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# Key lessons for achieving biodiversity-sensitive cities and towns

**Summary**

Australia's urban landscapes offer opportunities to marry socio-economic and biodiversity conservation objectives. Yet, information is needed on what urban landscape and habitat features are important for wildlife. In this paper, we draw together our research from southeastern Australia to describe key lessons for biodiversity-sensitive cities and towns. Lesson 1: The effects of urbanisation on wildlife extend into adjacent habitats. We recommend retaining large, undisturbed areas of habitat away from development, avoiding intensive development adjacent to important conservation areas, prioritising areas of ecological and social significance, screening light and noise pollution at the urban fringe and around large nature reserves, and planting appropriately-provenanced locally native species for public streetscapes, parks and gardens. Lesson 2: Strategic enhancement of urban greenspace offers biodiversity gains. We recommend increasing the total amount of greenspace cover, maintaining ecological structures as habitat islands, using landscaping techniques to minimise risks to human safety, and gardening with low-flowering native shrubs. Lesson 3: Large old trees need to be managed for long-term sustainability. We recommend retaining large old trees in new developments, increasing the maximum standing life of urban trees, protecting regenerating areas and planting more seedlings, supplementing habitat features associated with large trees, and ensuring that young trees have space to grow through time. Lesson 4: Education and engagement connects residents with nature and raises awareness. We recommend education programs to enhance opportunities for residents to experience and learn about biodiversity, engaging residents in the establishment and maintenance of wildlife habitat, providing 'cues to care', facilitating access to garden plants that benefit wildlife, and

encouraging cat containment. These lessons provide an evidence-base for implementing conservation and management actions to improve the capacity of our cities and towns to support a diverse and abundant biota.

**Keywords**

Community integration, Strategic conservation planning, Human-wildlife interactions, Large old trees, Public education, Spatial zoning, Urban fringe, Urban greenspace, Wildlife management

## Introduction

Nine out of ten people living in Australia reside in a city or town, with the nation consequently having one of the most urbanised populations in the world (United Nations 2014). Australia is experiencing rapid urban development with an annual urban growth rate of 1.47%, more than double the average rate for developed regions (0.60%) (United Nations 2014). Land conversion for urban development causes habitat destruction and introduces novel anthropogenic disturbances and threats (Forman 2014). These changes affect a myriad of species and ecological processes (Grimm et al. 2008), and research to date has demonstrated mostly negative impacts of urbanisation on biodiversity (McKinney 2008).

However, cities and towns are important for biodiversity conservation, offering novel habitats and opportunities to integrate people in conservation (McDonnell and Hahs 2013). Worldwide, 20% and 5% of bird and plant species, respectively, occur in cities (Aronson et al. 2014). In Australia, cities are disproportionately important for the conservation of species of national significance, with urban regions supporting more threatened species per unit-area than non-urban regions (Ives et al. in review). Furthermore, conservation investment in cities can lead to greater conservation gains compared with investment in landscapes where threats to biodiversity are fewer, such as in some large protected areas (Maron et al. 2013).

The conservation of urban biodiversity has profound benefits for human well-being (Turner et al. 2004). Interacting with urban biodiversity has been shown to benefit physical and psychological health, improve quality of life, and raise real-estate prices. For instance, Luck et al. (2011) found that residents' satisfaction with their neighbourhoods was positively related to the richness and abundance of birds. Mitchell and Popham (2008) found that death from circulatory diseases was less common in greener city areas, and Taylor et al. (2015) found that antidepressant prescription rates were lower in areas with a higher density of street trees. People are also willing to invest financially in greener cities (Lo and Jim 2010). Viewing urban biodiversity from this ecosystem services perspective thus provides a powerful motivation for biodiversity conservation in urban areas (Wiens 2009).

Cities are spatially heterogeneous landscapes, with land use and population density varying both within and between cities (Forman 2014). This heterogeneity of urban form leads to variability in the capacity of cities to support biodiversity (Sushinsky et al. 2012). The legacy of past development decisions has 'locked in' biodiversity trajectories and shaped available conservation and management actions (McDonald 2008). For example, small house blocks and narrow street verges limit tree planting. Innovative urban design and planning strategies are needed to improve biodiversity conservation outcomes and realign development and management practices with research-based conservation recommendations.

Urban landscapes offer many exciting and novel opportunities to marry socio-economic and biodiversity conservation objectives, both retrospectively (i.e. in established urban areas) and prospectively (i.e. in new urban development). Ideally, sympathetic design and management principles that aim to protect the ecological values of existing and future urban areas, as well as adjoining habitat such as peri-urban nature reserves, should be articulated during the planning phase and carried through the full development process. To design biodiversity-sensitive urban landscapes, and to prioritise biodiversity considerations against other social and economic factors, conservationists, policy makers, planners, and developers need information on what urban landscape and habitat features are important for biodiversity (Stagoll et al. 2010; Ikin et al. 2012).

In this paper, we draw together our collective ecological and social research from urban areas in southeastern Australia. We synthesise the key conservation and management implications of our research into four key lessons relevant to (1) the urban fringe, (2) greenspaces, (3) large old trees and (4) the human community. These lessons arise from our work in the ACT and coastal NSW and are not intended to be exhaustive. Several environmental considerations are beyond the scope of our paper, including population processes (e.g. gene flow) and environmental quality (e.g. soil health). In describing our four lessons, we draw on examples from our own and other researchers' work with the aim of translating current academic knowledge of biodiversity responses to urbanisation into practical conservation and management actions (Table 1, Figure 1). We hope this will stimulate much needed discussion between urban ecologists and practitioners and lead to greater implementation of biodiversity-sensitive practices within Australian cities and towns.

**Lesson 1: Effects of urbanisation on wildlife extend into adjacent habitats.**

Development at the urban fringe has effects that extend into surrounding landscapes (Renjifo 2001; Brearley et al. 2010). For example, artificial light and noise from urban development can spill-over into nature reserves, with negative effects on species and ecosystems (Parris and Schneider 2008; Threlfall et al. 2013b). Effects include changes in animal behaviour, increased risk of predation, and reduction in reproductive success and fitness (Newport et al. 2014). Exotic species common in urban settlements, such as the European Red Fox (*Vulpes vulpes*), Cat (*Felis catus*), Dog (*Canis familiaris*) and Common Myna (*Acridotheres tristis*), also can encroach upon adjacent habitat (Villaseñor et al. 2015), with negative effects on native wildlife (Grarock et al. 2012).

How far the effects of urbanisation on wildlife extend into adjacent habitat varies between species and environments, but is likely to extend beyond 250 m for many mammals and birds. For instance, the Yellow-bellied Glider (*Petaurus australis*) avoids forest boundaries in coastal NSW, and its sensitivity to urban disturbance extends beyond 300 m from the urban fringe (Villaseñor et al. 2014). In the ACT, although the likelihood of encountering native birds sensitive to urban development increases with distance from suburban areas, bird assemblages 250 m into nature reserves remain characterised by common suburban species (Ikin et al. 2013b; Ikin et al. 2014). The occurrence of approximately half of Canberra's birds is strongly linked to the proximity of their habitat to urban fringe development (Rayner et al. 2015). Small woodland-dependent birds, in particular, occur more frequently further from the urban fringe (Conole and Kirkpatrick 2011; Rayner et al. 2014), with effects extending up to 5 km for some urban-sensitive bird species, e.g. the Scarlet Robin (*Petroica boodang*) (Rayner et al. 2015). In addition, a number of birds of conservation concern, e.g. the Brown Treecreeper (*Climacteris picumnus*), respond negatively to the rate of urban fringe development, irrespective of proximity to development (Rayner et al. 2015).

The distribution of animals across urban edges varies depending on the characteristics of the residential landscape adjacent to the natural habitat. For example, suburban housing developments (0.06 ha average block size) in coastal NSW have lower arboreal marsupial diversity compared with rural housing developments (0.2 – 16 ha), which provide suitable habitat for most arboreal mammals in the region (Villaseñor et al. 2014). Rural housing developments retain mature trees (Villaseñor et al. in review), which may explain why arboreal marsupials persist in these areas. For example, Common Ringtail Possum (*Pseudocheirus peregrinus*) abundance within Melbourne forest remnants is higher when food and den trees are available in the surrounding landscape (Harper et al. 2008). How species cope with the degree of urban development in the landscape is species-specific. For example, with increasing urban development in south-east Queensland, the Rufous Bettong (*Aepyprymnus rufescens*) rapidly declines in abundance, but the Northern Brown Bandicoot (*Isoodon macrourus*) is unaffected (Brady et al. 2011). Similarly, bat species that forage in densely vegetated habitats are uncommon in urban areas but those that forage in open habitats are likely more tolerant of greater housing density (Threlfall et al. 2011; Luck et al. 2013a).

Planning ecologically-sensitive suburbs at the urban fringe, and sensitively managing established urban areas adjacent to large areas of greenspace, is important to reduce negative effects on adjacent habitats. Urban planning should carefully consider the impacts of encroachment, housing density and urban-related disturbances at the urban fringe and implement strategies to mitigate impacts. By retaining large, undisturbed areas of habitat away from urban areas, and avoiding intensive development adjacent to important conservation areas, planners can retain core habitat and limit impacts on urban-avoiding species (Palmer et al. 2008; Ikin et al. 2013b; Villaseñor et al. 2014). Conservation planning techniques can be effectively used to identify areas of conservation significance and prioritise land for protection (Gordon et al. 2009; Bekessy et al. 2012). A case study from the Lower Hunter region shows that it is also possible to integrate social values into conservation planning to achieve socially-feasible urban plans of equivalent biological value (Whitehead et al. 2014). Measures also can be implemented to reduce negative edge effects on adjacent habitat. For example, Newport et al. (2014) review potential measures to reduce light and noise pollution, including the use of shields and barriers, such as directional covers for lights. Planting appropriately-provenanced locally native trees in streets, parks and gardens will increase the number of bird species in both residential areas and adjacent habitats (White et al. 2005; Ikin et al. 2013b; Barth et al. 2015) (Fig. 1A). This is because native eucalypt street trees provide food and nest sites that are reduced or absent at exotic trees.

**Lesson 2: Strategic enhancement of the urban greenspace offers biodiversity gains.**

Urban greenspace encompasses public and private unbuilt areas, such as parks, backyards, wetlands, roadside margins, and golf courses. These spaces provide important habitat for wildlife, increase connectivity, and facilitate animal movement through the wider landscape (Shanahan et al. 2011). Therefore, the amount and configuration of greenspace are important, in addition to the characteristics of the greenspace itself. For example, small suburban parks with large amounts of greenspace in the surrounding neighbourhood have high bird richness and abundance, including for species that are woodland-dependent, insectivorous and hollow-nesting (Ikin et al. 2013a). For bird species that are able to easily fly between greenspace patches, increasing the total amount of greenspace area is more important than aiming for large or well-connected patches (Fig. 1B). This would also benefit amphibian, reptile and small mammal assemblages (Garden et al. 2010; Hamer and Parris 2010). For example, frog species richness in urban ponds across regional Victoria is positively related to the proportion of vegetation cover within the surrounding landscape (Smallbone et al. 2011).

Maintaining habitat structures in urban greenspace that are important foraging and nesting resources for a wide range of animal groups is also important. Uncommon suburban birds are more likely to be encountered when there is complex vegetation structure (Ikin et al. 2013b) (Fig. 1C). The Brown Antechinus (*Antechinus stuartii*) and the Bush Rat (*Rattus fuscipes*) are also more likely to occur in urbanising landscapes when understorey cover is high (Villaseñor et al. 2015). However, when compared with nature reserves, urban greenspaces have reduced availability of live and dead trees, seedlings, hollows, logs, and native ground and mid-storey vegetation (Le Roux et al. 2014a). In turn, many species may not be able to persist in urban greenspace habitats simply because these habitat structures are in short supply or absent.

One overarching reason why particular habitat structures are reduced in urban landscapes is due to concerns over human safety. A primary concern is that the retention of eucalypt trees, native shrubs, and woody debris constitutes a bushfire risk. Importantly, these habitat structures do not represent a significant fire risk if located >100 m from the urban fringe, as a vast majority (80-90%) of house loss due to bushfire in Australia have occurred ≤ 100 m from the urban-bushland interface (Chen and McAnency 2010; Gibbons et al. 2012). Design features such as low-traffic edge roads and landscaped areas for passive recreation (e.g. bike trails) can create asset protection zones for fire management (Eyles 2013) (Fig. 1D). In the ACT, these design features are now mandatory in new subdivisions adjoining nature reserves (Eyles 2013). Furthermore, if correctly managed, these ‘soft’ boundaries can support native and threatened wildlife (Wong et al. 2011; Ikin et al. 2013b), highlighting their multi-functionality as a biodiversity-benefiting greenspace.

Innovative management strategies also need to be employed to retain habitat structures in urban greenspace that are perceived as ‘hazardous’ or ‘untidy’ by the public. This is especially important as these structures are often difficult to replace once removed. Spatial zoning techniques can be used to partition greenspace habitat in a way that mitigates risk and minimizes conflicts of interest (Le Roux et al. 2014a). For example, using low, thick and non-weedy plantings, such as large tussock grasses, can create visible management boundaries (Marshall 2013). A complementary approach is to establish ‘habitat islands’ around existing habitat structures, such as rocky outcrops, logs, or large old trees (Fig. 1E). Creating or restoring habitat in riparian zones or areas with fertile geology can be especially valuable, particularly for insectivorous bats (Threlfall et al. 2012b, a). Multiple habitat islands can be juxtaposed to create a diversity of wildlife habitats. Moreover, habitat islands can be established in advance of greenfield urban development, for example through the use of strategic grazing (Fischer et al. 2009) to promote tree recruitment around mature farm trees. Replacing weedy understorey plants with native species will also maintain important shrub habitat for many small birds (Kath et al. 2009; Stagoll et al. 2010).

Private gardens provide another opportunity to restore and maintain habitat complexity in urban landscapes (Goddard et al. 2010). Gardens can support very high levels of plant diversity, reflecting diversity in people's preferences and socio-economic backgrounds (Kirkpatrick et al. 2007; Kendal et al. 2012a; Kendal et al. 2012b). This variation in garden characteristics consequently has a large influence on the diversity of native birds (Luck et al. 2013b). For example, in Hobart, native species richness in gardens is positively influenced by garden size, canopy height and the cover of small shrubs (Daniels and Kirkpatrick 2006). People's preferences for some plants, however, can lead to negative outcomes. For instance, planting flowering native cultivars (i.e. "bird attracting plants") can lead to overabundance of aggressive native honeyeaters that exclude many small species (Parsons et al. 2006; Davis and Wilcox 2013). Choosing to instead plant dense, low-nectar producing native shrubs can help to minimise these competitive interactions (Kath et al. 2009).

**Lesson 3: Large old trees need to be managed for long-term sustainability.**

Maintaining large old trees in urban landscapes is important because they provide resources such as hollows, dead branches, peeling bark, and nectar, which are crucial to the persistence of wildlife, and cannot be provided by younger trees (Stagoll et al. 2012). Large eucalypt trees in small urban parks increase the number of individuals and species of birds, and also increase the probability of birds breeding (Stagoll et al. 2012). Interspecific competition between birds and bats at hollows shows that they are a limiting resource in urban landscapes (Davis et al. 2013; Threlfall et al. 2013a).

The addition of a single large tree to a suburb or park results in the equivalent accumulation of bird species and individuals as the addition of many small and medium trees (Le Roux et al. in review-b). However, the loss of a single large eucalypt in urban areas cannot be completely offset by establishing many younger trees, and simple revegetation offset tactics inadequately compensate all species. For instance, approximately one third of the Canberra region's birds, representing many different functional guilds, exclusively use trees >80 cm DBH (i.e. at least 100 years old) (Le Roux et al. in review-b). Large tree retention in addition to small tree revegetation is a more balanced and considered offset approach that is anticipated to cater to a wider range of species (Le Roux et al. in review-b). In Canberra, suburbs have similar densities of mature trees as nature reserves, but the percentage of these trees with hollows is low (33% compared with 72% in nature reserves) (Le Roux et al. 2014a). The future availability of hollow-bearing trees in urban Canberra under current management practices is also predicted to decline by at least 87% over the next 300 years (Le Roux et al. 2014f). The situation is possibly grimmer in Melbourne urban forest remnants, where only 5% of trees are large and thus short-term ecological sustainability under threat (Harper et al. 2005a).

It is vital that trees in urban areas are managed with long-term sustainability in mind (i.e. over centuries). This involves increasing the maximum standing life of urban trees, maintaining appropriate numbers of trees in different age-classes – including regenerating and intermediate-sized trees – to replace old trees removed over time, and supplementing habitat features associated with large trees (Le Roux et al. 2014f). Installing nest boxes to supplement hollow resources may be an option, but this is expensive and unlikely to be a feasible long-term solution (Harper et al. 2005b; Le Roux et al. In review-a). An alternative, but to our knowledge untested, approach would be to use arboriculture to create artificial hollows. Similarly, using other artificial structures that mimic natural resources (e.g. fence posts as a substitute for coarse woody debris) has had positive outcomes in abandoned farmland restoration sites in the Wet Tropics (Shoo et al. 2014), and may be applicable in urban landscapes. It is also essential to designate greenspace needed for future tree replacement and to ensure that current younger trees have sufficient 'safe space' needed to grow in size over time (e.g. through spatial zoning) (Fig. 1F).

**Lesson 4: Education and engagement connects residents with nature and raises awareness.**

Public awareness and education about local biodiversity values can have a strong effect on how people perceive and interact with urban greenspace and adjacent reserve habitat (Shanahan et al. 2014). Promoting these areas as important, multi-functional spaces for people and biodiversity provides an opportunity to connect residents with nature and engender feelings of stewardship for the local environment (Turner et al. 2004). For example, in Wollongong, visitors to a suburban bushland reserve value recreational opportunities within the "natural" landscape (e.g. walking, jogging) and this experiential connection promotes support for the reserve's ongoing ecological protection (Gill et al. 2009).

By committing to take responsibility for the environment during design and construction of new suburbs, developers can reframe how new urban developments are perceived (Hostetler et al. 2011; Eyles 2013). Innovative development practices can be used to differentiate new suburbs, and awareness programs for new residents can guide the behaviour of individual householders. For example, residents' decisions to buy homes in the new Canberra suburb of Forde were influenced by the natural amenity and landscape setting of the urban greenspaces, as well as proximity to the adjacent Mulligans Flat Nature Reserve and Woodland Sanctuary (www.bettongs.org) (Eyles 2013). Welcome programs incorporated sustainable living workshops (composting, water-wise and bush friendly gardens) and guided walks in the reserve. These activities are important in shaping an environmentally-aware residential community; for instance, some residents have joined a 'Friends Group' that assists with research and management activities within the reserve, such as weeding and wildlife monitoring (Eyles 2013) (Fig. 1G). Incentive-based polices can promote the wider implementation of similar conservation practices and resident engagement programs by developers (Hostetler et al. 2011; Feinberg et al. 2015).

Engaging residents in the establishment and maintenance of habitat for wildlife is a fundamental step in the provision of wildlife habitat in urban areas (Marshall 2013; Le Roux et al. 2014a; Villaseñor et al. 2015). Through engagement and education, current cultural preferences towards highly-manicured 'park-like' greenspaces can be shifted to embrace more biodiversity-sensitive greenspaces (Nassauer 1995). For example, whilst office workers in Melbourne prefer living "green" roofs over concrete roofs, those with a stronger connection to nature prefer more structurally complex vegetation (Lee et al. 2014). Similarly, in Fremantle, householders with pro-environmental worldviews are more likely to garden with native plants (Uren et al. 2015). Providing "cues to care" in public greenspace - such as attractive seating, pathways, managed access points, landscaped garden beds, and informative signage - can help dispel negative misconceptions and encourage tolerance (Hands and Brown 2002; Le Roux et al. 2014a). Further, providing residents with information about appropriate garden plants (and ensuring that these plants are available from local nurseries), as well as the safe disposal of garden waste and use of pesticides and fertilisers, can help to minimise weed invasion and reduce ongoing maintenance costs (Marshall 2013) (Fig. 1H). These practices will help mitigate the impacts of urbanisation on native flora and fauna.

Public education and engagement is also vital to reduce the impact of pet animals on native wildlife, such as predation from roaming cats, which may travel up to 900 m into adjacent habitats (Eyles and Mulvaney 2014). Many Canberra residents strongly support management to regulate cats, such as cat containment (Eyles and Mulvaney 2014). In new Canberra suburbs adjacent to nature reserves, cats are required to be contained to their owner's yard at all times (24 hour containment). Some new suburbs have street signs that depict a symbol of a cat within a house to reinforce containment rules (Eyles 2013). The negative effects of domestic dogs on wildlife, including predation, disturbance, and disease transmission, can be reduced by excluding dogs from nature reserves and providing alternative dog exercise areas, such as designated off-leash dog parks (Weston et al. 2014). The success of these measures depends on public education campaigns that highlight pet ownership responsibilities, and an ongoing program of compliance and enforcement (Eyles and Mulvaney 2014).

**Conclusions**

Cities and towns are a human habitat that are managed first and foremost for the needs of people (Grimm et al. 2008; Forman 2014). Urban biodiversity, however, provides a wealth of ecosystem services that are essential for human health and well-being (Turner et al. 2004). Through the enlightened growth of prospective developments and management of established urban areas (informed and underpinned by comprehensive scientific evidence), biodiversity-sensitive urban landscapes can be achieved. We have drawn together a body of research from southeastern Australia that provides an evidence-base for proactive actions that are anticipated to achieve biodiversity and conservation benefits in urban landscapes. Avoiding and mitigating urban edge effects, strategically enhancing urban greenspace, managing large old trees for long-term sustainability, and engaging residents through education programs are likely to have tangible and long-term outcomes. We believe that these lessons are general and widely applicable. As Australia's urban population continues to grow, and the size and number of cities increases, it is imperative that urban areas are not overlooked in conservation management strategies. With better information on ecological processes within urban areas, more effective conservation actions can be implemented, improving the capacity of our cities and towns to support diverse and abundant biota.

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## References

Aronson, M.F.J., La Sorte, F.A., Nilon, C.H., Katti, M., Goddard, M.A., Lepczyk, C.A., Warren, P.S., Williams, N.S.G., Cilliers, S., Clarkson, B., Dobbs, C., Dolan, R., Hedblom, M., Klotz, S., Kooijmans, J.L., Kühn, I., MacGregor-Fors, I., McDonnell, M., Mörtberg, U., Pyšek, P., Siebert, S., Sushinsky, J., Werner, P., Winter, M., 2014. A global analysis of the impacts of urbanization on bird and plant diversity reveals key anthropogenic drivers. Proceedings of the Royal Society B: Biological Sciences 281.

Barth, B.J., FitzGibbon, S.I., Wilson, R.S., 2015. New urban developments that retain more remnant trees have greater bird diversity. Landscape and Urban Planning 136, 122-129.

Bekessy, S.A., White, M., Gordon, A., Moilanen, A., McCarthy, M.A., Wintle, B.A., 2012. Transparent planning for biodiversity and development in the urban fringe. Landscape and Urban Planning 108, 140-149.

Brady, M.J., McAlpine, C., Miller, C., Possingham, H., Baxter, G.S., 2011. Mammal responses to matrix development intensity. Austral Ecology 36, 35-45.

Brearley, G., Bradley, A., Bell, S., McAlpine, C., 2010. Influence of contrasting urban edges on the abundance of arboreal mammals: a study of squirrel gliders (*Petaurus norfolcensis*) in southeast Queensland, Australia. Biological Conservation 143, 60-71.

Chen, K., McAneny, J., 2010. Bushfire penetration into urban areas in Australia: a spatial analysis. Risk Frontiers and Bushfire Cooperative Research Centre.

Conole, L., Kirkpatrick, J., 2011. Functional and spatial differentiation of urban bird assemblages at the landscape scale. Landscape and Urban Planning 100, 11-23.

Daniels, G.D., Kirkpatrick, J.B., 2006. Does variation in garden characteristics influence the conservation of birds in suburbia? Biological Conservation 133, 326-335.

Davis, A., Major, R.E., Taylor, C.E., 2013. Housing Shortages in Urban Regions: Aggressive Interactions at Tree Hollows in Forest Remnants. PLoS ONE 8, e59332.

Davis, R., Wilcox, J., 2013. Adapting to suburbia: Bird ecology on an urban-bushland interface in Perth, Western Australia. Pacific Conservation Biology 19, 110-120.

Eyles, K., 2013. Nature on the doorstep: Social perspectives of nature reserves and developing urban areas. Case study of Forde and Mulligans Flat, Fact Sheet prepared for the ACT Land Development Agency.

Eyles, K., Mulvaney, M., 2014. Responsible pet ownership and the protection of wildlife: options for improving the management of cats in the ACT. A background paper prepared for the ACT Responsible Cat Ownership Steering Committee, http://www.feral.org.au/wp-content/uploads/2014/06/RespCatOwnershipACT2014.pdf.

Feinberg, D.S., Hostetler, M.E., Reed, S.E., Pienaar, E.F., Pejchar, L., 2015. Evaluating management strategies to enhance biodiversity in conservation developments: Perspectives from developers in Colorado, USA. Landscape and Urban Planning 136, 87-96.

Fischer, J., Stott, J., Zerger, A., Warren, G., Sherren, K., Forrester, R.I., 2009. Reversing a tree regeneration crisis in an endangered ecoregion. Proceedings of the National Academy of Sciences 106, 10386-10391.

Forman, R.T.T., 2014. Urban ecology: Science of cities. Cambridge University Press, Cambridge.

Garden, J., McAlpine, C., Possingham, H., 2010. Multi-scaled habitat considerations for conserving urban biodiversity: native reptiles and small mammals in Brisbane, Australia. Landscape Ecology 25, 1013-1028.

Gibbons, P., van Bommel, L., Gill, A.M., Cary, G.J., Driscoll, D.A., Bradstock, R.A., Knight, E., Moritz, M.A., Stephens, S.L., Lindenmayer, D.B., 2012. Land Management Practices Associated with House Loss in Wildfires. PLoS ONE 7, e29212.

Gill, N., Waitt, G., Head, L., 2009. Local engagements with urban bushland: Moving beyond bounded practice for urban biodiversity management. Landscape and Urban Planning 93, 184-193.

Goddard, M.A., Dougill, A.J., Benton, T.G., 2010. Scaling up from gardens: biodiversity conservation in urban environments. Trends in Ecology & Evolution 25, 90-98.

Gordon, A., Simondson, D., White, M., Moilanen, A., Bekessy, S.A., 2009. Integrating conservation planning and landuse planning in urban landscapes. Landscape and Urban Planning 91, 183-194.

Grarock, K., Tidemann, C.R., Wood, J., Lindenmayer, D.B., 2012. Is It Benign or Is It a Pariah? Empirical Evidence for the Impact of the Common Myna (*Acridotheres tristis*) on Australian Birds. PLoS ONE 7, e40622.

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., Briggs, J.M., 2008. Global Change and the Ecology of Cities. Science 319, 756-760.

Hamer, A.J., Parris, K.M., 2010. Local and landscape determinants of amphibian communities in urban ponds. Ecological Applications 21, 378-390.

Hands, D.E., Brown, R.D., 2002. Enhancing visual preference of ecological rehabilitation sites. Landscape and Urban Planning 58, 57-70.

Harper, M.J., McCarthy, M.A., van der Ree, R., 2005a. The abundance of hollow-bearing trees in urban dry sclerophyll forest and the effect of wind on hollow development. Biological Conservation 122, 181-192.

Harper, M.J., McCarthy, M.A., van der Ree, R., 2005b. The use of nest boxes in urban natural vegetation remnants by vertebrate fauna. Wildlife Research 32, 509-516.

Harper, M.J., McCarthy, M.A., Van Der Ree, R., 2008. Resources at the landscape scale influence possum abundance. Austral Ecology 33, 243-252.

Hostetler, M., Allen, W., Meurk, C., 2011. Conserving urban biodiversity? Creating green infrastructure is only the first step. Landscape and Urban Planning 100, 369-371.

Ikin, K., Barton, P., Knight, E., Lindenmayer, D., Fischer, J., Manning, A., 2014. Bird community responses to the edge between suburbs and reserves. Oecologia 174, 545-557.

Ikin, K., Beaty, R.M., Lindenmayer, D., Knight, E., Fischer, J., Manning, A., 2013a. Pocket parks in a compact city: how do birds respond to increasing residential density? Landscape Ecology 28, 45-56.

Ikin, K., Knight, E., Lindenmayer, D., Fischer, J., Manning, A., 2012. Linking bird species traits to vegetation characteristics in a future urban development zone: implications for urban planning. Urban Ecosystems 15, 961-977.

Ikin, K., Knight, E., Lindenmayer, D.B., Fischer, J., Manning, A.D., 2013b. The influence of native versus exotic streetscape vegetation on the spatial distribution of birds in suburbs and reserves. Diversity and Distributions 19, 294-306.

Ives, C.D., Lentini, P.E., Threlfall, C., Ikin, K., Shanahan, D.F., Garrard, G., Bekessy, S.A., Fuller, R.F., Mumaw, L., Rayner, L., Rowe, R., Valentine, L., Kendal, D., in review. Spatial patterning of threatened species distributions and the pivotal role of cities for conservation. Global Ecology and Biogeography.

Kath, J., Maron, M., Dunn, P.K., 2009. Interspecific competition and small bird diversity in an urbanizing landscape. Landscape and Urban Planning 92, 72-79.

Kendal, D., Williams, K.J.H., Williams, N.S.G., 2012a. Plant traits link people's plant preferences to the composition of their gardens. Landscape and Urban Planning 105, 34-42.

Kendal, D., Williams, N.G., Williams, K.H., 2012b. A cultivated environment: Exploring the global distribution of plants in gardens, parks and streetscapes. Urban Ecosystems 15, 637-652.

Kirkpatrick, J.B., Daniels, G.D., Zagorski, T., 2007. Explaining variation in front gardens between suburbs of Hobart, Tasmania, Australia. Landscape and Urban Planning 79, 314-322.

Le Roux, D., Ikin, K., Lindenmayer, D., Bistricer, G., Manning, A., Gibbons, P., In review-a. Spatial factors affecting artificial nest box occupancy: considerations for biodiversity offsets.

Le Roux, D., Ikin, K., Lindenmayer, D., Manning, A.D., Gibbons, P., in review-b. Single large or several small? Applying biogeographic principles to tree-level conservation and biodiversity offsets.

Le Roux, D.S., Ikin, K., Lindenmayer, D.B., Blanchard, W., Manning, A.D., Gibbons, P., 2014a. Reduced availability of habitat structures in urban landscapes: Implications for policy and practice. Landscape and Urban Planning 125, 57-64.

Le Roux, D.S., Ikin, K., Lindenmayer, D.B., Manning, A.D., Gibbons, P., 2014f. The future of large old trees in urban landscapes. PLoS ONE 9, e99403.

Lee, K.E., Williams, K.J.H., Sargent, L.D., Farrell, C., Williams, N.S., 2014. Living roof preference is influenced by plant characteristics and diversity. Landscape and Urban Planning 122, 152-159.

Lo, A.Y., Jim, C.Y., 2010. Willingness of residents to pay and motives for conservation of urban green spaces in the compact city of Hong Kong. Urban Forestry and Urban Greening 9, 113-120.

Luck, G., Davidson, P., Boxall, D., Smallbone, L., 2011. Relations between urban bird and plant communities and human well-being and connection to nature. Conservation Biology 25, 816-826.

Luck, G., Smallbone, L., Threlfall, C., Law, B., 2013a. Patterns in bat functional guilds across multiple urban centres in south-eastern Australia. Landscape Ecology 28, 455-469.

Luck, G., Smallbone, L.T., Sheffield, K.J., 2013b. Environmental and socio-economic factors related to urban bird communities. Austral Ecology 38, 111-120.

Maron, M., Rhodes, J.R., Gibbons, P., 2013. Calculating the benefit of conservation actions. Conservation Letters 6, 359-367.

Marshall, A., 2013. Start with the grasslands: design guidelines to support native grasslands in urban areas. Melbourne, Victorian National Parks Association.

McDonald, R.I., 2008. Global urbanization: can ecologists identify a sustainable way forward? Frontiers in Ecology and the Environment 6, 99-104.

McDonnell, M., Hahs, A., 2013. The future of urban biodiversity research: Moving beyond the 'low-hanging fruit'. Urban Ecosystems 16, 397-409.

McKinney, M.L., 2008. Effects of urbanization on species richness: a review of plants and animals. Urban Ecosystems 11, 161-176.

Mitchell, R., Popham, F., 2008. Effect of exposure to natural environment on health inequalities: an observational population study. The Lancet 372, 1655-1660.

Nassauer, J.I., 1995. Messy ecosystems, orderly frames. Landscape Journal 14, 161-169.

Newport, J., Shorthouse, D.J., Manning, A.D., 2014. The effects of light and noise from urban development on biodiversity: Implications for protected areas in Australia. Ecological Management & Restoration 15, 204-214.

Palmer, G.C., Fitzsimons, J.A., Antos, M.J., White, J.G., 2008. Determinants of native avian richness in suburban remnant vegetation: Implications for conservation planning. Biological Conservation 141, 2329-2341.

Parris, K., Schneider, A., 2008. Impacts of Traffic Noise and Traffic Volume on Birds of Roadside Habitats Ecology and Society 14, 29.

Parsons, H., Major, R.E., French, K., 2006. Species interactions and habitat associations of birds inhabiting urban areas of Sydney, Australia. Austral Ecology 31, 217-227.

Rayner, L., Ikin, K., Evans, M.J., Gibbons, P., Lindenmayer, D., Manning, A.D., 2015. Avifauna and urban encroachment in time and space. Diversity and Distributions 21, 428-440.

Rayner, L., Lindenmayer, D.B., Wood, J.T., Gibbons, P., Manning, A.D., 2014. Are protected areas maintaining bird diversity? Ecography 37, 43-53.

Renjifo, L.M., 2001. Effect of natural and anthropogenic landscape matrices on the abundance of subandean bird species. Ecological Applications 11, 14-31.

Shanahan, D.F., Lin, B.B., Gaston, K.J., Bush, R., Fuller, R.A., 2014. Socio-economic inequalities in access to nature on public and private lands: A case study from Brisbane, Australia. Landscape and Urban Planning 130, 14-23.

Shanahan, D.F., Miller, C., Possingham, H.P., Fuller, R.A., 2011. The influence of patch area and connectivity on avian communities in urban revegetation. Biological Conservation 144, 722-729.

Shoo, L.P., Wilson, R., Williams, Y.M., Catterall, C.P., 2014. Putting it back: Woody debris in young restoration plantings to stimulate return of reptiles. Ecological Management & Restoration 15, 84-87.

Smallbone, L.T., Luck, G.W., Wassens, S., 2011. Anuran species in urban landscapes: Relationships with biophysical, built environment and socio-economic factors. Landscape and Urban Planning 101, 43-51.

Stagoll, K., Lindenmayer, D.B., Knight, E., Fischer, J., Manning, A.D., 2012. Large trees are keystone structures in urban parks. Conservation Letters 5, 115-122.

Stagoll, K., Manning, A.D., Knight, E., Fischer, J., Lindenmayer, D.B., 2010. Using bird-habitat relationships to inform urban planning. Landscape and Urban Planning 98, 13-25.

Sushinsky, J.R., Rhodes, J.R., Possingham, H.P., Gill, T.K., Fuller, R.A., 2012. How should we grow cities to minimize their biodiversity impacts? Global Change Biology 19, 401-410.

Taylor, M.S., Wheeler, B.W., White, M.P., Economou, T., Osborne, N.J., 2015. Research note: Urban street tree density and antidepressant prescription rates—A cross-sectional study in London, UK. Landscape and Urban Planning 136, 174-179.

Threlfall, C., Law, B., Penman, T., Banks, P.B., 2011. Ecological processes in urban landscapes: mechanisms influencing the distribution and activity of insectivorous bats. Ecography 33, 1-13.

Threlfall, C.G., Law, B., Banks, P.B., 2012a. Influence of Landscape Structure and Human Modifications on Insect Biomass and Bat Foraging Activity in an Urban Landscape. PLoS ONE 7, e38800.

Threlfall, C.G., Law, B., Banks, P.B., 2012b. Sensitivity of insectivorous bats to urbanization: Implications for suburban conservation planning. Biological Conservation 146, 41-52.

Threlfall, C.G., Law, B., Banks, P.B., 2013a. Roost selection in suburban bushland by the urban sensitive bat Nyctophilus gouldi. Journal of Mammalogy 94, 307-319.

Threlfall, C.G., Law, B., Banks, P.B., 2013b. The urban matrix and artificial light restricts the nightly ranging behaviour of Gould's long-eared bat (Nyctophilus gouldi). Austral Ecology 38, 921-930.

Turner, W.R., Nakamura, T., Dinetti, M., 2004. Global Urbanization and the Separation of Humans from Nature. Bioscience 54, 585-590.

United Nations, 2014. 2014 Revision of World Urbanization Prospects ed. P.D. United Nations Department of Economic and Social Affairs.

Uren, H.V., Dzidic, P.L., Bishop, B.J., 2015. Exploring social and cultural norms to promote ecologically sensitive residential garden design. Landscape and Urban Planning 137, 76-84.

Villaseñor, N., Blanchard, W., Driscoll, D., Gibbons, P., Lindenmayer, D., 2015. Strong influence of local habitat structure on mammals reveals mismatch with edge effects models. Landscape Ecology 30, 229-245.

Villaseñor, N.R., Blanchard, W., Lindenmayer, D., in review. Stronger decline of forest vegetation structures across forest-urban interfaces of high than low residential density.

Villaseñor, N.R., Driscoll, D.A., Escobar, M.A.H., Gibbons, P., Lindenmayer, D.B., 2014. Urbanization Impacts on Mammals across Urban-Forest Edges and a Predictive Model of Edge Effects. PLoS ONE 9, e97036.

Weston, M., Fitzsimons, J., Wescott, G., Miller, K., Ekanayake, K., Schneider, T., 2014. Bark in the Park: A Review of Domestic Dogs in Parks. Environmental Management 54, 373-382.

White, J.G., Antos, M.J., Fitzsimons, J.A., Palmer, G.C., 2005. Non-uniform bird assemblages in urban environments: the influence of streetscape vegetation. Landscape and Urban Planning 71, 123-135.

Whitehead, A.L., Kujala, H., Ives, C.D., Gordon, A., Lentini, P.E., Wintle, B.A., Nicholson, E., Raymond, C.M., 2014. Integrating Biological and Social Values When Prioritizing Places for Biodiversity Conservation. Conservation Biology 28, 992-1003.

Wiens, J., 2009. Landscape ecology as a foundation for sustainable conservation. Landscape Ecology 24, 1053-1065.

Wong, D., Jones, S., Osborne, W., Brown, G., Robertson, P., Michael, D., Kay, G., 2011. The life history and ecology of the Pink-tailed Worm-lizard Aprasia parapulchella Kluge – a review. Australian Zoologist 35, 927-940.

**Table 1:** Key management actions for achieving biodiversity-sensitive urban design based on scientific research in southeastern Australia.

| Lessons | Actions |
|---|---|
| Lesson 1: Effects of urbanisation on wildlife extend into adjacent habitats | 1. Retain large, undisturbed areas of habitat away from urban areas to maximise core habitat for urban-avoiding species. |
| | 2. Minimise intensive urban development adjacent to important conservation areas.. |
| | 3. Use conservation planning methods to prioritise areas of ecological and social significance. |
| | 4. Use screens (e.g. directional covers for lights) at the urban fringe or around large nature reserves to reduce light and noise pollution. |
| | 5. Plant appropriately-provenanced locally native street, park and garden trees, especially at the urban fringe (Fig. 1A). |
| Lesson 2: Strategic enhancement of the urban greenspace offers biodiversity gains | 6. Increase the amount and diversity of greenspaces within urban areas, including parks, roadside margins, golf courses, private gardens and wetlands (Fig. 1B). |
| | 7. Design new developments to incorporate existing locally native vegetation into planned greenspace areas. |
| | 8. Retain and enhance trees and understory vegetation cover (e.g. shrubs and groundcovers) at the urban fringe (Fig. 1C). |
| | 9. Manage fire risk by adopting design features within asset protection zones, such as low-traffic edge roads and landscaped areas for passive recreation (e.g. walking and bike trails) (Fig. 1D). |
| | 10. Establish habitat islands around existing habitat structures that are difficult to restore (e.g. large trees, dead trees, floristically diverse sites, and rocky outcrops) (Fig. 1E). |
| | 11. Establish habitat islands in advance of greenfield urban development through the use of farm management (e.g. stock control and input reduction to encourage tree regeneration). |
| | 12. Juxtapose and arrange habitat islands so that they are sufficiently connected to improve persistence and colonisation by wildlife. |
| Lesson 3: Large old trees need to be managed for long-term sustainability | 13. Retain large old trees in new developments by designing greenspace areas around where they occur and improve protection by explicitly acknowledging the biodiversity value of large trees in tree preservation policies. |

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|---|---|
| | 14. Increase the maximum standing life of trees so that they reach full habitat potential. |
| | 15. Protect regenerating areas, and increase the number of seedlings planted elsewhere. |
| | 16. Accelerate the formation of habitat structures associated with large trees (e.g. supplementing hollow formation by installing artificial nest boxes). |
| | 17. Proactively plan for future large trees by ensuring that younger trees have sufficient 'safe space' needed to grow in size and using spatial zoning to minimise future risks (Fig. 1F). |
| Lesson 4: Education and engagement connects residents with nature and raises awareness | 18. Use resident education programs to promote sensitive ways of living near nature reserves (Fig. 1G). |
| | 19. Introduce incentive-based polices to promote implementation of conservation practices and resident engagement programs by developers. |
| | 20. Provide information about suitable plant species for landscaping gardens; responsible pet ownership; and appropriate recreational activities in and around nature reserves (Fig. 1H). |
| | 21. Provide opportunities for new residents to experience and learn about biodiversity values. |
| | 22. Engage residents in the establishment and maintenance of habitat for wildlife and provide 'cues to care', such as amenities and signage. |
| | 23. Implement cat containment, particularly in fringe suburbs, and reinforce with signage and education. |
| | 24. Exclude dogs from nature reserves and develop designated dog exercise areas. |