickly foliage being attractive to fairy-wrens and finches. Finches were observed to build nests in plants at least two years old. The species palette was kept as diverse as possible to offer a range of food resources; seed, nectar or insect attracting species. Vines were also included as an important enhancement to vegetation structure, habitat values and food resources.

Plants were planted in like-species groups resulting in a matrix of species coppices allowing groundcovers to have access to sunlight and reduced competition. Ideally a good groundcover layer was encouraged to establish quickly to create a seedbank so the site can react to changes in the environment. Shrub density was generally 1-2 shrubs/m^2 but depended on the species – short lived pioneer species can be planted this densely while larger species require more space. Groundcover species were generally planted at a density of 4-6 plants/m^2, but again depended on species used.

This habitat enhancement program was applied to areas where three primary conditions could be met: the site would enhance and/or increase the area of corridors and current habitat areas used by woodland birds, there was no conflict with other threatened species habitats and complementary to other Park uses such as recreation. As at 2020, the program has covered 3.1ha across six precincts, with plans to expand those areas over the next few years. The program is staged with each section incrementally adding to woodland bird habitat each year. Maintenance of these sites is ongoing under bush regeneration contracts to ensure they meet the criteria of the Biodiversity Management Plan: >40% canopy cover located in the shrub layer (1-8m high), with an open tree canopy of less than 30% cover and the groundcover layer to be a mix of grasses/sedges, and fine and coarse mulch, including fallen branches. All sites receive maintenance weeding, supplementary planting where needed and application of grass seed to ensure vigour and diversity in both vegetation structure and age classes.

The monitoring program

There have now been four reviews of vegetation and woodland bird status at Sydney Olympic Park. This longitudinal study has evaluated change over time (from 2005 to 2019) of woodland birds and measured the success of the planting program in providing habitat for woodland bird species.

Thirty-seven 20m by 50m plots were established during the period from 2002 to 2014. As landscaping over Sydney Olympic Park has been undertaken in different stages affecting different precincts within the Park, several plots were added during this period to better sample evolving landscapes within the Park. At present only 15 of these plots are monitored as part of this study. Nine of these quadrats have been subject to some form of revegetation under the woodland bird habitat enhancement program (Appendix 2). The other plots form baseline data as they were either in natural habitat areas where no habitat modifications were considered appropriate or were duplicates of the plots monitored in the present study.

In each quadrat, both a vegetation analysis and bird survey program was completed with sampling occurring in 2005, 2009, 2014 and 2019. Many of the plots have been sampled during all four survey periods while a few have only been sampled over 2 surveys. The locations of the 15 current plots are shown in Figure 2.

Bird surveys

The fifteen quadrats were sampled for birds six times during spring and six times during autumn in 2004 and 2009 so that each quadrat was surveyed 12 times. Birds were sampled three times during spring and three times during autumn in 2014 and 2019 and so quadrats were sampled six times during the latter two survey periods. Each quadrat was surveyed for 20 minutes using an area search method. A total of 420 surveys were undertaken for a total survey effort of 140 hours.

Data collected on birds from each quadrat survey consisted of:

- numbers of each species present (birds passing over quadrats were not recorded unless actively foraging);
- position of each bird in one of the following habitat layers:
  - ground/grass layer;
  - shrub layer;
  - sub-canopy layer;
  - canopy layer;
  - air over canopy.
- the behaviour or activity of each bird as one of the following:
  - foraging (substrate [air, ground, foliage, bark, flowers, seed or fruit etc.] substrate species/ food used);
  - interacting with other birds or other animals or;
  - other non-foraging activities (perching, preening, calling or breeding).

Vegetation characteristics

Vegetation variables measured included tree height, shrub cover, tree canopy cover and the first four dominant species in each vegetation layer (canopy, shrub and groundcover). Vegetation types were separated into trees (greater than 10m), shrubs (1m to 10m) and groundcovers (less than 1 m).

Shrub index was measured at ten random points within the quadrat using a density board (Saunders 2005). The density board was viewed along the 50m edge of the quadrat to the opposite side. Visibility through the shrub layer for each 0.5 metre interval from the ground up to 2 metres above ground was scored as present at each level if vegetation obscured the view across the plot. This gave a score of 0 to 4 for each measure and then the scores were summed for all ten measures. This index ranged from 0 to 40, with zero indicating an absence of shrub cover and 40 indicating a dense cover of shrubs to 2 metres.

Tree canopy cover was estimated using the method described in Walker & Hopkins (1998). Canopy diameters and spacing between trees were measured along the mid line along the long axis of each quadrat. Measurements were made using a fibreglass measuring tape with the tree canopy cover projected onto the ground, and the means of each measure were used to estimate the tree canopy cover. A maximum of ten trees were used within each quadrat where sufficient trees were available.

Figure 2 Location of quadrats for woodland bird surveys at Sydney Olympic Park

Analysis

Twelve bird surveys were undertaken each year in 2004 and 2009, while 6 were undertaken in 2014 and 2019. Six surveys were randomly selected from the first two sampling periods so that 6 surveys were used to determine the average number of birds of each species detected per quadrat for each sampling period.

The birds were arranged into the following groups:

- aerial species foraging above the canopy of each quadrat;
- birds larger than Noisy Miners;
- Noisy Miners;
- birds smaller than Noisy Miners.

Correlations and regression analyses were done to examine relationships between vegetation structure and bird groups in the following combinations:

- tree cover vs shrub cover;
- tree cover vs small bird count;
- tree cover vs Noisy Miner count;
- tree cover vs large bird count;
- large bird count vs Noisy Miner count;
- shrub cover vs small bird count;
- shrub cover vs Noisy Miner count;
- shrub cover vs large bird count;
- small bird count vs Noisy Miner count;
- small bird count vs large bird count.

The correlations and trend lines revealed whether a relationship was not evident, positive or negative and the regression analyses determined strength of those relationships.

Results

Figure 3 shows the overall trend in tree and shrub cover across the 15 quadrats from 2005 to 2019. There was a decrease in shrub cover from 2004 to 2009 over all quadrats combined, but since then it has gradually increased but has not yet reached the same level as in 2004. Tree cover has increased from 33% to 57% during the same time period. Although trees have died or have been removed from some quadrats the remaining trees are maturing and their crowns are spreading to fill the gaps between trees with the consequence of increased tree canopy cover.

Bird richness

Seventy-one bird species were detected during 480 surveys of the 15 quadrats examined. The list of species in order from most to least common is shown in Appendix 3.

The Noisy Miner was the most common species detected followed by 4 smaller species. Smaller species make up 9 out of the 15 most common species detected during the surveys.

There has been a change over the study period in species composition; thirty-nine species were detected in 2004 and most of these were bird species were smaller than Noisy Miners. Forty-six species were detected in 2019 but these were mostly species larger than Noisy Miners. The change in species number within the three groups of birds - birds smaller than Noisy Miners, Noisy Miners and birds larger than Noisy Miners, are shown in Figure 4.

Bird abundance

There has been a gradual increase in the number of birds detected between 2004 and 2019 (Figure 5). The overall trend in average counts for small birds is a small decrease with the increase in bird count taken-up by increases in large birds and in particular Noisy Miners which have increased from an average count of 9.84

for all quadrats combined to an average count of 37.50 over the study period. Aerial species are shown, but they do not appear to be influenced by other bird groups as there is no competition between them and these other groups. Their presence does indicate good habitat below as this is often the source of insects above the canopy. There appears to be little change in the numbers of aerial species foraging over quadrats.

The patterns shown in Box 1 suggest that shrub cover and tree canopy cover influence bird species composition found within quadrats. The correlations and regression analyses tested the strength of these perceived relationships between birds and vegetation structure and are shown in Figures 8 to 17.

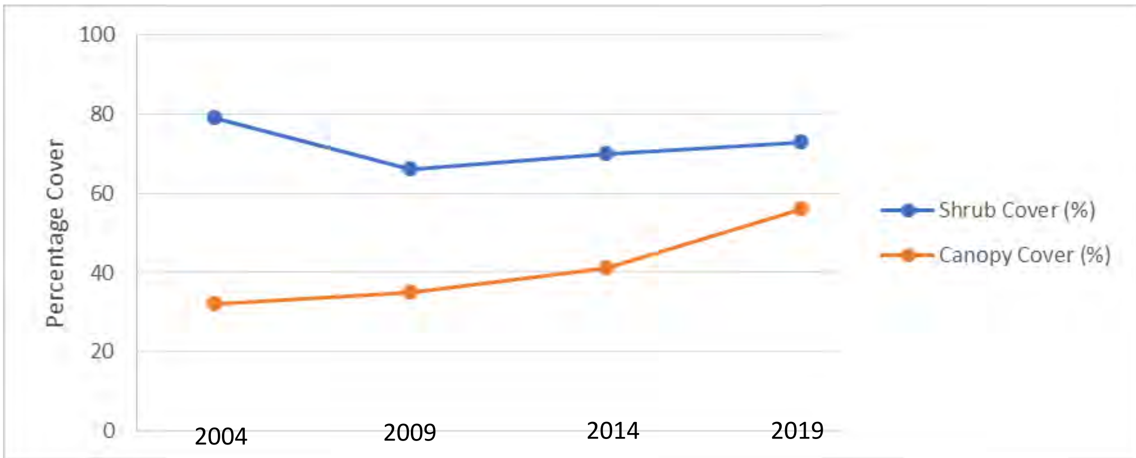

Figure 3 Average density of tree cover and shrub cover for all 15 quadrats combined within each survey period.

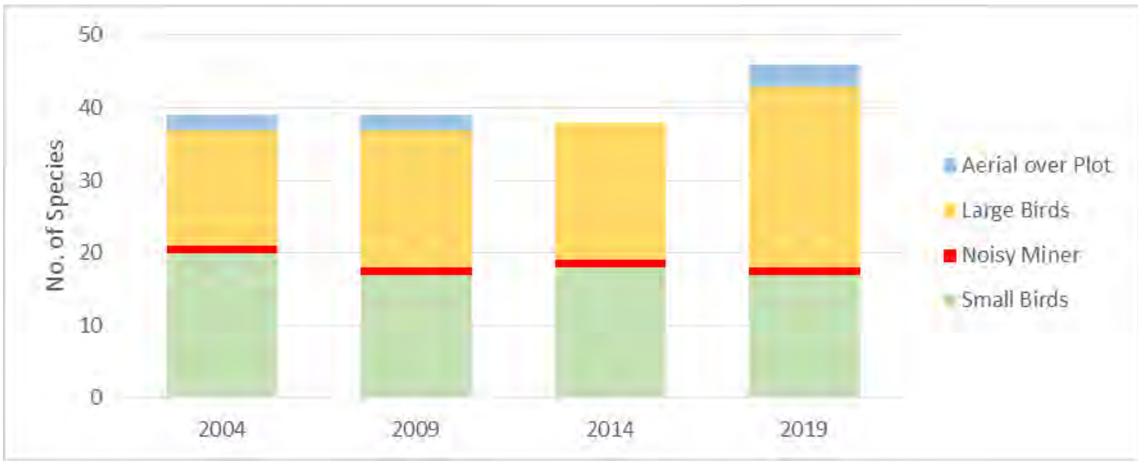

Figure 4 Number of birds in all quadrats combined within each survey period (small birds are smaller than Noisy Miners, large birds are larger than Noisy Miners and aerial birds are those that were seen foraging over the canopy of the quadrat).

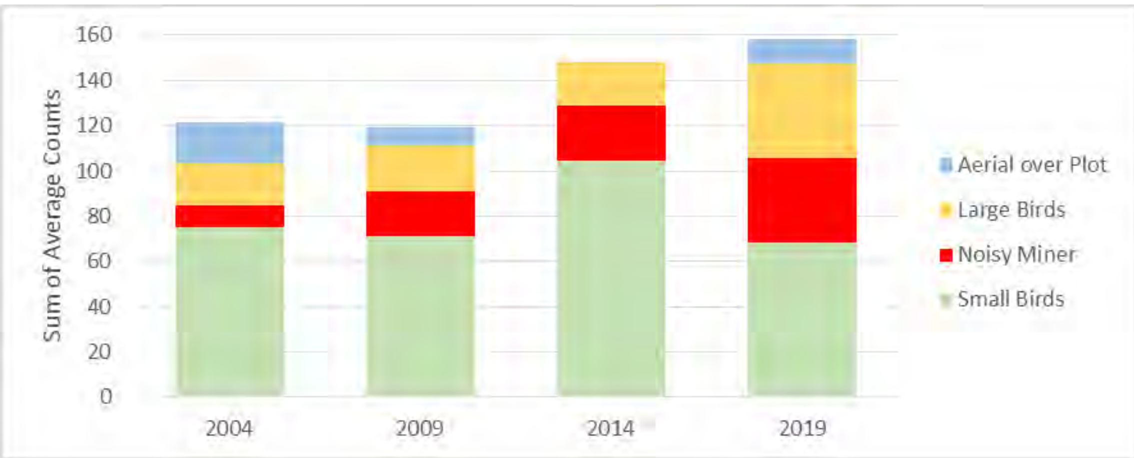

Figure 5 Sum of the average counts for birds in all quadrats combined within each survey period (small birds are smaller than Noisy Miners, large birds are larger than Noisy Miners and aerial birds are those that were seen foraging over the canopy of the quadrat).

Correlation analysis

Correlations were found between bird groups and between bird groups and vegetation structure. There was a significant negative correlation between shrub cover and tree cover (R^2 = 0.0936, P = 0.0368). Quadrats with higher tree cover generally had lower shrub cover. Small birds were strongly, positively correlated with shrub cover (R^2 = 0.2166, P = 0.0007), but strongly negatively correlated with tree cover (R^2 = 0.1183, P = 0.0145). Shrub cover accounted for 22% of the variation in counts of small birds. Small birds were very strongly negatively correlated with Noisy Miners (R^2 = 0.4509, P = 0.0001). The pattern of Noisy Miner count accounted for 45% of the variation in counts for smaller birds. Large bird numbers declined with increase in shrub cover, but the correlation was very weak (R^2 = 0.0689, P = 0.0565). Noisy Miners were strongly negatively correlated with shrub cover (R^2 = 0.1452, P = 0.0063). Tree cover was strongly positively correlated with Noisy Miners (R^2 = 0.2617, P = 0.0001) and with larger birds (R^2 = 0.2410, P = 0.0003).

Tree cover accounted for 26% of the variation in Noisy Miner counts and 24% of counts of larger birds. There was also a strong positive correlation between large birds and Noisy Miners (R^2 = 0.3994, P = 0.0001) and a strong negative correlation between small birds and large birds (R^2 = 0.1694, P = 0.0030).

Box 1 Examples of typical patterns that occur on quadrats that retain a dense canopy of eucalypts and quadrats with a high shrub cover and little to no tree cover.

Quadrat 1: Terrestrial vegetation on the edges of Narawang Wetland have a very simple structure consisting mostly of planted eucalypts. These began as a dense cover of shrubs which gradually grew into a tall layer of trees with narrow canopies – an overall increase in tree cover. As the trees changed from an immature shrub-like form to tall trees there was a loss of understorey. During that time small birds have disappeared from the quadrat while large birds and Noisy Miners have become very common. In 2015, there has been some tree thinning and planting of understorey shrubs, but at this stage they are very young and have only made a small contribution to the shrub layer.

Quadrat 2: This quadrat within the Brickpit was dominated by Lantana with no canopy for the 2005 study. The site then underwent a three stage removal process from 2009 to 2015 to replace the Lantana with native shrubs. With no canopy and a good water supply, the shrubs grew very quickly and formed good habitat within 4 years. The dense shrub layer, no canopy and absence of eucalypts are likely to be the reason why small birds are found so frequently. Small bird density remained high throughout the process with the last two surveys recording good abundance and an increasing diversity of species. Noisy Miners were recorded at very low densities which is typical of the Brickpit precinct.

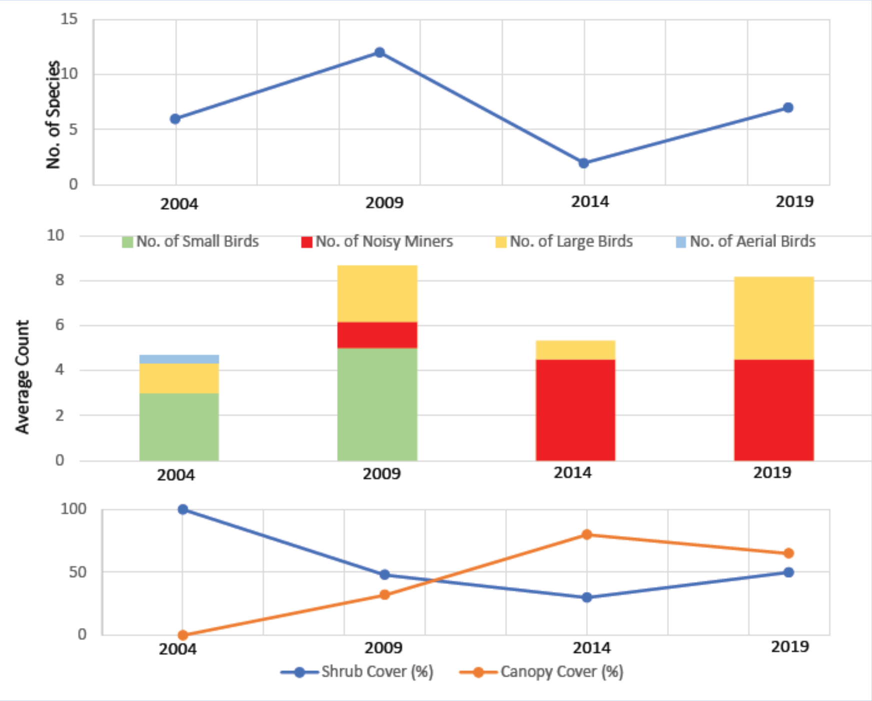

Figure 6 Changes in tree and shrub cover over the survey period along with changes in bird species count and changes in bird group composition in Narawang Wetland.

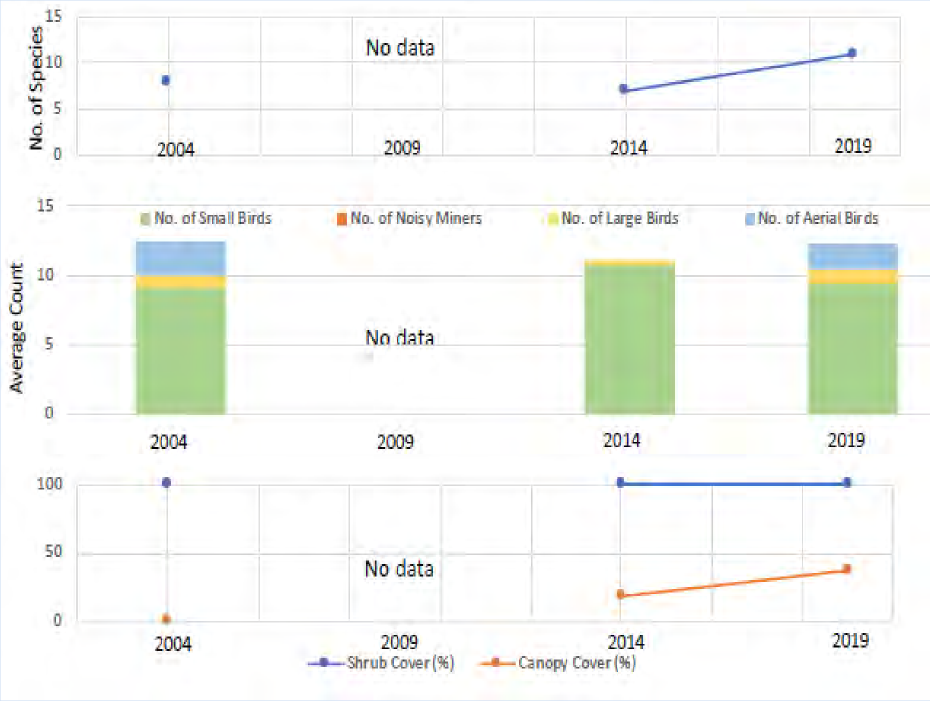

Figure 7 Changes in tree and shrub cover over the survey period along with changes in bird species count and changes in bird group composition in the Brickpit.

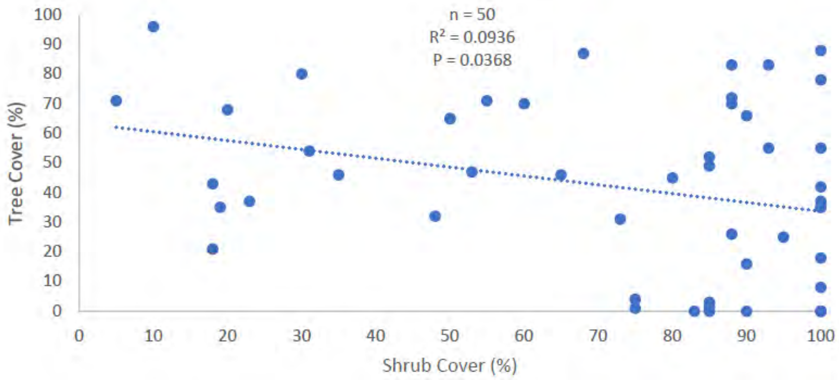

Figure 8 Correlation and regression analysis between shrub cover and tree cover for all plots and survey periods combined

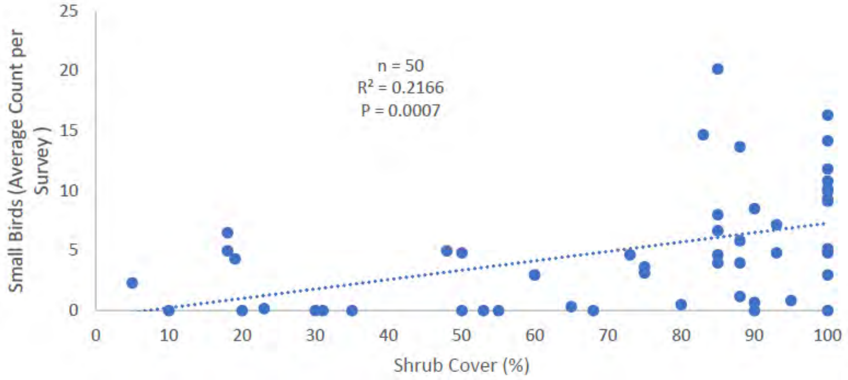

Figure 9 Correlation and regression analysis between shrub cover and average number of birds smaller than Noisy Miners for all plots and survey periods combined

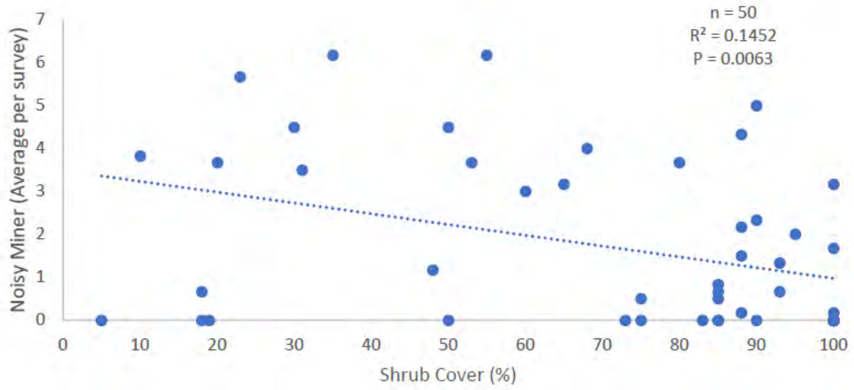

Figure 10 Correlation and regression analysis between shrub cover and average number of Noisy Miners for all plots and survey periods combined

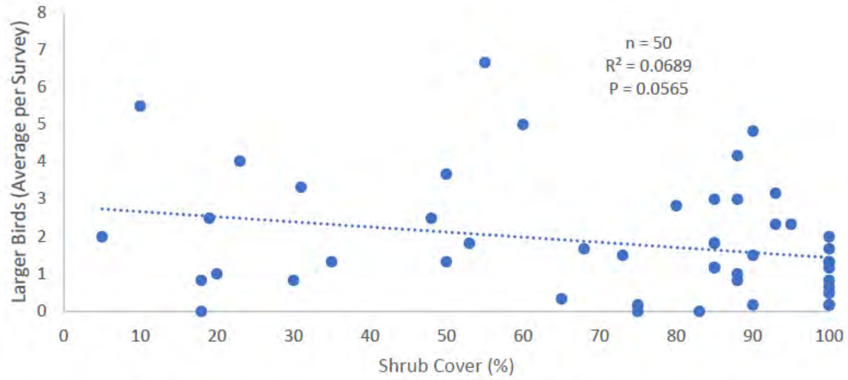

Figure 11 Correlation and regression analysis between shrub cover and average number of birds larger than Noisy Miners for all plots and survey periods combined

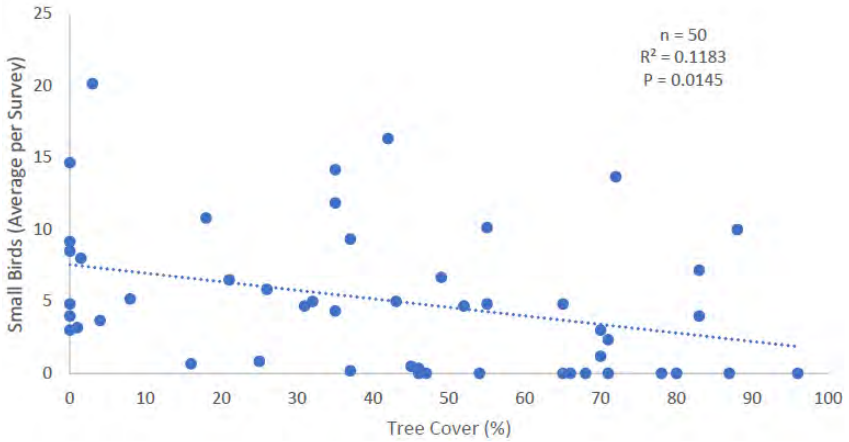

Figure 12 Correlation and regression analysis between tree cover and average number of birds smaller than Noisy Miners for all plots and survey periods combined

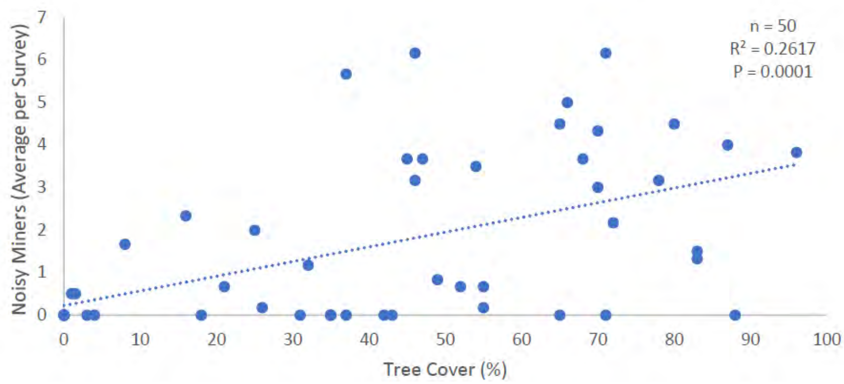

Figure 13 Correlation and regression analysis between tree cover and average number of Noisy Miners for all plots and survey periods combined

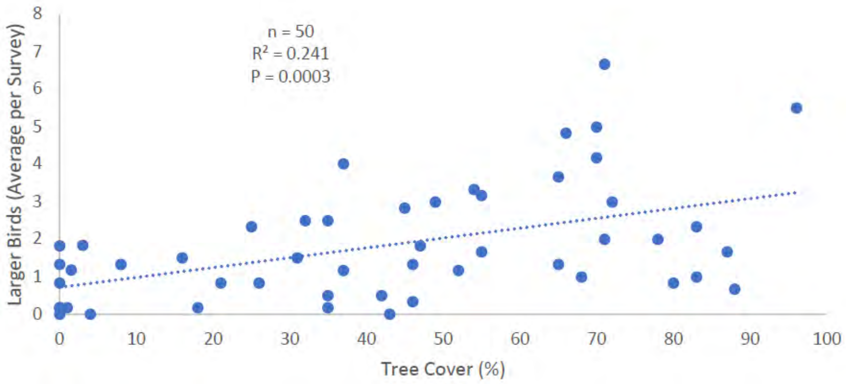

Figure 14 Correlation and regression analysis between tree cover and average number of birds larger than Noisy Miners for all plots and survey periods combined

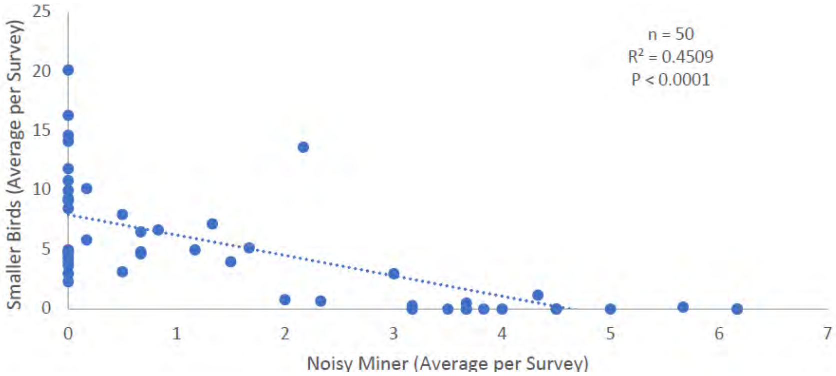

Figure 15 Correlation and regression analysis between Noisy Miners and average number of birds smaller than Noisy Miners for all plots and survey periods combined

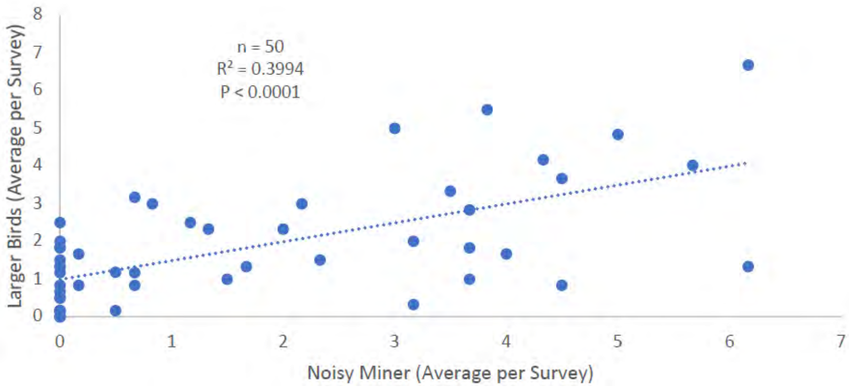

Figure 16 Correlation and regression analysis between Noisy Miners and average number of birds larger than Noisy Miners for all plots and survey periods combined

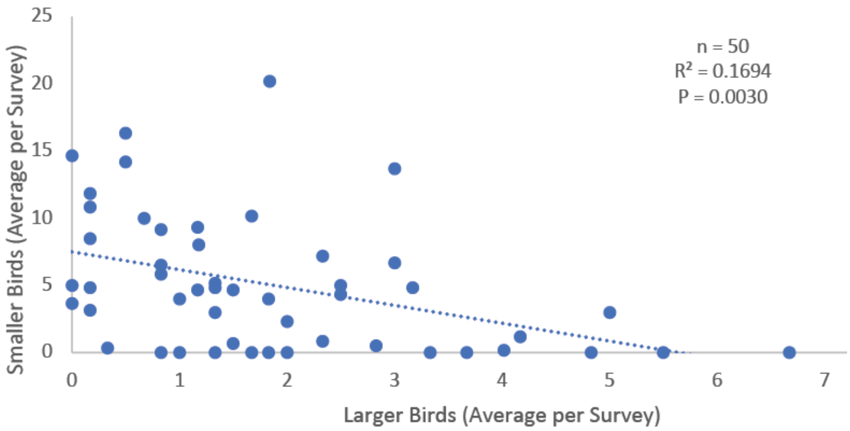

Figure 17 Correlation and regression analysis between average number of birds larger than Noisy Miners and average number of birds smaller than Noisy Miners for all plots and survey periods combined

Discussion

Summary of results

There was great variation in the vegetation structure between the 15 quadrats, however, patterns were found in the relationship between vegetation structure, as measured by shrub and tree cover, and bird community structure. Quadrats that were dominated by trees with only a sparse understorey of shrubs or were isolated and narrow were found to contain mostly Noisy Miner and larger birds. These quadrats were generally structurally very simple or were edge-affected, characteristics that favour larger birds. The more open habitat suits their foraging habits and also allows them to defend foraging and breeding territories more easily. Quadrats that had a dense shrub layer may also contain Noisy Miners and some larger birds, but they often occur at lower densities. The quadrats with a dense cover of shrubs with or without an open cover of trees generally supported a greater variety and higher density of smaller woodland bird species.

The results of this study accords with other studies (Evans *et al.* 2009, Howes *et al.* 2014, White *et al.* 2005). These studies found that increasing the shrub complexity with locally indigenous species will increase the richness and abundance of woodland birds. The positive correlation of bird species richness and abundance to shrub density and negative correlation with a simplistic eucalyptus canopy and the presence of the Noisy Miner provides evidence for adopting practices that increase shrub density and diversity.

Landscape design for woodland birds

Landscapers and park managers can change vegetation composition and structure in ways that can have profound impacts on biodiversity outcomes as much as on the aesthetics and social utility of public open spaces. The 1997 Sydney Olympic Park landscaping design master plan aimed for an aesthetic outcome based on canopy trees with a simplistic grass understory. This design contributed to a decline in woodland birds and an increase in Noisy Miners and other large bird species between 2000 and 2009. The initial planting of canopy trees was designed to provide an instant forest rather than to provide for biodiversity. Eucalypts were selected to tolerate the 'constructed' landscape produced by the significant on-site remediation necessary across the site.

The maturation of this forest resulted in change in overall vegetation structure from shrubs without trees to trees without shrubs within approximately 10 years from initial planting. An unintended consequence of this landscaping design has been reduced bird diversity over time. The loss of the shrub layer and development of a tall canopy dominated by eucalypts reduced habitat value for small woodland birds. This was exacerbated by the impact of more aggressive species such as the Noisy Miner (Thomson *et al.* 2015) that cumulatively alienated and negatively impacted on small bird populations and compositions.

Since 2006, Sydney Olympic Park Authority has implemented a habitat modification program aimed at increasing the structural diversity and complexity of key areas of the Park to support woodland birds. The program seeks to build connectivity between key woodland bird habitats identified in the Brickpit, Narawang Wetland, Newington Nature Reserve, Kronos Hill and Woo-la-ra. Areas for future works have been identified in Blaxland Riverside Park and Haslams Creek Flats that will contribute to the linking of woodland bird hotspots within the Park and to the region. The modifications have been shown by the surveys over 15 years to have had a positive influence on woodland bird population and composition.

It is expected that it will take another 5-10 years for landscape planting programs at Sydney Olympic Park to have a more significant impact on woodland bird populations, consistent with the results of a study by Barrett (2000). For this reason, the habitat modification program at Sydney Olympic Park is ongoing with maintenance of current woodland bird habitats continuing and additional areas planned.

Successful habitat enhancement at Sydney Olympic Park

This study shows that in areas of Sydney Olympic Park where dense shrubs were present and tree canopy was minimised, small bird abundance and diversity was higher. The Brickpit, a 27 hectare precinct with few eucalypts and little tree cover, had the highest proportion of small birds across the study area. The literature suggests that this is due to the lack of eucalypts, which are favoured by Noisy Miners, and the density of the shrub layer. The Brickpit is also one of the few precincts within the Park not dissected by pathways and experiences low levels of human disturbance which also may play a role in maintaining a woodland bird community.

At an individual species level, the study has revealed that habitat modification, even at the small patch scale, can have a positive impact. Edge specialists such as the Red-browed Finch and Superb Fairy-wren were advantaged by the introduction of successional stages into the vegetation structure. New plantings with vigorous groundcover growth provided new habitat niches not available in the original single aged landscape. Inclusion of shrubs with prickly leaves such as Hakeas provided nesting habitat.

Small patches of habitat were manipulated to reduce their attractiveness to Noisy Miners through canopy thinning to encourage the growth of shrubs, the preferential removal of eucalyptus species, the retention of casuarinas, or clustering of the eucalyptus canopy (maximum of 30 trees per hectare) above a very dense planting of shrubs. The shrub densities required by small woodland birds were only produced with a minimum tree canopy cover. Where maturing trees are densely planted and the tree canopy cover is high, shrub density is slow to establish and after more than 8 years, is not attracting small birds. Ongoing monitoring is required to test whether the patterns observed at the quadrat scale are also occurring at the precinct and whole-of-Park scales.

Recommendations for designing and managing woodland bird habitat

The results of this study are relevant to design of urban parkland landscapes throughout eastern Australia and are a step towards providing knowledge of the relationship between particular bird species and restoration efforts that will enable fine-tuning of habitat design. Landscape designers and land managers can benefit from the lessons learnt at Sydney Olympic Park and can use them to refine and adapt biodiversity planning for urban green space.

The specific recommendations for landscapers and park managers include:

Design of woodland bird habitat

Planning for new sites incorporating woodland bird habitat should consider locally indigenous plant species that provide a variety of resources to woodland birds including prickly foliage for shelter and nesting, insect attracting species and grasses for granivores. The design should consider the following points:

- tree density should be < 30/ha;
- the eucalyptus component should be limited and supplemented by other genus such as Casuarina or Melaleuca;
- shrub density should be 1-2 shrubs/m2;
- groundcover density should be 4-6 plants/m2;
- coarse mulch incorporated;
- potential for future shading of groundcovers minimised by planting in bands or clumps to allow sunlight penetration.

Planning for woodland bird habitat

Woodland bird habitat can take up to four years to establish under good conditions and planning must consider funding for long-term management needs. Long-term management should consider the following points:

- weed control to prevent establishment of woody weeds that can replace woodland bird habitat. If woody weeds are established, removal should not take place until replacement habitat has been shown to support a similar diversity of woodland birds;
- follow up planting to replace unsuccessful individual plants and ensure that all habitat layers are well represented over time;
- potential thinning of all layers to ensure that shading and over competition between plants does not remove total habitat complexity and heterogeneity.

Acknowledgements

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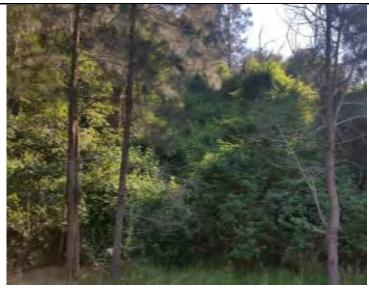
Appendix 1 Vegetation types in woodland bird monitoring quadrats 2005-2019, Sydney Olympic Park.

2005 | 2009 | 2015 | 2019

Figure 1a Unmodified landscapes (MP12-8) – Maturing trees with a canopy of eucalyptus and simple grassy understorey. No shrubs or groundcovers installed.

2005 | 2009 | 2015 | 2019

Figure 1b Modified landscape (MP12-7) – shrub planting under densely planted mature trees and kikuyu groundcover. Shrub density is slow to establish and after more than 8 years, remains scattered and thin.

2005	2009	2015	2019
No data			
Figure 1c Highly modified landscape (MP12-9) – thinning of trees and planting of a dense shrub/groundcover layer.			
			
Figure 1d Natural landscape (MP17-11) located within Newington Nature Reserve	**Figure 1e** Weed dominated (MP13-7) mature canopy (*Casuarina glauca*) with an understorey of woody weeds (*Lantana camara*)	**Figure 1f** Modified Landscape (MP14-8) woody weeds have been removed and replaced with shrubs. Trees limited to perimeter of quadrat.	**Figure 1g** Modified landscape (MP13-6) woody weeds have been removed and replaced by shrubs. No tree canopy.

Appendix 2 Landscape categories, survey effort and descriptions for woodland bird quadrats, Sydney Olympic Park

Quadrat		SOPA Precinct	Previous surveys				History
			2005	2009	2015	2019	
Remnant	MP17-11	Newington Nature Reserve	X	X	X	X	Sited within Newington Nature Reserve and part of the remnant critically endangered Sydney Turpentine Ironbark Forest community. All three canopy layers in good condition.
Landscape (modified)	MP3-5	Newington Armory		X	X	X	Revegetated in 2006 as part of the extension of the Sydney Turpentine Ironbark Forest community. All three canopy layers in good condition, natural recruitment occurring.
	MP4-2	Woo-la-ra		X	X	X	Site for storing and treating soils as a result of land remediation elsewhere across the site. Restored in 2003 with a mix of shrubs and trees in a woodland matrix. Groundcover layer consists mostly of mulch.
	MP6-27	Narawang Wetland	X		X	X	Located on lands created by landfilling and remediation. Vegetation comprises solely of eucalypts planted in 1999-2000 with a mulched understorey. Tree canopy thinned and shrubs and groundcovers installed in 2015 – vegetation is still immature. Linear shape, highly edge-affected.
	MP11-6	Triangle Pond, Wentworth Common	X	X	X	X	Original edge of Homebush Bay, some dumping of clean fill in 1998. Revegetated in 2010 and 2014 to create a shrub layer which is now in good condition. Canopy trees retained throughout industrial history.
	MP12-7	Kronos Hill	X	X	X	X	Located on a remediated landfill topped with constructed soils. Originally planted with native grasses underneath a eucalypt canopy in 1996. Now dominated by trees and exotic grasses. Shrubs planted under tree canopy in 2006 and 2008 to increase structural diversity.
	MP12-9	Kronos Hill	X	X	X	X	Located on the northerly slope of a remediated landfill topped with constructed soils. In 2014, 50% of trees were removed and a mix of local and regional provenance shrubs and groundcovers installed.

	MP13-6	Brickpit		X	X	X	Located on the entry track of an old brickpit quarry. Primarily a monoculture of *Lantana camara*, one third of the quadrat was replanted in 2011 with regional provenance shrub species. No tree canopy present.
	MP13-8	Brickpit	X	X	X	X	Located on the floor of a disused brickpit quarry. Topography a result of piled demolition material. Planted with shrubs and groundcovers in 2010. Supplementary planting in 2012. No tree canopy present.
	MP14-8	Badu Mangroves	X	X	X	X	Highly modified due to historic construction of seawalls and bunds in Homebush Bay. First planted with trees and shrubs in 2008 and supplementary planted in 2012 after staged removal of woody weeds.
Landscape (unmodified)	MP2-4	Blaxland Riverside Park	X	X	X	X	Located on the slopes of a capped landfill. Vegetation primarily *Casuarina glauca* planted in 1998-99.
	MP15-10	Bicentennial Park	X	X	X	X	Located in a formal landscape derived from a capped landfill. An isolated forest patch surrounded by mown turf, vegetation is comprised of eucalypts, shrubs and grasses planted in 1993. Linear shape, highly edge-affected.
	MP12-8	Kronos Hill			X	X	Located on a remediated landfill topped with constructed soils. Originally planted with native grasses underneath a eucalypt canopy in 1996. Now dominated by trees and exotic grasses with a simplified structure.
	MP11-4	Wentworth Common	X	X	X	X	Located on remediated land capped and topped by constructed soils. Planting comprised of eucalypts and melaleucas that form a primarily canopy only structure.
Weed dominated	MP13-7	Brickpit	X	X	X	X	Located on the lower slopes of a disused brickpit quarry. Vegetation comprised of an understorey of *Lantana camara* and a canopy of *Casuarina glauca*.

Appendix 3 Bird species detected on quadrats during the 2004 to 2019 woodland birds study at Sydney Olympic Park, listed from most to least common based on average count for each species across all quadrats. Birds are grouped into colour categories: red: Noisy Miner, yellow: large Birds (>63g); light green: small birds (<63g); dark blue: aerial over quadrat.

Scientific Name	Common Name	All Surveys
Manorina melanocephala	Noisy Miner	91.39
Malurus cyaneus	Superb Fairy-wren	88.57
Zosterops lateralis	Silvereye	63.99
Neochmia temporalis	Red-browed Finch	45.46
Lichenostomus penicillatus	White-plumed Honeyeater	25.61
Hirundo neoxena	Welcome Swallow	21.45
Trichoglossus haematodus	Rainbow Lorikeet	20.04
Acanthiza nana	Yellow Thornbill	15.18
Petrochelidon ariel	Fairy Martin	14.73
Anthochaera carunculata	Red Wattlebird	14.30
Strepera graculina	Pied Currawong	12.87
Phylidonyris novaehollandiae	New Holland Honeyeater	12.12
Sericornis frontalis	White-browed Scrubwren	11.51
Pardalotus punctatus	Spotted Pardalote	10.15
Pynonotus jocosus	Red-whiskered Bulbul	9.82
Cracticus torquatus	Grey Butcherbird	7.25
Cracticus tibicen	Australian Magpie	7.23
Coracina novaehollandiae	Black-faced Cuckoo-shrike	5.49
Corvus coronoides	Australian Raven	4.74
Carduelis carduelis	European Goldfinch	4.17
Rhipidura leucophrys	Willie Wagtail	3.85
Grallina cyanoleuca	Magpie-lark	3.68
Lichenostomus chrysops	Yellow-faced Honeyeater	3.27
Pachycephala pectoralis	Golden Whistler	3.25
Rhipidura albiscapa	Grey Fantail	3.13
Porphyrio porphyrio	Purple Swamphen	2.75
Accipiter fasciatus	Brown Goshawk	2.35
Glossopsitta concinna	Musk Lorikeet	2.33
Sturnus vulgaris	Common Starling	2.22
Egretta novaehollandiae	White-faced Heron	2.18

Sturnus tristis	Common Myna	2.17
Threskiornis molucca	Australian White Ibis	1.99
Lonchura punctulata	Nutmeg Mannikin	1.95
Streptopelia chinensis	Spotted Dove	1.73
Dacelo novaeguineae	Laughing Kookaburra	1.61
Psephotus haematonotus	Red-rumped Parrot	1.35
Petroica rosea	Rose Robin	1.18
Alisterus scapularis	Australian King-Parrot	1.17
Calyptorhynchus funereus	Yellow-tailed Black-Cockatoo	0.85
Taeniopygia bichenovii	Double-barred Finch	0.84
Eolophus roseicapillus	Galah	0.83
Philemon corniculatus	Noisy Friarbird	0.83
Platycercus eximius	Eastern Rosella	0.78
Pachycephala rufiventris	Rufous Whistler	0.73
Anthochaera chrysoptera	Little Wattlebird	0.68
Hirundapus caudacutus	White-throated Needletail	0.67
Ocyphaps lophotes	Crested Pigeon	0.56
Coturnix ypsilophora	Brown Quail	0.55
Anas superciliosa	Pacific Black Duck	0.55
Platycercus elegans	Crimson Rosella	0.55
Dicaeum hirundinaceum	Mistletoebird	0.55
Falco peregrinus	Peregrine Falcon	0.51
Cacatua galerita	Sulphur-crested Cockatoo	0.50
Scythrops novaehollandiae	Channel-billed Cuckoo	0.50
Gallinago hardwickii	Latham's Snipe	0.45
Lichmera indistincta	Brown Honeyeater	0.45
Cisticola exilis	Golden-headed Cisticola	0.28
Acrocephalus australis	Australian Reed-Warbler	0.28
Chalcites basalis	Horsfield's Bronze-Cuckoo	0.23
Falcunculus frontatus	Crested Shrike-tit	0.23
Podargus strigoides	Tawny Frogmouth	0.17
Phalacrocorax varius	Pied Cormorant	0.17
Gallirallus philippensis	Buff-banded Rail	0.17
Ninox novaeseelandiae	Southern Boobook	0.17
Myzomela sanguinolenta	Scarlet Honeyeater	0.17

Sphecotheres vieilloti	Australasian Figbird	0.17
Oriolus sagittatus	Olive-backed Oriole	0.17
Dicrurus bracteatus	Spangled Drongo	0.17
Rhipidura rufifrons	Rufous Fantail	0.17
Myiagra rubecula	Leaden Flycatcher	0.17
Turdus merula	Common Blackbird	0.17

Recent reptile surveys in Sydney Olympic Park

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Australian Herpetological Society

We present a summary of the observations on the reptile fauna recorded during annual surveys conducted by members of the Australian Herpetological Society in Sydney Olympic Park, focusing in particular on the last four years. These surveys are part of a more general long-term systematic monitoring program that aims at gaining a better understanding of the distribution, abundance and dynamics of the vertebrate fauna occurring in the Park.

Introduction

The Australian Herpetological Society (hereafter referred to as the AHS) has been conducting surveys of the herpetofauna that is present in Sydney Olympic Park for many years in collaboration with the Sydney Olympic Park Authority (SOPA). These activities are specified in a yearly renewed agreement between the two parties, and are part of a long-term amphibian and reptile monitoring program as originally proposed by Hal Cogger in a document prepared for SOPA that also summarises our knowledge about the frogs and reptiles in the Park up to then (Cogger, 2005), following previous surveys dating back to 1993 and 2003 (Greer, 1993; Denny & Hoye, 2001; Denny, 2002).

The purpose of the current surveys is manifold:

- to gain a better understanding of the reptile diversity, abundance and distribution within the boundaries of Sydney Olympic Park;
- to establish baselines and assess trends; inform management about the status and integrity of the various ecological communities for the implementation of conservation measures;
- to promote the understanding and appreciation of the roles that reptiles play in the Park and in our urban ecosystems in general.

One of the more iconic inhabitants is the Green-and Golden Bell Frog (*Litoria aurea*), and the Park plays a critical role in the conservation of this beautiful yet strongly declining species.

The AHS is responsible for appointing a co-ordinator who is responsible for overseeing all aspects of the surveys, and in particular with the identification of specimens if necessary; recruiting a team of volunteers to undertake the surveys, ensuring they are skilled in reptile surveys, and communicating with, rostering and managing the volunteers throughout the survey period. In addition, prior to the commencement of each survey, the SOPA representative organises an on-site Volunteer Induction Briefing to ensure that the volunteers are aware of potential dangers and local restrictions. For the last few years, the first author of this report has taken up the co-ordinator role. Because of the educational aspects of these activities, we try to organise them in a very inclusive way, and we make them attractive to our younger members. There are some additional benefits also to participating with these excursions, because some of the localities that we visit are in non-accessible areas.

These surveys are usually happening in spring, when reptiles tend to be more active. The AHS provides a team of volunteers to investigate a set of predetermined and established quadrats for the presence and abundance of reptiles. We also document the incidental presence of frogs and other animals if we encounter them while looking for reptiles. This report however will only discuss the reptiles that occur in Sydney Olympic Park and were observed over 2015–2019.

During this period reptile-specific surveys were organised on Saturday 21 February, Saturday 12 September and Saturday 17 October 2015; Saturday 29 October and Sunday 27 November 2016; Saturday 21 October and Sunday 12 November 2017; Saturday 22 September and Sunday 21 October 2018; and Sunday 22 September and Saturday 19 October 2019. From spring 2015 onwards the number of reptile surveys was reduced to two per year, whereas before the AHS ran up to four such events per season. All the data are entered in the appropriate biodiversity databases by the SOPA staff who oversee these excursions.

For the current species nomenclature we decided to follow Cogger (2018). Other literature useful for the identification of reptiles in the Sydney area and NSW are Griffiths (2012), and Swan *et al* (2017).

Results

Before 2005, 13 species of reptiles (and 7 species of frogs) had been recorded from Sydney Olympic Park. These observations included some species for which there was only anecdotal evidence of their presence within the boundaries of the Park, as discussed below.

AHS survey quadrats cover a broad range of habitat types, and the abundance of reptiles reflects this variation (Figures 1 and 2). The existing wildlife database of Sydney Olympic Park Authority is supplemented with incidental and opportunistic observations by various other people, SOPA staff and otherwise, at other times and places in the Park. Eighteen species of locally-native reptiles are now known to occur in the area, although a number of species appear to be either very rare or are perhaps easily overlooked. Compared with our pre-2005 knowledge, some reptile species have been added to the list of animals known to occur in the Park, yet for some other species no evidence of their continued presence exists at this stage despite many years of systematic monitoring. One should however keep in mind that some of the fossorial reptile species display very cryptic behaviour, and some species are active at different times of the day, and so their potential presence may not easily be confirmed because of the limitations imposed by the survey methodology.

Each quadrat that is scheduled to be surveyed on a particular day is visited for a set time period. The volunteers disperse and cover the plot in an organised and methodological way, carefully monitoring for the presence of reptiles and looking under tree trunks and rocks, taking great care that everything that is moved is returned to its original position to minimise the disturbance of the habitat. An overview of the current plots is given in Figure 1, and the observed distributions of the various reptile species are at Figure 3.

Snakes in particular appear to be quite rare, which is perhaps appreciated more by the large number of day visitors (and their pets) than by the more intrepid naturalist, with only one snake—a Blackish Blind Snake (*Anilios nigrescens*)—encountered during our actual reptile surveys (in 2013; Figure 4). This is a fossorial species that can become active on the surface at night. As indicated in Figure 3, there are a few more recent incidental observations of the Red-bellied Black Snake (*Pseudechis porphyriacus*), Green Tree Snake (*Dendrelaphis punctulatus*), and some Carpet Pythons (*Morelia spilota variegata*). The latter subspecies is not native to the Sydney area and so are either escapees or hitchhikers with cargo. Needless to say, these animals are removed from the Park and relocated to a new home with a friendly AHS member or so. There is one pre-2015 record of the native Diamond Python (*Morelia spilota spilota*) from within the boundaries of the Park. A significant part of the diet of the Red-bellied Black Snake consists of frogs, and the species has been observed adjacent to some of the frog ponds and elsewhere in 2015 and 2017, but not during the recent systematic AHS surveys. There are also incidental recordings of road-killed specimens (one from 2015), and we are aware of one intrepid individual that made it into the Silverwater Correctional Complex before 2015. It is encouraging to note that there are recent incidental observations of Green Tree Snakes, recorded twice in 2018 at different sites in the Park.

Figure 1. Reptile survey plots at Sydney Olympic Park (yellow). Green lines denote precinct boundaries of the Park.

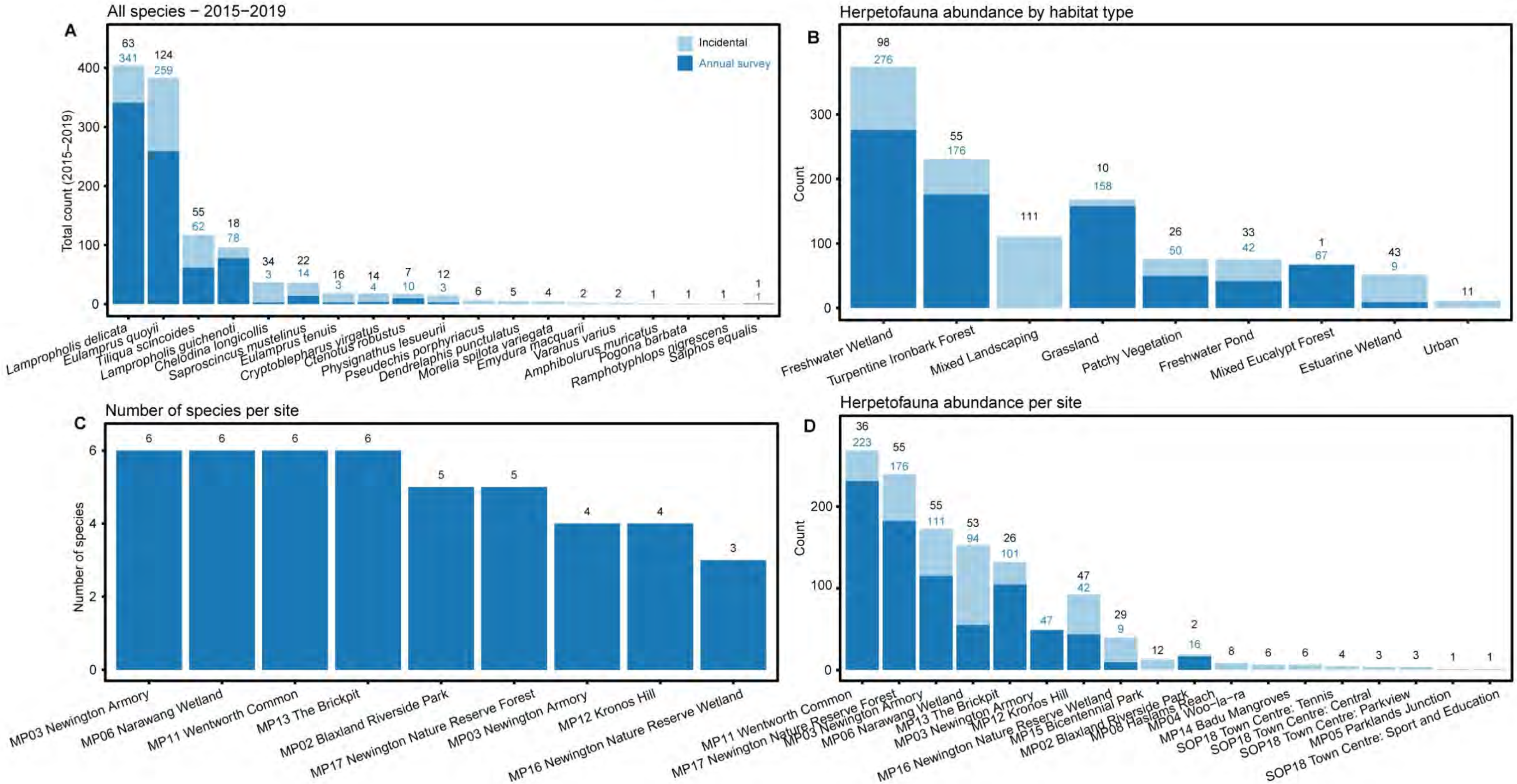

Figure 2. Reptile community structure in the survey period 2015–2019. A) Number of individuals observed for each species across the survey period. B) Number of individuals observed in different habitat type. C) Number of species and D) Number of individuals observed at each assigned survey site. Dark blue bar charts represent counts or observations within the annual survey, and light blue bar charts represent incidental findings.

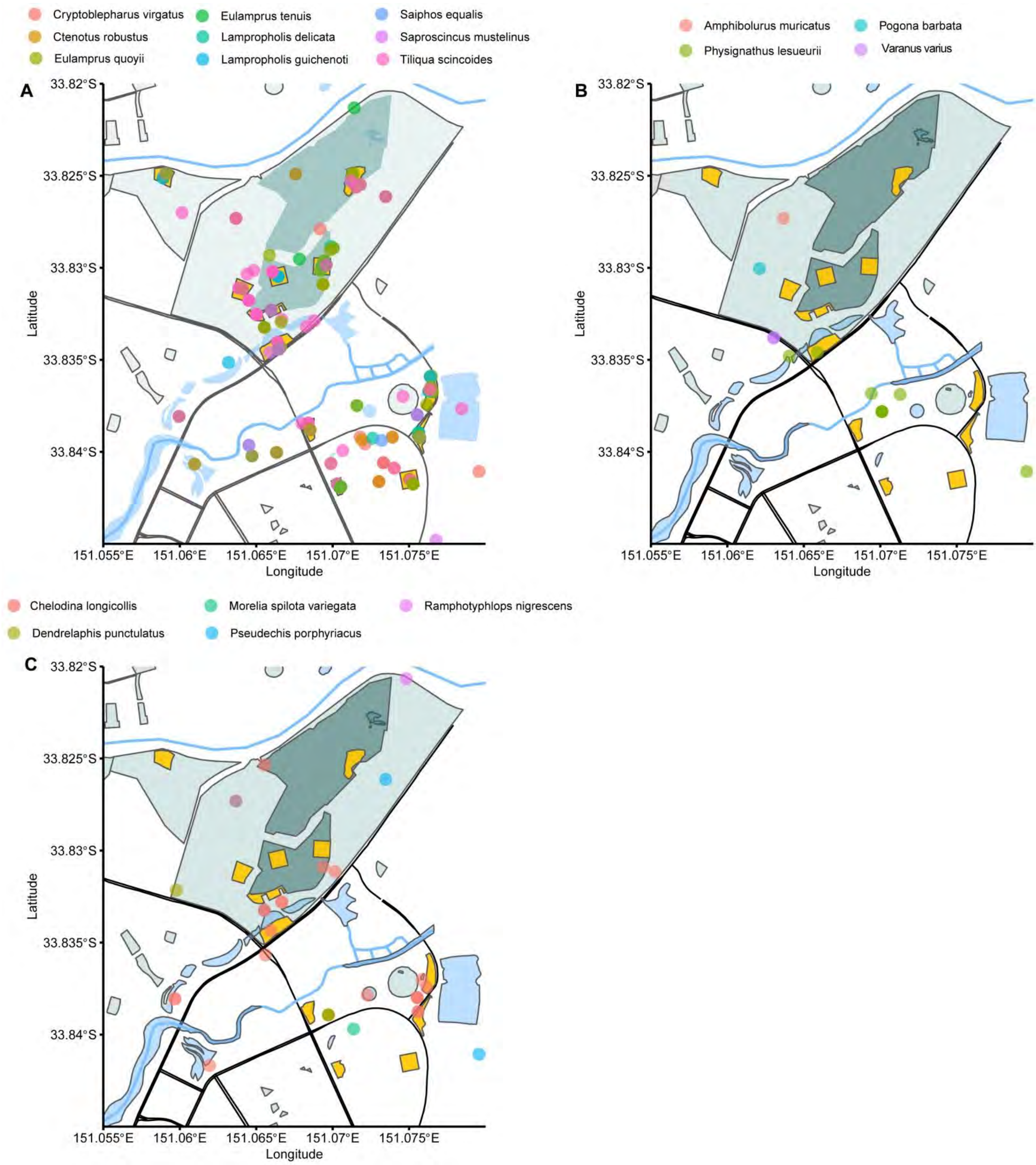

Figure 3. Reptile distribution in Sydney Olympic Park separated by A) skinks, B) agamid and varanid, and C) snakes and turtles

Figure 4. A Blackish Blind Snake from Macquarie Park, Sydney

The two most observed species are the (Dark-flecked) Garden Sunskink (*Lampropholis delicata*) and the Eastern Water Skink (*Eulamprus quoyii*); in fact, they are so common that they are almost certainly under-reported. Both species can tolerate considerable urban development, and many people are familiar with them. As indicated by its English name, the Eastern Water Skink is often (but not always) living in the vicinity of aquatic bodies of some sort, and is usually quite conspicuous where it occurs. It is a fairly large sized active brownish lizard with two more or less distinctive golden-coloured stripes on the back, and darker flanks with many small light spots (Figure 5a). The Garden Sunskink on the other hand is a small brown, more uniformly coloured and perhaps less conspicuous skink, which is abundant throughout the Park.

Another skink that superficially looks very similar to the Eastern Water Skink is the Bar-sided Skink (*Concinnia tenuis*; Figure 5b); in fact, until fairly recently it shared its genus name with the former species. This is essentially a tree-dwelling species, often seen when it pokes its head from a hole in a tree trunk or when basking nearby, and we have observed them elsewhere in the Sydney area, active after sunset, hunting for insects under house lights. Because of its arboreal habitat it is probably easily overlooked; in fact, Cogger (2005) states that at that time there was only a single record from the Park from 1994 or so. The systematic monitoring has shown that it actually occurs in several localities in the Park, and this illustrates the scientific value of such regular surveys.

a)

b)

Figure 5. Eastern Water Skink (a) and Bar-sided Skink (b) in Sydney Olympic Park

Also common are the iconic and distinctive Eastern Blue-tongued Lizard (*Tiliqua scincoides*) and the far less conspicuous Grass Sun-Skink or Pale-flecked Garden Sunskink (*Lampropholis guichenoti*). The latter species can look quite similar to its dark-flecked relative, in particular when it dashes off and disappears in the undergrowth, but usually has a more or less conspicuous dark vertebral stripe and may look more greyish. The Eastern Blue-tongued Lizard is a well-known large-sized and slow-moving skink with a large triangular head, often with beautiful patterns on the back (Figure 6). For one reason or another, they tend to lose many of their toes when they grow older, but that is admittedly somewhat harder to see without closer inspection.

Figure 6. One of many Eastern Blue-tongued Lizards in Sydney Olympic Park

Another species that is almost certainly under-reported during the surveys is the Robust Ctenotus (*Ctenotus robustus*), a species that also looks somewhat similar to the Eastern Water Skink with which it may sometimes share similar habitats (Figure 7). A closer look (if possible) will reveal that they have a delicate pattern of several longitudinal stripes on the back, including a mid-dorsal black line which is enclosed by two very narrow golden stripes. These moderate-sized diurnal skinks are extremely fast and agile when they have reached their preferred body temperatures and tend to be quite shy, so they are easier to find during the earlier hours of the day when they may still be hiding under rocks and various other debris on the surface. They appear particularly common in the relatively open areas in the Brickpit, but we have also observed them in other grassy areas in the Park. There exist also some older records of the related Copper-tailed Skinks (*Ctenotus taeniolatus*), but this species was not observed during the years 2015–2019. As indicated by its name, this active diurnal lizard has a conspicuous reddish tail.

Figure 7. A Robust Ctenotus found in the Brickpit

Fence Skinks or Striped Snake-eyed Skinks (*Cryptoblepharus virgatus*) are small, active and diurnal lizards, that are usually seen basking or moving on rocks or trees or even house walls, and they occur even in some of the urban habitats in inner Sydney. Because of their small size and arboreal habits, they are easily overlooked. Its common name originates in the structure of its eyelids, with a transparent scale covering the eyes, which cannot close as is the case with snakes. They have a conspicuous pair of longitudinal dorsolateral silvery-grey stripes along their backs, and so they may look vaguely similar to juvenile Eastern Water Skinks until one has a proper look. Most of the observations so far occurred in the Brickpit and the Newington Nature Reserve area.

The Weasel Skink (*Saproscincus mustelinus*) is another species added to the fauna list of Sydney Olympic Park because of the more systematic monitoring for the presence of reptiles, with a single record from 2001 and more frequently encountered in the last decennium in several localities in the Park. During daytime they are usually found hiding under debris, because they appear to prefer moister areas, becoming active in the evening or at night in particular on warmer nights. They are brown to russet brown above with many scattered pale flecks; the tail is sometimes distinctively reddish brown, and they have a small distinctive white spot behind the eyes (Figure 8a).

The Three-toed Skink (*Saiphos equalis*) was unknown in the Park until 2017 when an incidental sighting occurred in the Brickpit. One specimen was then found during the 2018 surveys in Newington Armory but managed to escape before photographic evidence could be obtained. The species is known to be present in two disjunct precincts and could be rare in the Park. This is a burrowing species that is usually found under rocks or logs. It is a moderately sized brown elongate skink with short limbs with three digits each, and a distinctive yellow to orange belly (Figure 8b). A few species of dragon (family *Agamidae*) also occur in the Park, but they don't appear to be common. Jacky Lizards (*Amphibolurus muricatus*) appear to be also a more recent addition to the fauna list of Sydney Olympic Park, with the first records in the database appearing in 2010. So far, the species has only been recorded from a few localities, and a specimen basking on a fallen tree was observed during one of our 2016 surveys.

Although common in the Sydney basin, the familiar Eastern Water Dragon (*Intellagama lesueurii*) is notoriously absent from the AHS surveys. There are fewer than 20 incidental records in the SOPA database from various locations in the Park, although these large and active dragons are usually very conspicuous when present. These lizards are usually associated with creeks and larger streams, and so one would expect that colonisation would occur via the Parramatta River.

a)

b)

Figure 8. Weasel Skink (a) and Three-toed Skink (b)

Another dragon that is known to occur in Sydney Olympic Park is the Bearded Dragon (*Pogona barbata*). There is however only one record in the SOPA database in the last few years, and this is an incidental observation from October 2018, with previous records from 2013 and 2010. Although this is also a rather large dragon, it is much more cryptic than the previous species, usually seen on fence post or tree trunks. Perhaps a more systematic search that is focused on this species would be useful, although it is secure in NSW. In any case, these dragons appear to be rare in the Park.

Although one would expect Lace Monitors (*Varanus varius*) to naturally occur in the Park, there are only two records in the SOPA database, both dating from 2019, where the same individual was observed on two different days in October 2019. Lace Monitors are common in the Sydney basin, often associated with picnic sites in national parks, where some individuals can become very bold and a bit of a nuisance, scavenging on leftovers abandoned by careless individuals of our own primate species.

Eastern Long-necked Turtles (*Chelodina longicollis*) are quite common in the wetlands of Sydney Olympic Park. Basking individuals are frequently observed also during the AHS surveys in the larger water bodies. Turtles occur in the big water body in the Brickpit where they can be observed from above from the Brickpit Ring Walk, but also in other ponds in the Park, for instance at Wentworth Common. Occasionally one can encounter more intrepid individuals on land when they are migrating from one pond to another one, as has happened on one of the recent AHS surveys.

Two turtle species have thus far eluded the annual surveys. The Murray River Turtle (*Emydura macquarii)* has been observed incidentally by an AHS member sunning in two separate ponds in the Narawang Wetland in 2014. This species has also been seen in the Eastern Pond and may be more widely spread than currently known. The Red-eared Slider (*Trachemys scripta elegans),* a highly-invasive introduced species, is also present on site in unknown numbers, with one individual recently captured and removed by SOPA staff. AHS members assisted with identification and transfer of the turtle to the Department of Primary Industries.

Other reptile species documented from within the boundaries of the Park include perhaps the Wood Gecko (*Diplodactylus vittatus*) and the Common Scaly-Foot (*Pygopus lepidopodus*) but these observations remain unconfirmed (Cogger, 2005). Given that these two species are mainly nocturnal, we cannot expect to encounter them easily anyway during our daytime surveys.

Some habitat types in Sydney Olympic Park are not currently covered by the AHS surveys. For instance, none of the current quadrats overlaps with mangroves. The latter are usually considered to be more reptile-unfriendly, although some species such as Bar-Sided Skinks and Eastern Water Dragons can be found in these habitats.

In summary, there is arguably much more work that can be done to obtain a more complete picture of the abundance and short and long-term spatiotemporal distribution of the various reptile populations within the boundaries of the Park, although some of the larger frogs are remarkably sedentary (Figure 9). Continued collaboration between AHS and SOPA will contribute to a better understanding of reptile fauna in the Park, and how to manage habitat to conserve them.

Figure 9. One of several inclusive and friendly AHS reptile survey teams (2016) with Wentworth Common's sedentary frog.

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Beyond the brink: The White-fronted Chat's path to extinction

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The White-fronted Chat is a small insectivorous bird that is now extinct at Sydney Olympic Park and most likely across the entire Sydney basin. The population size had already shrunk to a non-viable level by the time the plight of this species was identified. A program of investigations and management actions aimed to conserve the population as best we could, and also to investigate factors contributing to its decline with the hope it would help conservation of chats elsewhere. The decline and eventual local extinction of this species serves as a reminder that there are tipping points beyond which a species is not recoverable – in small populations the impact of threats like predation, human disturbance and extreme weather events are magnified and can ultimately prove fatal. The challenge going forward is to remember the chats and to not allow our other species to get to that tipping point.

Introduction

White-fronted Chats *(Epthianura albifrons)* have a widespread distribution across southern Australia but have declined over much of their range. They have historically been recorded from 56 different locations across the Sydney region, but by 2003 the Sydney population was limited to two isolated and closed subpopulations located at Towra Point Nature Reserve near Kurnell, and within Newington Nature Reserve at Sydney Olympic Park. Very low numbers were present at both locations, and they were separated by 25 kilometres of urbanised land across which the birds were unlikely to fly.

At Sydney Olympic Park, the birds were regularly recorded in the saltmarshes of Newington Nature Reserve, with occasional sightings reported from other parts of Sydney Olympic Park and on grassland on the northern side of the Parramatta River. White-fronted Chats were once found in saltmarsh adjoining the Waterbird Refuge at Bicentennial Park, but no sightings had been recorded at that location since 1997.

Population size determination

A 2004 review of Sydney Olympic Park's long-term bird monitoring data (Major 2004) identified the White-fronted Chat as a species of high priority due to its declining numbers. The chat population had dropped from an estimated 60-100 birds in 1996 (when regular monitoring of the Park's bird population began), to just 26 birds recorded in 1997 to 22 birds recorded in 2000 (Straw 1999; Spencer & Saintilan 2005), though there was much uncertainty around the actual population size. A targeted monitoring program was recommended to determine population size, with the resulting information to then guide any further monitoring or management decisions.

White-fronted Chat (male), Newington Nature Reserve

Chats tend to forage in pairs or small groups for most of the year, however during autumn they typically aggregate into flocks each evening and share communal nocturnal roosts. By counting birds at this time, it was believed that a reasonably accurate estimation could be made of the total number of birds comprising the local population.

The areas that White-fronted Chats most often frequented at Newington Nature Reserve were determined in two preliminary surveys. Two transects through the wetlands were chosen to cover as much of this area as possible, accounting for the unexploded ordnance access restrictions which then applied to the Reserve. These transects were surveyed on eight occasions between March and May 2005 over a two-hourly survey period. The largest flock observed in these surveys was 19 birds, which was taken to be the total population size.

In spring 2005, one chat nest containing three eggs was identified – one egg hatched and the chick appeared to successfully fledge, indicating successful recruitment was still occurring within the population.

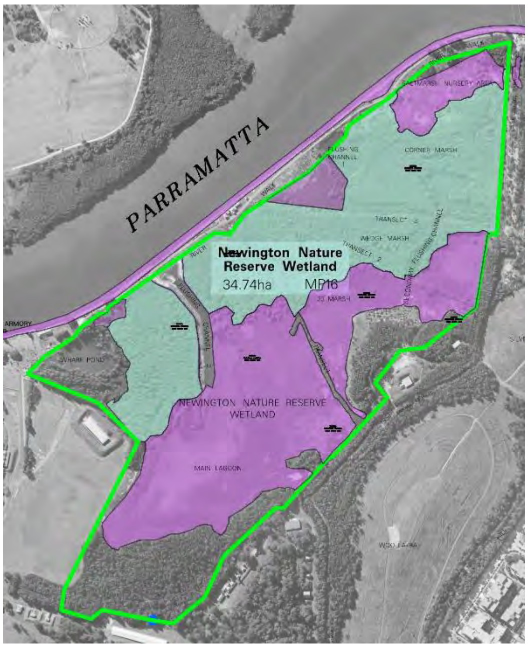
Annual population count

Targeted annual surveys were subsequently conducted within Newington Nature Reserve each autumn using the same methodology as the initial 2005 survey. These surveys sought to:

- determine the size and sex ratio of the chat population;
- observe foraging locations and determine roost site location/s;
- observe numbers and behaviour of other bird species, particularly potential predators, utilising saltmarsh habitat.

Annual surveys recorded the progressive decline and extinction of the population, with females eliminated several years before the males (Figure 1).

As in the initial 2005 survey, the birds were primarily observed foraging in the saltmarsh at Main Lagoon east of Flushing Channel 2, often perching for short periods on the single-strand wire fence that demarcates the boundary of the unexploded ordnance area. They were also observed foraging on the mudflats of Main Lagoon at low tide, as well as in the saltmarsh at 33 Marsh. Towards sunset, the birds generally flew towards the northwest corner of 33 Marsh, apparently to roost in or amongst the mangroves adjacent to the saltmarsh. On numerous occasions outside of the survey period, the flock was also observed foraging on mown grassland immediately west of Main Lagoon (The Flats, Newington Armory), and they were also often observed in rough grassland north of the Parramatta River, directly opposite Newington Nature Reserve and occasionally at Kronos Hill.



Newington Nature Reserve wetland supports mangrove forest (green) and saltmarsh/mudflats (purple)

Other birds observed during the autumn survey period included:

- raptors hunting over the Main Lagoon saltmarsh;
- flocks of Australian Ravens, flying over saltmarsh or calling from adjoining casuarinas and mangroves; and
- large numbers of the Superb Fairy-wren, observed amongst saltmarsh and mangroves.

Investigations and management interventions

With the population size fairly confidently determined to be 19 birds, the population was considered to be at risk of extinction within twenty years. Discussions with managers at Towra Point Nature Reserve revealed that the population there was also estimated to be less than 20 birds. In collaboration with Dr Richard Major (a research scientist at the Australian Museum), the Authority developed a program of management actions supported by a targeted monitoring program, and also provided funding for a student research project to investigate factors contributing to population decline (Jenner 2011).

1. Mark-recapture surveys

Prior to a 2008 mark-recapture program, eleven birds (six males and five females were regularly recorded in and around the nature reserve.

Three mark-recapture surveys were carried out between June and September 2008 using mist-nets at locations where the chats were commonly recorded. Wooden 'lures' in conjunction with chat calls played on an MP3 player attached to a speaker were used to attract birds towards the mist-nets. When in close proximity to the nets, however, chats appeared to be aware of their presence and generally flew over them. Nevertheless, birds were successfully captured after being 'herded' towards the nets by researchers.

Eight birds (six males and two females) were captured and marked with different colour band combinations to enable identification of individual birds. A third female was observed during the June survey but was not captured, and was not observed again during the subsequent mark-recapture surveys. Three of the banded birds (two males and one female) were first year adults (i.e. fledged during the 2007/08 breeding season).

Other bird species captured in the mist-nets were the Superb Fairy-wren, Golden-headed Cisticola and Black-fronted Dotterel, all of which are common in the Main Lagoon saltmarsh.

2. Raven control

A raven control program commenced in November 2007 (licensed under the *National Parks & Wildlife Act 1974*), with culling events taking place whenever flocks of more than ten ravens were observed within the Reserve or on adjacent land. Culling was undertaken by a licensed contractor using firearms fitted with a silencer. A total of 104 ravens were culled over 2007/08, successfully reducing the number of ravens present in the chat's breeding grounds.

3. Nest predation investigation

The nature and extent of nest predation was investigated in November 2007. A total of 32 artificial nests (made from rubber tennis ball inners covered in coconut fibre) containing artificial eggs made of plasticine were installed in saltmarsh and mangroves in Newington Nature Reserve for two weeks in November 2007, after which they were removed and checked for signs of predator activity. Foxes, cats, rats and particularly ravens were believed to be likely predators. Ravens are a known nest predator and large flocks were regularly present in and around the saltmarsh areas where chats were known to breed.

There was no clear indication of predation by ravens or other species although approximately one third of the artificial nests had been disturbed to some extent, apparently by small birds and possibly rodents.

4. Nest monitoring

Mark-recapture surveys enabled extensive observations of chat behaviour in their saltmarsh habitat. During the September 2008 survey, a pair of birds was observed periodically flying in and out of a stand of *Suaeda australis,* and a search of the area revealed a nest with three eggs. Another pair of birds was observed exhibiting similar behaviour a few days later and a search revealed a nest with three eggs at the base of a mangrove sapling. Both nests were monitored every few days to determine hatching and nestling survival rates, and with a view to banding nestlings (which is best undertaken when they are 5-10 days old).

Making artificial nests used to investigate nest predation

Approximately a third of all artificial nests showed signs of disturbance and damage

Wooden lures used to attract birds to mist nets

Banded birds were individually colour-coded

Nest concealed in *Suaeda australis.* Chicks and female parent subsequently lost to predation

Chick in this nest appeared to successfully fledge

Eggs in the first nest had hatched by September 25 when two nestlings were observed. There was no sign of the remaining egg or a third nestling. Banding was proposed for September 28, however, the nest was found empty, and the remains of both chicks plus those of the female parent (including the leg bands) were found below the nest. Predation was consistent with that of an Australian Kestrel, which feeds on its prey where it catches it and which is frequently observed hunting over the saltmarsh.

Two eggs hatched in the second nest on October 3. Banding was proposed for October 9, however the nest was found destroyed and empty the day before banding, with no signs of the nestlings or unhatched egg. This was most likely the result of a terrestrial predator such as a rat, fox or cat.

5. Sensitivity to human disturbance

Sensitivity to human disturbance was investigated in the student research project. Chats reacted to the presence of people at around 32 metres distance, whereas two other species of small birds found in the same saltmarsh habitats – Richard's Pipit and Superb Fairy Wren - allowed humans to get much closer before reacting (Jenner 2011). This finding is consistent with the chat's Sydney distribution shrinking over the years to the point where they were only found in nature reserves where there was no human disturbance.

Decline leading to local extinction

In 2010, the White-fronted Chat was listed under New South Wales threatened species legislation as a 'vulnerable species', and the Sydney regional population (Newington and Towra Point) was listed as an 'endangered population'. Justification for these listings was strongly based on the data and analysis arising from the student research project undertaken at Sydney Olympic Park and Towra Point.

The last individual of the species at Sydney Olympic Park was recorded in 2017; this same sole bird had been

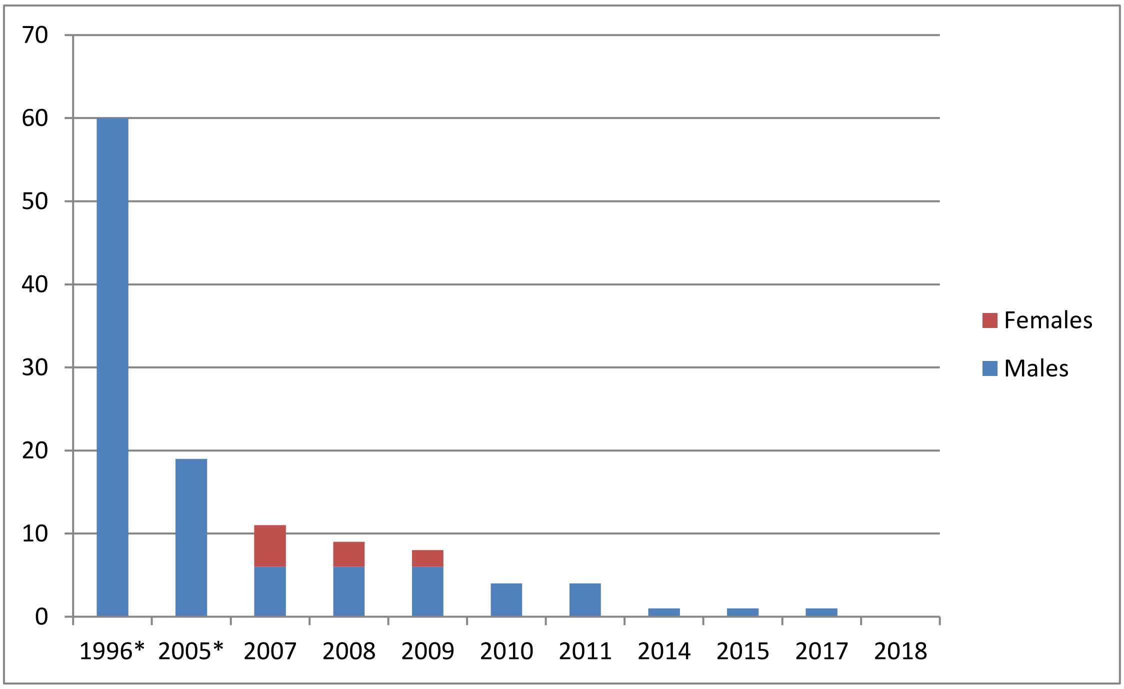


Figure 1 Decline of the White-fronted Chat at Sydney Olympic Park
*Sexes were not separately recorded in 1996 and 2005 surveys

recorded regularly over a long period of time, and is believed to have died later that same year. This male bird was banded as an adult in 2008 and thus would have been over ten years of age at the time he was last seen, which is a considerable age for a small bird to survive in the wild, and the longest-lived chat on record (Richard Major, pers comm.).

The chat population was already in trouble when it came to our attention in 2005, and the pattern of decline continued despite efforts to reduce potential nest predators, protection of core habitat from human disturbance, evidence of successful recruitment in successive years, and increases in the extent of saltmarsh habitat. Females died out several years before the males, and this may have been exacerbated by predation whilst on the nest, as was observed during monitoring. Female chats undertake all nocturnal incubation; thus they are likely to be more susceptible to predation by raptors at their peak hunting times of dusk and dawn, and perhaps also to nocturnal predators such as the fox, rat and cat.

The plight of the White-fronted Chat illustrates the vulnerability of small populations to threats like predation, human disturbance and extreme weather events. Sydney Olympic Park is widely recognised as an urban biodiversity hotspot, but its habitats are small, isolated, highly modified and subject to increasing human disturbance. Careful stewardship is needed for them to sustain a rich diversity and abundance of wildlife into the future. Our challenge going forward is to prevent other species from declining to the point where a species is not recoverable.

Acknowledgements

The White-fronted Chat project was led by Katie Oxenham, formerly Parklands Ecologist at Sydney Olympic Park Authority, and was conducted in partnership with Dr Richard Major of the Australian Museum. Ben Jenner undertook the student research project. Multiple SOPA staff and community volunteers participated in field surveys.

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What the twitchers saw – delving into 16 years of bird census data

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Sydney Olympic Park Authority, in partnership with the Cumberland Bird Observers' Club, has conducted an annual Spring Bird Census across Sydney Olympic Park since 2004 using a standardised approach. The long-term dataset generated by this program provides an important tool for identifying trends and changes in bird populations, to inform and test habitat management against conservation goals. The 2019 census represents the 16th annual snapshot of birds across the Park generated by these surveys. Generally, bird abundance and richness across the Park in 2019 was consistent with data from recent years. Long-term trends include significant increases in urban adapted species, particularly the Noisy Miner, in parallel with long-term declines in small passerines such as honeyeaters and finches. State-wide climatic events have had a strong influence on abundance of bird groups such as waterbirds and vagrant and migratory species recorded at the Park from year to year. The Spring Bird Census dataset is due to the generosity of volunteers who have freely provided their birdwatching expertise to help inform the environmental management of Sydney Olympic Park.

Introduction

The Parklands of Sydney Olympic Park cover 430 hectares and are a mosaic of freshwater wetlands, estuarine wetlands, constructed landscapes, historic landscapes and remnant bushland. The Park supports three Endangered Ecological Communities and many threatened species listed under the NSW *Biodiversity Conservation Act* 2016.

Nearly half (304 hectares) of the Park is zoned under NSW planning legislation for environmental conservation and management. The site has been recognised from the early 1990's as having high ecological values at a local, regional, national and international level and has been managed by the Sydney Olympic Park Authority (the Authority) since 2000 to protect and enhance those values (Major 2004).

The Authority maintains and enhances habitat areas to

- protect threatened species, groups and communities;
- sustain and increase biodiversity at the community level, and;
- foster resilience for long term conservation against numerous and ongoing threats.

To achieve the Authority's commitment to best practice environmental management, adaptive management of habitats is guided by an ecological monitoring program that allows the performance of management activities to be assessed against proposed outcomes, refined and reassessed. This environmental management system enables the Authority to deliver informed management decisions, to direct limited resources to the management actions that are most likely to be effective and to measure improvement of ecological outcomes in relation to corporate and legislative environmental objectives.

Birds are a highly visual part of biodiversity, they are easy to see and identify, are comparatively well-studied, and are able to respond quickly to environmental change. This makes them useful indicators of environmental health (Mekonen 2017). Bird populations are known to be dynamic and may fluctuate over seasons or years, so long-term monitoring is needed to allow for meaningful interpretation of trends (State of Australia's Birds 2015). The two main purposes of long-term monitoring of birds as part of an adaptive management framework are:

1) to identify changes in populations that indicate a need for management intervention, and;
2) to measure the success of any intervention.

The Spring Bird Census and citizen science

Due to the size of the Park and the diversity of habitat types present, an intense sampling effort was required to achieve a robust snapshot of bird populations. The ability of citizen science programs to engage large numbers of volunteers provided the opportunity to gather information at the scale required that would otherwise be impossible for individual researchers or the Authority to achieve due to limitations of time and resources (Koboria *et al.* 2016). For this reason, volunteers have been involved in ecological monitoring programs at Sydney Olympic Park since 1995, providing the foundation for long-term assessment of trends in species diversity and abundance.

In 2004, the Authority entered into a partnership with the Cumberland Bird Observers' Club (CBOC) under a memorandum of understanding for their

members to participate in the 'Spring Bird Census'. CBOC has been a birdwatching club since 1979 and offered a source of field experience, practical skills and scientific knowledge.
The Spring Bird Census is now the fundamental source of data for monitoring performance indicators for birds such as species richness, abundance and breeding occurrence at both precinct and Parkland scales, and answers the following fundamental questions:

- General population trends - how does total species richness and abundance change over time?
- Is the number of introduced species increasing?
- Is the population of Noisy Miners increasing with time?
- Is the population of Pied Currawongs, Australian Ravens and other large urban-adapted birds increasing?
- What are the trends in different bird groups over time?

These questions relate directly to how the bird populations respond to a maturing Parkland and direct management of their habitats. Other questions were posed in 2004 that are now resolved or answered by other modules within the ecological monitoring program.

CBOC members have become champions of the Census and exhibit a collective passion and commitment towards the program with many members having participated every year. This strong and enduring partnership has been at the heart of the success of this 16-year program. Thanks to their dedication, the Census now has 16 years of repeated data that allows analysis of changes in the population size and distribution of the majority of species present.

Volunteers from CBOC are also recruited when required for other ecological monitoring programs or community events.

Survey methodology

Each year between September and November, surveys of 46 quadrats amounting to approximately 126 hectares are undertaken by approximately forty to forty-five volunteers from CBOC between 6am and 9am (Figure 3) concurrently each week for eight weeks. The quadrats are representative of all habitat types and varying mixed-use zones in the Park from the highly urbanised town centre to remnant bushland.

All quadrats are surveyed for 20 minutes. During each survey, all birds seen or heard were recorded on survey datasheets or on the BirdLife Australia Birdata app, along with observations on habitat and behaviour, breeding activity and species interaction.

The resulting data was then examined for bird richness and abundance across the Park, as well as by precinct, and by group, and compared to previous years. At a quadrat level, a regression analysis using R^2 value was undertaken to investigate if any trends were evident in bird richness and abundance.

Key management issues such as the influence of the Noisy Miner were investigated through changes in abundance and distribution. Trends for each species and for major bird groups were also examined across the whole Park. A table of bird groups and species belonging to each group can be seen in Appendix 2.

Box 1

Citizen science programs help to achieve broader environmental and social outcomes

Citizen science involves the collection of data by volunteers as part of scientific inquiry (Silvertown 2009). In addition to the contribution of data collection for the Spring Bird Census, CBOC volunteers also participate in other surveys in the Authority's bird monitoring program and make valuable contributions by reporting incidental sightings. These interactions serve to build stronger relationships, increasing shared learning and motivation through collective capital (Newman *et al.* 2012).

Volunteers that regularly participate in scientific research via citizen science programs benefit from increased scientific knowledge and associated skills, as well as increased appreciation and positive attitudes toward science and environmental stewardship (Brossard *et al.* 2005; Bell *et al.* 2008; Bonney *et al.* 2009; Silvertown 2009; Dickinson and Bonney 2012). CBOC members' understanding, connection with and appreciation for biodiversity at Sydney Olympic Park have resulted in participants actively participating in advocacy for the Park. Volunteers promote Park values to their personal networks and contribute to education and engagement at events at the Park.

Tony Dymond has been volunteering at Sydney Olympic Park for 17 years. As president of the Cumberland Bird Observers' Club in 2004, he was instrumental in constructing the first Census and has been a staunch supporter ever since. During an interview in May 2020, Tony indicated that the reason he became a volunteer was to help ensure that the rehabilitation works of the Parklands did not go to waste; *'to make sure it stays pristine'.*

"*People are gobsmacked by the wildlife at Sydney Olympic Park. There are very few, if any, big cities in the world where you have this sort of habitat within 30minutes of the CBD,*" said Tony.

Tony believes "*One of the key benefits of volunteering at Sydney Olympic Park is the knowledge that data is then used to maintain the quality of all the wetlands, woodlands, grasslands and parklands. Volunteers feel they are making a major contribution to preserve the area - our contributions to the Park are valued.*"

Figure 1 Volunteers surveying birds during the Spring Bird Census at Sydney Olympic Park

Figure 2 Regular presentations of survey results assist in building volunteers' understanding of monitoring program aims, their contributions to Park management and empowerment.

Figure 3 Spring Bird Census monitoring sites at Sydney Olympic Park

Results

1. Volunteer contribution

In 2019 volunteers contributed 3,824 records of 109 bird species composed of 102 native species and 7 introduced species, for a total of 21,193 birds. Over the 16 years of the survey a total of approximately 13,078 hours have been contributed and 70,625 records entered into the database.

2. General population trends

2.1 Species richness

The 2019 Spring Bird Census captured 82% of bird species seen between July 2018 and June 2019 (109 of 133 species) indicating a high capture rate of avian biodiversity across the site. The Census recorded cryptic residents such as the Australian Spotted Crake, species at the edge of their range like Mangrove Gerygone and many migratory species including those protected by international agreements such as the Red-necked Stint (last recorded in 2014); and notable species such as the Tree Martin (last recorded in 2007).

Over 16 years of the Census, a cumulative total of 189 bird species has been recorded, which is approximately 83% of all bird species recorded since 2000 (189 of 229 species). Species richness has remained similar throughout the survey period (Figure 4). Species not detected by the Census are rare, vagrant visitors and nocturnal species some of which are surveyed through separate targeted surveys. Examples from the 2019 period are nocturnal species such as the Barn Owl and Southern Boobook, many seasonal migrants and nomadic species, including the first sighting of the Fuscous Honeyeater and a return of the Swift Parrot (last recorded 1998).

At the quadrat level, quadrats with a combination of large wetlands and associated terrestrial plantings are the most diverse and have the highest avian abundance. This habitat mix supports a mix of both waterbirds and terrestrial species and reflects the large contribution of waterbirds to overall abundance and diversity in the Park.

Quadrats with lower species richness tended to be urban sites with limited vegetation cover.

2.2 Abundance

With a total count of 21,193 birds, bird abundance in 2019 was comparable to recent years except a below-average year in 2016 (Figure 5). Native bird abundance was also comparable to previous years and higher than the long-term (2004-2018) average.

2.3 Abundance of introduced species

Introduced species recorded in the 2019 census included Common Myna, Common Starling, Red-whiskered Bulbul, Rock Dove, Spotted Dove, and farm ducks. Abundance of introduced species has decreased from a cumulative high of 1,520 birds in 2005 to 322 birds in 2019, a further decrease from a record low of 386 birds in 2018. The trend of decline began in 2013, and abundance in 2019 was markedly lower than the long term average of 998 birds (Figure 6). The House Sparrow has not been recorded during a Census since 2011 and Nutmeg Mannikin since 2017. European Goldfinch was not recorded in 2019.

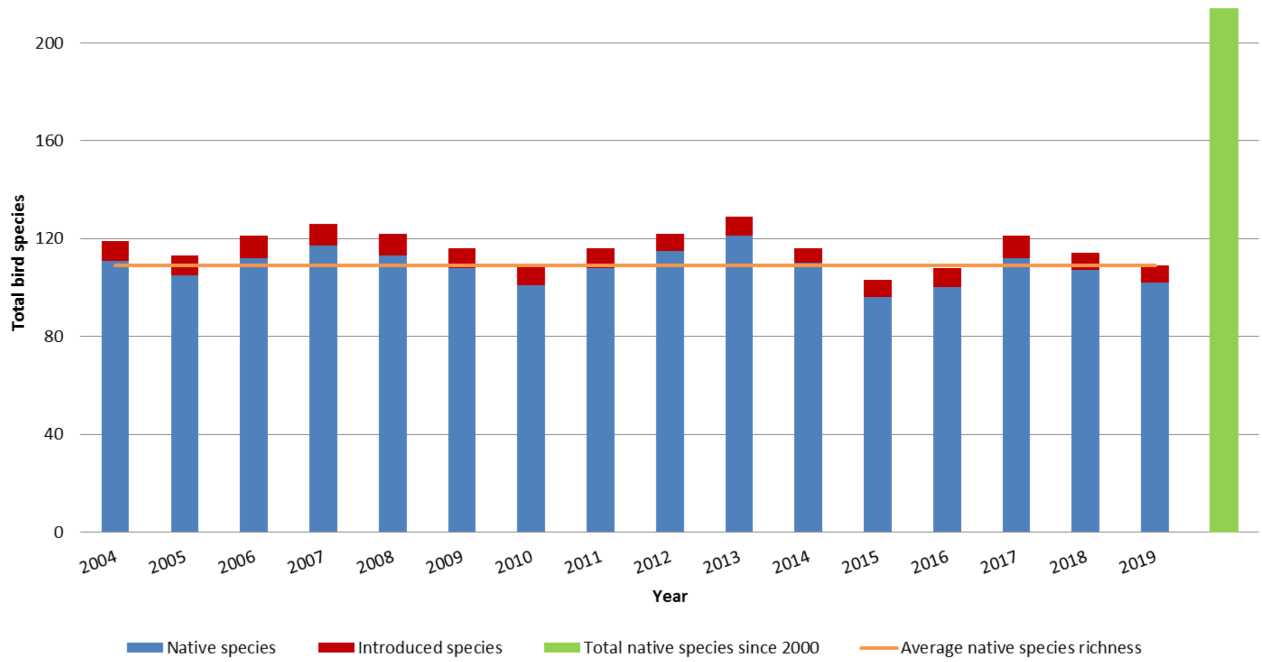

Figure 4 Native and introduced species richness recorded during the Spring Bird Census at Sydney Olympic Park from 2004 to 2019. Average native species richness from the Spring Bird Census 2004-2018 and total native species richness from all surveys since 2000 are provided for comparison.

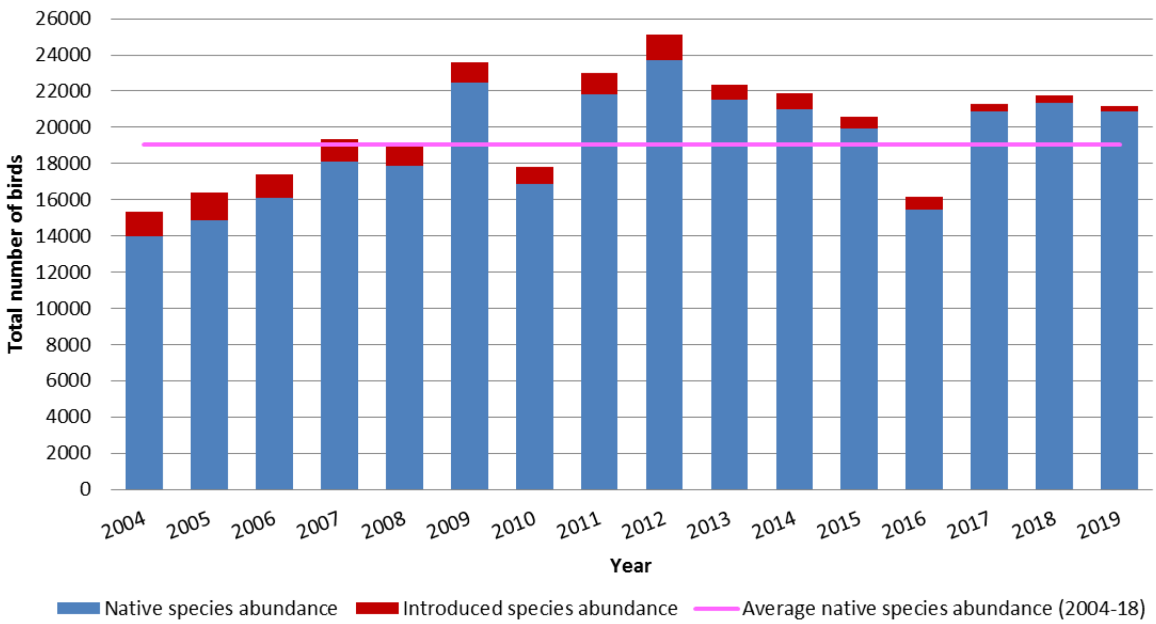

Figure 5 Abundance of native and introduced birds recorded during the Spring Bird Census at Sydney Olympic Park from 2004 to 2019. Average native species abundance from the Spring Bird Census 2004-2018 provided for comparison.

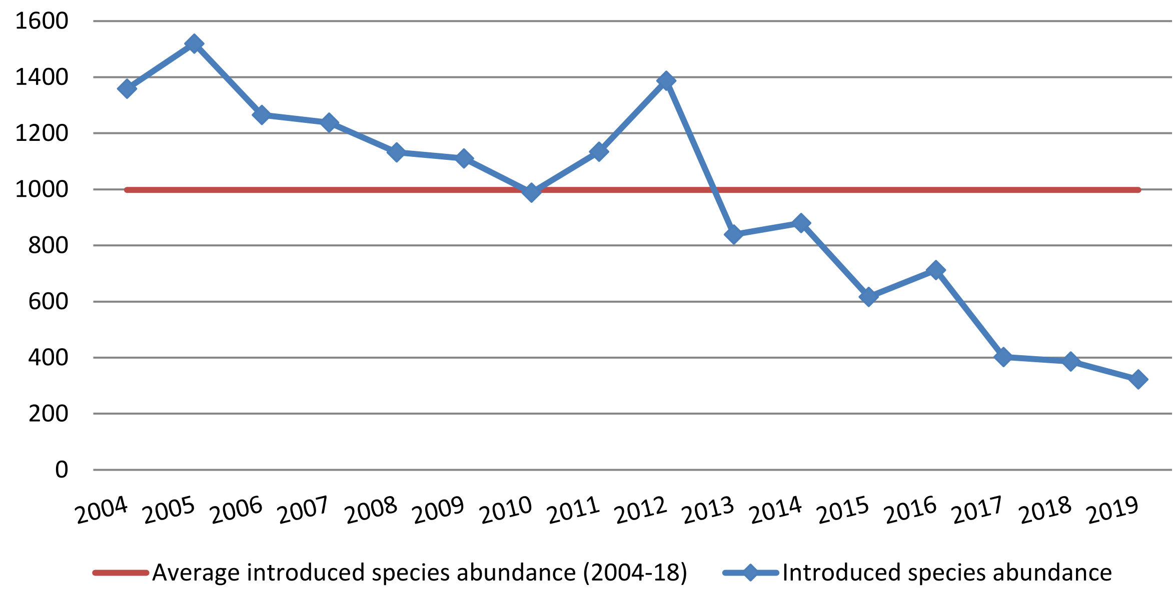

Figure 6 Introduced species cumulative abundance and long term average during the Spring Bird Census at Sydney Olympic Park from 2004 to 2019

2.4 Long-term comparisons

A regression analysis using R^2 was examined to quantify the magnitude of change in quadrats for species richness and average abundance over time (Appendix 1). For this data set, these parameters were considered to be increasing if R^2 was greater than 0.3, decreasing if less than -0.3. Quadrats with R^2 values between -0.3 and 0.3 were ranked as stable. Quadrats were then sorted into:

1. management types; Parklands (generally high presentation standards across turf, gardens and simplistic bushland comprised of trees and a grassy understory) or Natural Areas (generally managed for their environmental values);
2. vegetation type/structure. Examples include saltmarsh, freshwater, estuarine or bushland;
3. whether quadrats were terrestrial or wetland.

The results are shown in Appendix 1 and summarised in Table 1.

Table 1 Changes in bird species richness and abundance by quadrat (2004-19)

Richness:	Increasing: 4 (8%)
	Decreasing: 10 (22%)
	Stable: 32 (70%) consisting of 3 quadrats at 0, 10 increasing and 19 decreasing
Average abundance	Increasing: 5 (11%)
	Decreasing: 3 (7%)
	Stable: 38 (82%) with 1 quadrat at 0, 19 increasing and 18 decreasing

Richness increased considerably in 8% of all quadrats and decreased in 22% of quadrats. The majority of quadrats in the stable category (59%) showed a small decline over the 16 years of the survey. Abundance increased considerably across 11% of quadrats but decreased in 7% of quadrats. There was close to an even divide between quadrats classified as stable that increased in average abundance versus those that decreased in average abundance.

Terrestrial quadrats were more likely to show a decreasing trend in richness than wetland habitats (8 quadrats cf. 2 quadrats); the decline was not restricted to simplistic or planted bushland or turf with scattered trees, as three of four remnant bushland quadrats decreased in richness. Freshwater wetland quadrats in Narawang Wetland declined in richness, while estuarine wetlands and saltmarsh habitats appear to be relatively stable. While some of the quadrats that had decreased in richness also decreased in abundance, there was no clear pattern associated with habitat type, with declines observed in one quadrat each in remnant bushland, estuarine wetland and turf with scattered trees. Increases in average abundance were observed in freshwater wetland, estuarine wetland, saltmarsh, and planted bushland.

The large wetlands of Lake Belvedere and the Waterbird Refuge have been known throughout the Census as hotspots of diversity, consistently ranking highly for both richness and abundance. In this study, both quadrats are shown to have the greatest increases in abundance and richness (Figures 7 and 8). In Figure 8, the Waterbird Refuge abundance visually reflects state-wide climactic patterns with waterbird numbers decreasing rapidly in 2010 and 2016; periods of above average rainfall in western New South Wales (BOM).

An example of increasing abundance in a terrestrial quadrat (planted bushland) can be seen in the Brickpit, an old quarry with a reputation as a refuge for small woodland birds (Figure 9). The vegetation adjacent to the service track is part of a 14 year staged program to remove invasive species such as *Lantana camara.* The shrub layer of this quadrat was primarily Lantana and as it was gradually removed and replaced by native shrubs and ground covers, bird

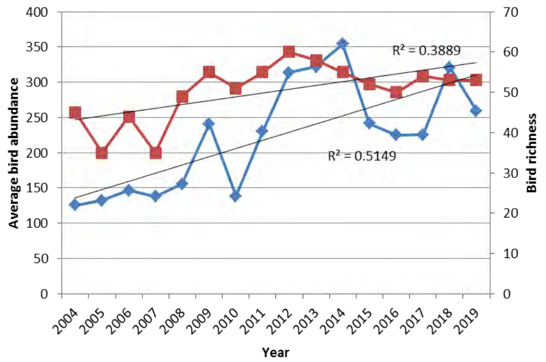

Figure 7 Bird species richness (red) and average abundance (blue) for Lake Belvedere during the Spring Bird Census 2004-2019.

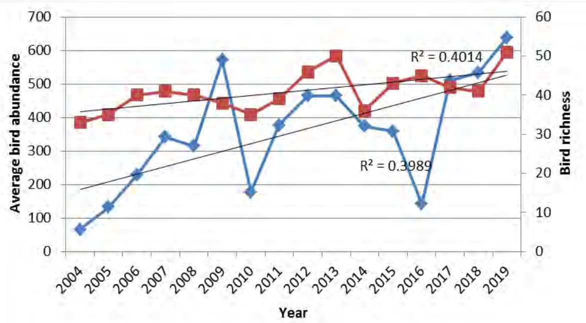

Figure 8 Bird species richness (red) and average abundance (blue) for the Waterbird Refuge during the Spring Bird Census 2004-2019.

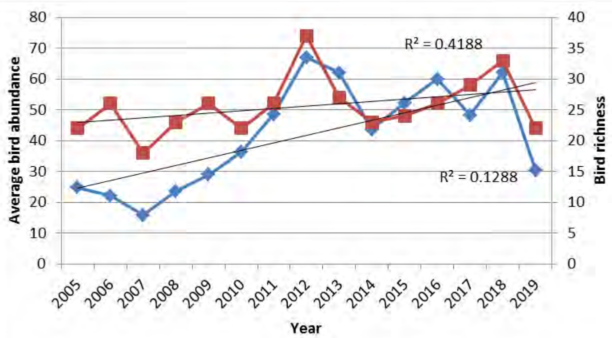

Figure 9 Bird species richness (red) and average bird abundance (blue) for the Brickpit service track quadrat 2005-2019.

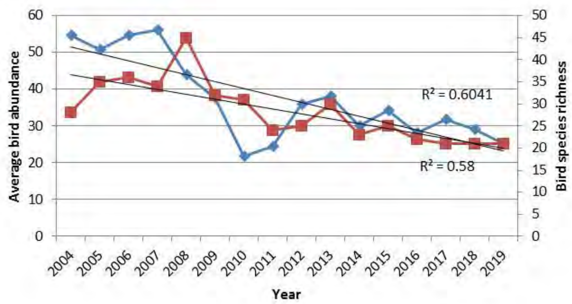

Figure 10 Bird species richness (red) and average bird abundance (blue) for Archery Park during the Spring Bird Census 2004-2019.

richness and abundance has performed positively. Works in this quadrat began in 2009 and was completed in 2015. Figure 9 also shows a trend seen in many terrestrial quadrats for 2019 – a significant decline in both richness and abundance.

Significant decline in bird species richness and abundance was observed in Archery Park, a turf dominated site with few trees (Figure 10). Of the five quadrats dominated by turf (Appendix 1), two were identified with considerably reduced richness and one with the highest loss in abundance.

2.5 Impact of Noisy Miners on species richness and abundance

To further investigate the relationship between declining richness and stable abundance in terrestrial quadrats, the impact of the Noisy Miner was examined.

The Noisy Miner is a honeyeater with a reputation for shifting bird diversity through their 'aggressive despotic behaviour' (MacNally *et al.* 2012). Thomson *et al.* (2015) found that the presence of Noisy Miners in a vegetation patch can reduce the richness and abundance of smaller birds (less than 63g) by 50% through aggressive exclusion (also Clarke and Oldland (2007), Maron and Kennedy (2007) and McNally *et al.* (2012)).

Average Noisy Miner abundance between 2004 and 2019 is shown to be steadily increasing (Figure 11). In 2019, this species made up more than 30% of total bird abundance in a quarter of all quadrats (11 of 46 quadrats or 24%). The quadrats with the highest percentage of Noisy Miners as a proportion of total abundance are located in the highly simplistic landscapes of the Town Centre and are associated with decreasing richness and abundance presented at Table 1. This is closely followed by quadrats in simplistic planted bushlands of Kronos Hill and Haslams Creek Flats and Bicentennial Park Forest Grids where they make up 54% total abundance. The vegetation of these quadrats consists of a eucalypt canopy over a grassy understory.

The terrestrial quadrats of Kronos Hill (Q2, Q3 and Q4) recorded the Noisy Miner at 34% of total abundance. Since 2016, these quadrats have been the focus of a staged planting program to create frog and woodland bird habitat. Closely

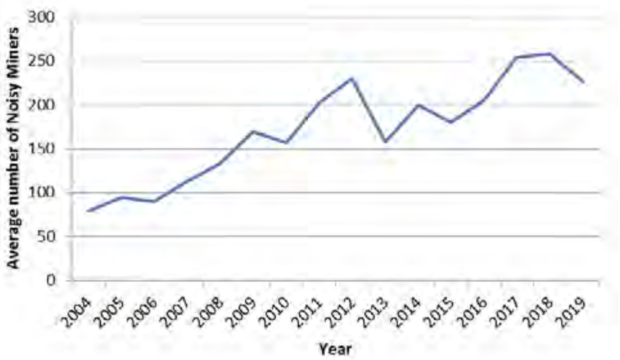

Figure 11 Average abundance per survey of Noisy Miners from Spring Bird Census 2004 to 2019

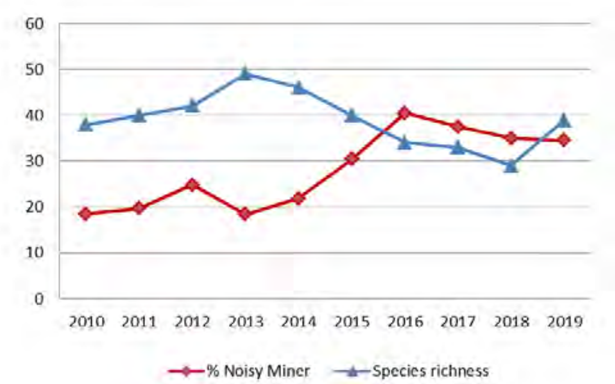

Figure 12 shows species richness declining over the long term from a peak of 49 species in 2013 to 29 in 2018 (then increasing to 39 in 2019), as Noisy Miner abundance increased from just below 20% in 2013 to 34% in 2019.

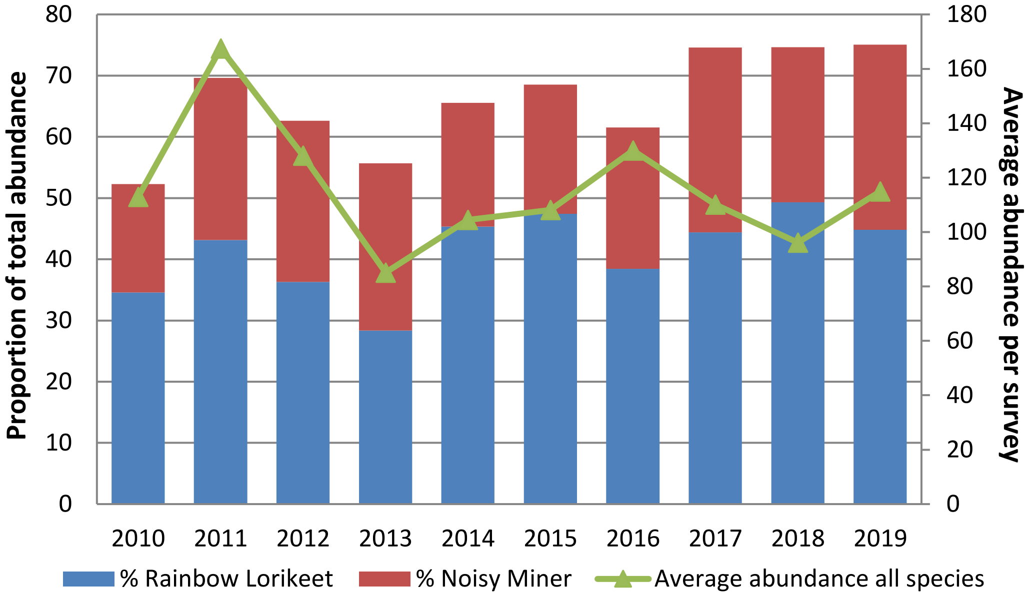

Figure 13 Average abundance per survey and percentage of Rainbow Lorikeet and Noisy Miner in Newington Nature Reserve forest from 2010 to 2019

planted stands of eucalypt trees have been thinned and replaced with shrubs including Acacia spp., Hakea spp., *Indigofera australis*, *Kunzea ambigua* and *Pomaderris spp.*, and ground covers such as *Dianella cearulea*, *Austrostipa spp.*, *Microlaena stipoides*, *Themada australis*, and *Einadia spp*. Replanted areas now comprise approximately 50% of the quadrat. This program of habitat enhancement is staged and still immature. Data from future Census surveys will shed light on how long it takes for habitat restoration to achieve its objective of supporting a diverse bird population.

A similar pattern of dominance by a few species is emerging in remnant bushland of Newington Nature Reserve forest (the Forest). Across a 13-hectare patch, species richness has decreased over time from a peak of 37 species in 2013 to 20 species in 2019, a decline of 46%. While some woodland bird species continue to be recorded on a regular basis, including the Superb Fairy-wren, Red-rumped Parrot, Spotted Pardalote and White-browed Scrubwren, other woodland bird species that were once recorded annually appear to have disappeared from the Forest in recent years. The White-plumed Honeyeater, for example, was recorded annually from 2010 to 2015; the Red-browed Finch from 2012 to 2016, and the Tawny Frogmouth from 2010 to 2017. The Forest has also provided habitat to woodland birds that are seasonal migrants/nomadic or infrequent visitors, including the Crested Shrike-tit, Rufous Fantail, Golden Whistler, Leaden Flycatcher and Varied Triller. However, in the last two years, only larger woodland birds such as the Australian King Parrot, Crimson Rosella, Eastern Rosella and Olive-backed Oriole were recorded (except the regularly recorded woodland bird species mentioned above).

The decline in species richness has not been mirrored by a decline in abundance, which has been relatively stable since 2014 (Figure 13). The two most abundant species in the precinct, the Noisy Miner and Rainbow Lorikeet, have gradually increased in abundance over time, so that they now comprise over 70% of total bird abundance in the precinct.

3. Bird group representation

Figures 14a to c examine trends in average abundance for bird groups using data from Spring Bird Census 2004-2019 (for bird groups see Appendix 2). Since 2004, the abundance of different bird groups has changed:

- The Urban-adapted group have been the dominant bird group since the Census began in 2004, and exhibit an increasing trend over the long term. Even though abundance decreased in 2019 compared to the two previous years, it is still the most abundant bird group, and has been the most abundant bird group in all years except 2010 (Figure 14a).
- Waterbirds and non-migratory waders have been recovering in abundance since a low in 2016. The sharp decrease in 2016 was most likely in response to state-wide climatic events (Figure 14a), which resulted in birds moving to wetlands in western NSW after rains. The increased abundance in 2019 may be related to drought and bushfires across the eastern states pushing waterbirds to take refuge in reliable wetlands.
- The obligate insectivores group is ranked third in abundance as in previous years. Their numbers have been declining from 2012 (Figure 14a).
- Gallinules and Crakes is the 4th most abundant group; it exhibits a similar but less dramatic pattern of fluctuation to the waterbirds and non-migratory waders group. Their numbers declined from 2013 to a low in 2016, but have been increasing since (Figure 14a). These variations are driven by Eurasian Coots who follow a similar behavioural response to state-wide rainfall as species in the waterbird group.
- Introduced species are decreasing steadily, and have done so since 2007 except for a peak in 2012; abundance in 2019 is approximately 20% of peak abundance recorded in 2005 (Figure 14b).
- Honeyeater abundance fluctuated over time with peaks in 2007, 2012 and 2015, but has been on a downward trajectory since 2015. Abundance in 2019 is approximately 30% of the peak abundance recorded in 2007 (Figure 14b).
- Parrot abundance showed a small increase, however, it is approximately 40% of the numbers recorded in 2004 (Figure 14c).
- Finch abundance continues to decline after a peak from 2012 to 2013; present abundance is approximately 20% of abundance at the peak in 2012. Only the Red-browed Finch was present in 2019; the Double-barred Finch and Zebra Finch were last recorded in 2017 (Figure 14c).
- Raptor abundance began declining after 2015; abundance in 2019 continues to be low (Figure 14c).

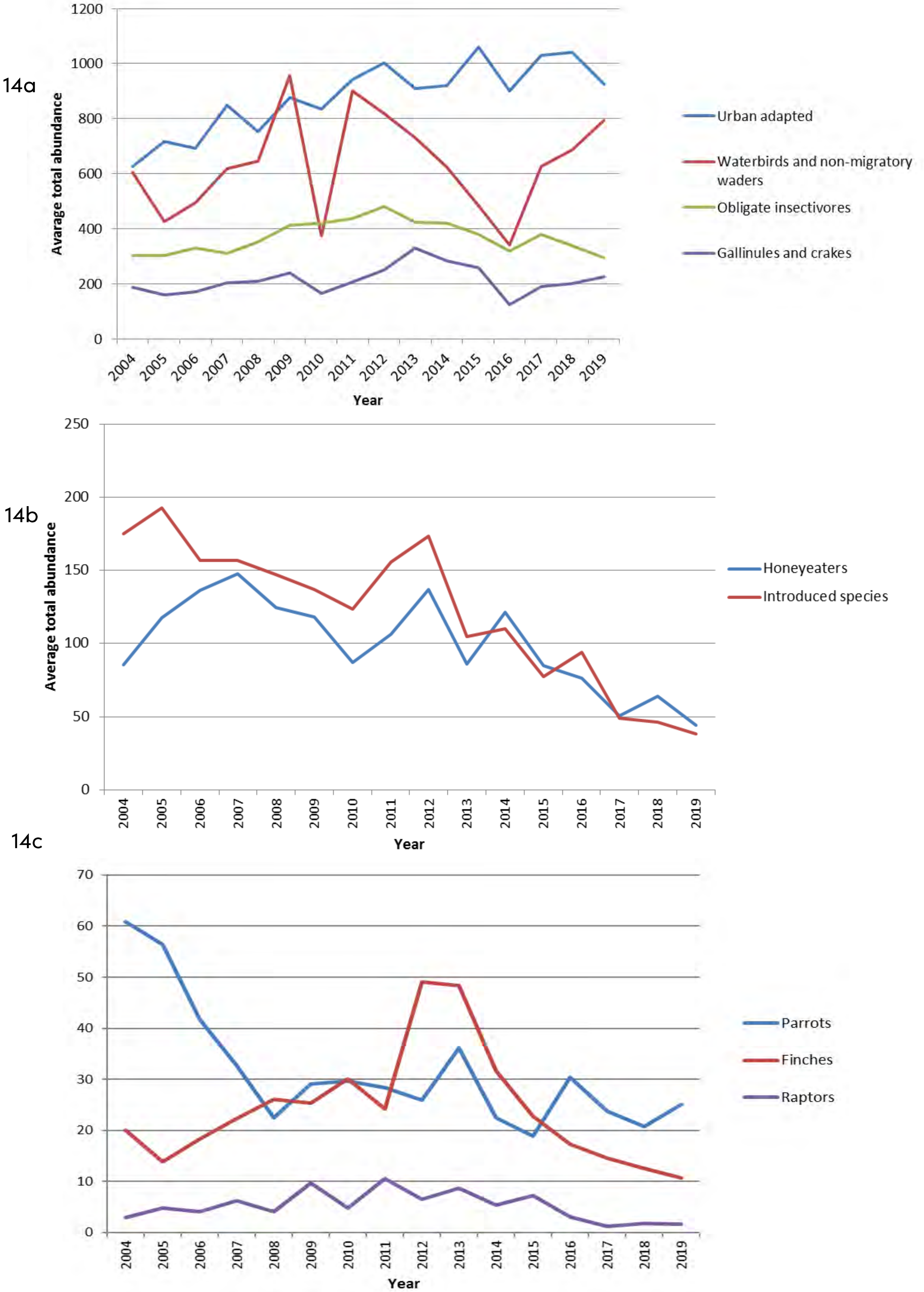

Figure 14 a–c. Average abundance of various bird groups during the Spring Bird Census at Sydney Olympic Park from 2004 to 2019

Discussion

Adaptive management is a fundamental process to achieve best practice environmental management; environmental monitoring is a central principle of this approach. The Spring Bird Census is one module in a large monitoring program enabling the Authority to manage habitat for endangered and protected species, including those of regional significance.

The Census allows temporal changes in the abundance of key bird species to be assessed as the habitats of Sydney Olympic Park mature. The Census remains a highly effective tool, consistently recording just over 80% of all bird species seen since the Census began in 2004.

Quadrats comprised of wetland and terrestrial elements consistently had the highest avian species richness and abundance. Large permanent wetlands show increases in bird abundance during times of drought and decreases during periods of high rainfall in western New South Wales. This is likely to be in response to species seeking refuge from drought illustrating the importance of the Park to state-wide bird movements. The last three years show the wetlands increasing in abundance of birds as the inland drought continued.

The story for terrestrial bird groups is very different. The Brickpit Service Track quadrat saw a sharp drop in species richness in 2019 (dropping by 10), particularly in woodland bird species that make seasonal or nomadic movements. These birds are likely to have been impacted by the warm and dry conditions prevalent over the last three seasons. This would no doubt have caused mortality of small woodland birds, and affected the movement of survivors. The State of Australian Birds (2015) also found a declining trend in East Coast Dry Sclerophyll Woodland/Forest Associated species with highly significant decreases for species such as fairy-wrens and finches.

Interestingly, introduced species continue to decline in species richness. Abundance in 2019 is only one-fifth of the abundance in 2005; although this is positive as introduced species compete with native species for resources (e.g. Common Mynas and Starlings are known to take over nest boxes).

While overall species richness and abundance appear stable, the story at the quadrat level is different. About 22% of quadrats have declined considerably in species richness. A further 59% of quadrats are currently ranked as stable but show slow declining trends. In contrast, only 7% of quadrats declined in abundance; of those ranked as stable, 47% show a slow decreasing trend. This suggests the quadrats are now dominated by large numbers of a few species. It is particularly concerning as this pattern of decline occurred across all habitat types, including precincts of high ecological value - the Brickpit, Narawang Wetland, Newington Nature Reserve wetland and forest. Climatic factors no doubt played a role; however, Noisy Miners and their aggressive territorial behaviour would have contributed as well.

Noisy Miner has consistently been the most abundant species in recent years and the most widely distributed. Noisy Miner made up more than a third of all bird abundance in a quarter of quadrats; with abundance exceeding 50% in five quadrats. As Noisy Miner abundance climbed, species richness declined.

Analysis by bird group illustrates the gradual decline in all groups except the waterbird group and the urban adapted group. The reasons for these declines need to be investigated in detail and possible means of reversing the decline identified. The reality may be that some solutions are beyond the capacity of Park management. Elements such as Park design, vegetation structure, plant selection and water availability can be manipulated but large-scale processes such as changing climactic patterns or landscape scale habitat loss cannot.

Future conservation of birds at Sydney Olympic Park will depend on addressing resilience in the many habitat types present. Steps may include accelerating revegetation and restoration efforts, consideration of active intervention to mitigate threats presented by introduced and native species alike, and recognition and increased protection of ecologically sensitive areas from further anthropogenic disturbances.

Spring Bird Census and Park management

Each year, the results of the Spring Bird Census are compared to previous surveys and an annual report created. This report includes management recommendations in response to changes observed in bird richness and abundance.

Following are some examples of how the Census stimulated new habitat enhancement programs or ecological infrastructure and tested habitat management against conservation goals:

1. **The installation of artificial roost habitat in the Waterbird Refuge**. This large estuarine waterbody hosts the greater part of a regionally significant population of Black-winged Stilts (Major 2004). Breeding by the stilts was noted in the surveys from 2004 to 2006 but successful recruitment was rare and breeding activity had contracted from three sites to one – the Waterbird Refuge. A dirt island 10 metres from the bank was installed in 2007 and five car tyre islands were installed in 2010. In 2010, the Census report recommended further artificial roost/nest sites be installed based on the success of the initial island. Two floating islands 70 metres from shore were added in 2012. A targeted survey was established and supplemented by the Census with both contributing important information to evaluate the success of these installations. Monitoring showed that the floating islands were the preferred roost and nest site for Stilts, probably due to their location further away from disturbance, with 18 other species also utilising them.
2. **Woodland bird habitat modification project**. From 2004, the Census was identifying changes to small woodland bird populations with some increasing but many decreasing. This was in parallel with increasing abundance of Noisy Miners and other large urban adapted birds. The Census data was used to identify where woodland bird hotspots existed and where potential corridors could be enhanced. Since 2006, a habitat modification program has been in place to improve the quality of Park habitat and management of site-specific factors to address woodland bird conservation. Monitoring is on-going as these changes to habitats mature. Initial monitoring is positive with strong correlations being found between increasing shrub density and small woodland bird diversity and abundance in a relatively short time (four years) (Saunders 2019).
3. **The Brickpit staged weed removal project**. In the Brickpit, two Census quadrats contained *Lantana camara*, an invasive weed species. This placed them in an excellent position to test the success of a staged weed removal

program. Over a period of 11 years, the Lantana was slowly removed and replaced with native shrubs and groundcovers. Census monitoring showed small bird density remained high throughout the process with surveys recording good abundance and an increasing diversity of species.

4. **Tidal flushing of the Waterbird Refuge.** The Census was used to assist in evaluating the success of the introduction of tidal flushing to the Waterbird Refuge in 2007. Increases in the target group of protected migratory shorebirds such as the Bar-Tailed Godwit were reported within one year in 2008. The 2009 Census report notes that abundance of Black-winged Stilts rose sharply from an average of 68 birds to over 150 post-restoration. The Census is used annually to check performance of this important wetland with the Refuge performing consistently as one of the most abundant waterbird sites at the Park.
5. **Red-rumped Parrot nest boxes.** In 2008, the Census identified a decline in Red-rumped Parrots. In response, the Authority conducted a study on hollow usage over 2011 and 2012, finding intense competition for hollows and constant displacement of the smaller Red-rumped Parrot by the larger Rainbow Lorikeets. In 2012, a successful nest box program designed specifically for the Red-rumped Parrot has led to the adoption of multiple boxes by the species. Placement of boxes was guided by Census data that identified their feeding grounds.
6. **Recognition of Sydney Olympic Park's role as a refuge and stepping stone.** The Park functions as a refuge for migratory and vagrant species that either remain for a period of time or use the Park as a stepping stone to other parts of the region/state or country. The Census data illustrates this ebb and flow of both terrestrial and wetland passage migrants over the years. Park management aims to maintain resilient habitats that provide for both resident and migratory species through provision of a wide range of habitat types, diverse plantings and vegetation structure to offer a range of food and shelter resources.

Citizen science

Citizen science has long been used to collect reliable environmental data, with federal and local governments, non-governmental organisations (NGOs), research institutes, museums, and conservation organisations relying on volunteer-compiled datasets to inform their resource management and conservation strategies (Silvertown 2009; Miller-Rushing *et al.* 2012; McKinley *et al.* 2015).

At Sydney Olympic Park, management has benefited from partnering with ecological community groups such as CBOC, with long-term partnerships now also in place with the Frog and Tadpole Study Group for auditory frog monitoring and with the Australian Herpetology Society for reptile surveys.

By engaging volunteers, the Authority has access to regular replicated estimates of the population size of important faunal groups over multiple quadrats across precincts, Park-wide and over time. This has contributed significantly to providing data to support conservation and management at Sydney Olympic Park, enabling analysis of the richness, distribution and abundance of species across spatial and temporal scales.

Acknowledgments

The Spring Bird Census is made possible through the contribution of volunteer hours from members of the Cumberland Bird Observers' Club. This contribution has enabled vast amounts of data to be collected, providing the foundation for long-term assessment of trends in species diversity and abundance at Sydney Olympic Park.

Our thanks go to the dedicated volunteers who have contributed to the Spring Bird Census over the past 16 years, with particular thanks to Judy Harrington for coordinating the Census for many years.

The dedication, time, and skill of our volunteers is critical to our bird monitoring programs.

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Appendix 1

Regression analysis values (R^2) for species richness and total average bird abundance in all quadrats from the 2004-2019 Spring Bird Census. Quadrats were considered to be increasing if R^2> 0.3, decreasing if R^2<-0.3. Notable increases/decreases are highlighted.

Management type	Description	Quadrat	Richness (R^2)	Av Abundance (R^2)
Natural area	Simplistic bushland	Kronos Hill - Q2	0	0.0798
		Kronos Hill - Q3	-0.5035	0.0304
		Kronos Hill - Q4	-0.5119	-0.1631
	Freshwater wetland	Narawang Wetland - Q1	-0.1097	0.0144
		Narawang Wetland - Q2	-0.4269	-0.1319
		Narawang Wetland - Q3	-0.4046	-0.0153
		Eastern Pond - Q1	0	-0.154
		Northern Water Feature - Q5	-0.0005	0.5409
		Wharf Pond - Q1	0.0251	0.0926
		Brickpit reservoir - Q2	-0.0003	0.1607
		Brickpit natural wetlands - Q4	-0.0009	0.0371
		Lake Belvedere - Q3	0.3889	0.5419
	Estuarine wetland	Nuwi Wetland - Q1	-0.1245	-0.5951
		Haslams Reach - Q1	-0.0477	-0.2972
		Waterbird Refuge - Q1	0.4014	0.3
		Billabong - Q3	-0.0255	0.0009
		Bennelong Pond - Q4	0.0876	0.2053
		Main Lagoon - Q3	-0.0535	-0.0109
		Parramatta River - Q1	0.001	-0.2604
	Saltmarsh	33 Marsh - Q4	-0.0385	0.0014
		Flushing Channel 1 - Q6	0.2214	0.2471
		Saltmarsh Nursery - Q7	0.005	0.2565
		Badu Saltmarsh - Q2	0.0171	0.3011
		Haslams Creek Flats - Q1	-0.019	0.125
	Remnant bushland	Newington Nature Reserve forest - Q12	-0.3155	-0.4586
		Newington Nature Reserve forest - Q2	-0.4718	-0.2409
		Newington Nature Reserve forest - Q3	-0.3135	-0.2538
		Swamp Oak Floodplain Forest - Q2	-0.1296	-0.0655
	Planted bushland	Newington Armory - Q2	0.0098	-0.0028
		Woo-la-ra Q1	-0.0387	-0.1222
		Wentworth Common - Q2	-0.472	-0.0001
		Brickpit mezzanine - Q3	-0.2923	-0.1379
		Brickpit entry track - Q9	0.1288	0.4188
Parklands	Turf with scattered trees	Wilson Park-Q1	-0.5453	-0.0106
		Wilson Park -Q2	-0.0068	-0.0102
		Newington Armory - Q1	0.0033	0
		Archery Park - Q1	-0.58	-0.6041
		Village Green - Q2	0	0.2025
	Planted bushland	Blaxland Riverside Park - Q1	0.3212	0.04
		Haslams Creek Flats - Q4	-0.0343	0.0063
		Wentworth Common - Q1	0.0312	0.1519
		Forest grid - Q1	-0.0966	-0.0002
		Boundary Creek - Q4	0.3451	0.0672
Urban	Street trees	Figtree Drive - Q3	-0.2132	0.0475
		Parklands Junction – Q1	-0.0446	0.2677
		Park Management Centre - Q5	-0.1152	-0.1032

Appendix 2

Bird species groups recorded during the 2004-2019 Spring Bird Census at Sydney Olympic Park; only bird species represented in more than 6 of the possible 16 years were included in the analysis.

Waterbirds and non-migratory waders			
Australasian Grebe	Cattle Egret	Grey Teal	Nankeen Night Heron
Australian Pelican	Chestnut Teal	Hardhead	Pacific Black Duck
Australian Wood Duck	Darter	Hoary-headed Grebe	Pied Cormorant
Black Swan	Glossy Ibis	Intermediate Egret	Royal Spoonbill
Black-fronted Dotterel	Great Egret	Little Black Cormorant	Striated Heron
Black-winged Stilt	Great Cormorant	Little Pied Cormorant	White-faced Heron

Gallinules and Crakes			
Dusky Moorhen	Purple Swamphen		
Buff-banded Rail	Eurasian Coot		

Obligate insectivores			
Eastern Shrike-tit	Spotted Pardalote	White-winged Triller	Leaden Flycatcher
Golden Whistler	Superb Fairy-wren	Yellow Thornbill	Little Grassbird
Grey Fantail	Yellow-rumped Thornbill	Australian Reed-Warbler	Welcome Swallow
Mangrove Gerygone	White-browed Scrubwren	Australian Pipit	Fairy Martin
Dollarbird	Tawny Grassbird	Black-faced Monarch	White-fronted Chat
Rufous Whistler	White-throated Gerygone	Golden-headed Cisticola	Tawny Frogmouth

Urban adapted			
Silver Gull	Sulphur-crested Cockatoo	Black-faced Cuckoo-Shrike	Pied Currawong
Australian White Ibis	Rainbow Lorikeet	Grey Butcherbird	Magpie-lark
Galah	Laughing Kookaburra	Australian Magpie	Crested Pigeon
Little Corella	Noisy Miner	Australian Raven	Willie Wagtail

Honey-eaters			
Brown Honeyeater	New Holland Honeyeater	White-plumed Honeyeater	
Little Wattlebird	Red Wattlebird	Yellow-faced Honeyeater	

Raptors			
Australian Hobby	Brown Goshawk	Nankeen Kestrel	White-bellied Sea-Eagle
Black-shouldered Kite	Collared Sparrowhawk	Peregrine Falcon	

Finches			
Double-barred Finch	Zebra Finch	Red-browed Finch	

Parrots			
Australian King-Parrot	Crimson Rosella	Eastern Rosella	Red-rumped Parrot

Cuckoos			
Channel-billed Cuckoo	Fan-tailed Cuckoo	Horsfield's Bronze-Cuckoo	Pacific Koel

Introduced species			
Common Myna	European Goldfinch	Mallard	Red-whiskered Bulbul
Common Starling	House Sparrow	Nutmeg Mannikin	Rock Dove
Spotted Turtle-dove			

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