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Review of the ecology of Australian urban fauna: A focus on spatially explicit processes

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Abstract Cities have a major impact on Australian landscapes, especially in coastal regions, to the detriment of native biodiversity. Areas suitable for urban development often coincide with those areas that support high levels of species diversity and endemism. However, there is a paucity of reliable information available to guide urban conservation planning and management, especially regarding the trade-off between investing in protecting and restoring habitat at the landscape level, and investing in programmes to maintain the condition of remnant vegetation at the local (site) level. We review the literature on Australian urban ecology, focusing on urban terrestrial and aquatic vertebrate and invertebrate fauna. We identify four main factors limiting our knowledge of urban fauna: (i) a lack of studies focusing at multiple ecological levels; (ii) a lack of multispecies studies; (iii) an almost total absence of long-term (temporal) studies; and (iv) a need for stronger integration of research outcomes into urban conservation planning and management. We present a set of key principles for the development of a spatially explicit, long-term approach to urban fauna research. This requires an understanding of the importance of local-level habitat quality and condition relative to the composition, configuration and connectivity of habitats within the larger urban landscape. These principles will ultimately strengthen urban fauna management and conservation planning by enabling us to prioritize and allocate limited financial resources to maximize the conservation return.

Key words: ecological level, habitat condition, landscape context, long-term study, scale

> The future is not just what lies ahead; it is something that we create.
>
> Forman and Collinge (1997)

INTRODUCTION

The primary driver of the global decline of biodiversity is habitat loss and fragmentation resulting from anthropogenic pressures on natural ecosystems. Urbanization is arguably the most damaging, persistent and rapidly expanding form of anthropogenic pressure (Vitousek *et al.* 1997; Lugo 2002; McKinney 2002; Miller & Hobbs 2002). Almost half (49.2%) the world's population currently reside in urban areas (United Nations 2005). As the human population continues to increase, so too do demands for residential, industrial, commercial and recreational space. Consequently, the Earth's landscapes are becoming increasingly urbanized; by 2010 humans will be a predominantly urban species, with 51.3% predicted to be living in urban areas (United Nations 2005).

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The primary impacts of urban development on biodiversity are extensive habitat loss and fragmentation, which significantly alters the structure of urban landscapes and the composition and structure of ecosystems embedded in these landscapes (Forman 1995; Baskin 1998; Wilcove *et al.* 1998; Marzluff & Ewing 2001; Faulkner 2004). Consequently, urban landscapes are dominated by the built environment composed of buildings, bridges, roads and paved areas, interspersed with 'green' habitat patches ranging from cultivated parks and gardens to remnant bushland, all of which vary in size, shape and condition (Burgman & Lindenmayer 1998; Angold *et al.* 2001). The cumulative impacts of urban development on fauna species are not restricted to urban areas, but may extend varying distances into neighbouring landscapes and affect species and ecological processes in adjacent ecosystems (Quarles *et al.* 1974; Rees 1997; Bisonnette 2002; Yeoman & MacNally 2005). As this urban footprint continues to expand and intensify, remnant vegetation patches and their dependent biota are subject to further habitat loss, fragmentation and degradation (Fahrig 1997, 2001). Such intense and widespread modification of natural landscapes and ecosystems produces an environment so different from its natural state that even if anthropogenic activities were removed, complete recovery would be unlikely (Lugo 2002).

Despite the significant destruction and degradation of habitats, urban areas have the capacity to support a wide diversity of vertebrate and invertebrate fauna species, perhaps due to the range of diverse natural and artificial habitat niches and conditions that occur in urban areas (Niemelä 1999a,b; Collins *et al.* 2000). Kühn *et al.* (2004), however, argue that high species diversity in urban areas occurs not because of but in spite of urbanization, with urban development often coinciding with areas of naturally high species diversity and endemism, such as coastal and tropical regions. This diversity of fauna species exhibits varying responses to urbanization. The magnitude and direction of urban impacts on each species depends on that species' life-history attributes, sensitivities to environmental disturbances, interspecies interactions and dispersal ability (Dickman & Doncaster 1989; Cox *et al.* 2003; Tischendorf *et al.* 2003). This diversity of responses has previously been used to categorize species based on similarities in their responses to, and abilities to persist within, the urban environment (e.g. Baskin 1998; McKinney 2002; Catterall 2004). For the purposes of this paper, species are discussed as either 'matrix-occupying', 'matrix-sensitive' or 'urban-sensitive'. Matrix-occupying species are those that commonly dominate the urban matrix due to their ability to move through and live within the built matrix. Conversely, matrix-sensitive species perceive the built matrix as unsuitable habitat with a lack of food and shelter resources, a barrier to movement and an area of increased risk of predation. Consequently, matrix-sensitive species are often restricted to vegetation patches of suitable habitat, resulting in fragmentation of populations and increasing the risk of localized extinctions. Species classed as urban-sensitive are unable to persist in urban landscapes, even in remnant patches of native vegetation. Characteristics shared by these species include limited dispersal ability and narrow or specialized dietary requirements.

Prior to the 1990s, urban areas were largely overlooked or ignored in ecological studies as they were considered to be non-viable habitat for fauna populations and therefore of no use for conservation efforts (Botkin & Beveridge 1997; McDonnell *et al.* 1997; Savard *et al.* 2000). As a result, the impacts of urbanization on fauna populations are not well understood, often resulting in poorly targeted conservation actions (Niemelä 1999a; Recher 2002). The results of studies conducted in non-urban environments (e.g. forest, agricultural) are not necessarily transferable to urban areas because of the increased rate and complexity of environmental changes, coupled with additional urban-based pressures such as increased densities of transport networks and associated usage, domestic dog and cat predation and significantly altered abiotic factors (e.g. water, noise, air and soil pollution). Therefore, management actions based on knowledge accrued from non-urban research may be inappropriate within the urban environment. This lack of appropriate ecological knowledge hinders the long-term success of existing and proposed urban conservation actions. This is of particular concern for tropical and coastal regions that commonly support high levels of biodiversity, yet where the rate of urban development is also higher than in any other region (Barrow 1991; Kühn *et al.* 2004).

Such issues are particularly evident in Australia, where the capital cities and most major urban developments are located along the nation's seaboard, especially the eastern seaboard (Commonwealth of Australia 2003b). Australia's human population is already predominantly urban, with more than 90% residing in urban areas (United Nations 2005). The fraction of people living in cities continues to increase with the highest rate of recent urban development occurring along the eastern tropical and subtropical coast, which also supports high species diversity and endemism (Queensland Museum 1995; Commonwealth of Australia 2003a).

The plight of biodiversity in Australia's urban landscapes has been recognized by Adams (1994), Jones (2003) and Lunney and Burgin (2004). To minimize this loss urban ecological researchers, both internationally and in Australia, need to understand and predict species–habitat relationships at multiple ecological levels and determine the relative importance of the amount of habitat, its spatial configuration and its condition on species survival. This knowledge is a prerequisite for urban planners and conservation managers to effectively conserve and restore urban biodiversity.

This paper provides a constructive review of the scientific literature of Australian-based urban ecological research in order to highlight the strengths and limitations of existing research knowledge. We focus on terrestrial vertebrate and invertebrate fauna, with an emphasis on spatial processes and long-term trends. Some studies on aquatic fauna are also included. Our primary target audience is urban ecologists, but we also highlight the need for research to meet the information needs of local government and regional planning authorities responsible for urban biodiversity conservation and whom also fund some ecological research. The paper is divided into three sections. First, we outline criteria used to select the papers reviewed, with a focus on recent Australian urban fauna studies. Next, existing research strengths and gaps are identified. Third, we develop a set of key principles to address these gaps and guide the development of a spatially explicit, long-term approach to the study of Australia's urban fauna, and thereby improve the conservation of Australia's urban fauna.

REVIEW CRITERIA

The research papers reviewed (Table 1) were selected based on the following criteria.

Focus on fauna (vertebrate and invertebrate) habitat relationships within Australian urban areas

For the purposes of this review, urban areas are defined as 'areas of intense human influence, dominated by the built environment and supporting a population cluster of more than 1000 people'. This definition is based on previous definitions by Forman and Godron (1986), Pickett *et al.* (2001) and the Australian Bureau of Statistics (Commonwealth of Australia 2003b). Papers were selected if they addressed fauna (vertebrate and invertebrate, terrestrial and aquatic) habitat relationships within Australian urban areas. We acknowledge the relevance of other studies of urban ecology issues such as: native and exotic pest species management (e.g. Marks & Bloomfield 1999; Matthews *et al.* 2004; Moriarty 2004; Ross 2004), human–fauna interactions and conflicts (e.g. Jones & Everding 1991; Miller *et al.* 1999; Shine & Koenig 2001; Warne & Jones 2003), changes in species behaviour, diet and fecundity (e.g. Smith & Carlile 1993; Statham & Statham 1997; Webster *et al.* 1999; Fearn *et al.* 2001; Parry-Jones & Augee 2001; Rollinson & Jones 2002; Hoye & Spence 2004; Markus & Hall 2004; Temby 2004; Everding & Jones 2006), wildlife mortalities due to vehicle collisions and predation (e.g. Barrat 1997; Koenig *et al.* 2002; Dique *et al.* 2003; Taylor & Goldingay 2004), urbanization impacts on flora species (e.g. Rose 1997; Buist *et al.* 2000; Leishman *et al.* 2004; Stenhouse 2004) and abiotic influences such as air, light and water pollution on urban flora and fauna populations (e.g. McDonnell *et al.* 1993; Riley & Banks 1996; Angold 1997; Spooner *et al.* 2003).

Published between 1990 and 2005

The surge of urban-based fauna ecology studies over the last 10–15 years influenced the decision to review only those articles published between 1990 and 2005. We acknowledge that several urban fauna–habitat studies were conducted in Australia prior to 1990, with the majority of these focusing on avian communities, particularly matrix-occupying assemblages (e.g. Jones 1981; Ford 1983; Jones 1983; Green 1984; Mason 1985; Catterall *et al.* 1989; Munyenyembe *et al.* 1989). However, their exclusion is not expected to significantly impact on the review content as many 'modern-day' studies draw and expand on the findings of earlier studies.

Keyword searches and accessibility

We selected publications in refereed journals, books and conference proceedings that were accessible via online databases and library searches. Online databases were searched using a combination of the following keywords: urban, suburban, city, town, wildlife, fauna, animal/s, mammal, bird, avian, reptile, amphibian, herpetofauna, aquatic, invertebrate, insect, coast/al, fragmentation, ecology, habitat, site, patch, landscape/s, scale, level, environment, mosaic, development, Australia. An examination of citations within selected papers was used to identify further references. Where possible, if a relevant paper was not available via online databases or library searches, authors were contacted and a copy of the paper was requested.

REVIEW OF AUSTRALIAN URBAN FAUNA RESEARCH

The review was stratified based on five broad fauna groupings: birds, mammals, herpetofauna (reptiles and amphibians), invertebrates and aquatics. With the exception of the aquatic group, all studies discuss either terrestrial or arboreal species, including species that utilize both aquatic and terrestrial systems (e.g. platypus, crocodiles, frogs and crabs). Aquatic studies include both freshwater and oceanic species, and microscopic organisms. Table 1 segregates studies based on these fauna groupings, and indicates the ecological level/s at which studies were conducted, as well as the location and key findings of each study. We use the term 'level' to refer to levels of ecological organization, as opposed to the term 'scale', which refers to spatial resolution and extent of the analysis (*sensu* Turner *et al.* 2001). Three levels are identified: site or *in situ* (<1 ha), patch (1–100s ha) and landscape (100s–1000s ha). Examples of environmental characteristics operating at each level are provided in Table 2.

Birds

Birds are by far the most obvious and readily identifiable fauna element of urban habitats and, as such, have received more research attention than other animal groups (35% of all papers, Fig. 1a) . Australian urban bird assemblages are generally species rich, yet

Table 1. Summary of 63 Australian urban ecology studies conducted between 1990 and 2005

Species	Ecological level/s	Location	Key findings and habitat features	Reference
Birds				
Splendid fairy-wren *Malurus s. splendens*	PVA	(near) Perth, WA	Habitat loss coupled with fire frequency. Habitat fragmentation. Secondary pressures such as nest predation.	Brooker and Brooker (1994)
Powerful owl *Ninox strenua*	Site	Melbourne, Vic.	Requires structurally diverse vegetation.	Cooke *et al.* (2002)
Australian Magpie *Gymnorhina tibican*	Long-term	Perth, WA	Habitat loss – prefers cleared, well watered areas such as urban lawns and open parks. Distributional changes over time.	Wood and Recher (2004)
Rainbow Lorikeets *Trichoglossus haematodus* Musk Lorikeets *Glossopsitta concinna*	Site	Melbourne, Vic.	Habitat type (streetscapes preferred). Vegetation composition (native species preferred). Vegetation age (well-established streetscapes preferred).	Fitzsimons *et al.* (2003)
Willie wagtail *Rhipidura leucophrys* Pied currawong *Strepera graculina*	Site	Various	Vegetation density. Inter-species interactions (predation).	Major *et al.* (1996)
Multiple owl species	Review	Sydney, NSW	Habitat loss and fragmentation – extensive bushland areas must be conserved. Prey species' habitat area must also be conserved.	Kavanagh (2004)
Multiple nectarivorous species	Site	Sydney, NSW	Vegetation composition (native plants more important than exotics).	French *et al.* (2005)
Multiple species	Site Patch, Landscape	South-east Qld (3100 km^2)	Overall relative importance: spatial, then habitat characteristics. Specifically specialist species: connectivity and patch shape. Specifically migrants and generalist species: site characteristics.	Bentley and Catterall (1997)
Multiple species	Patch, Landscape	Brisbane, Qld	Patch size, vegetation abundance and composition, spatial configuration of habitats. Inter-species interactions.	Catterall (2004)
Multiple species	Patch, Landscape	Brisbane, Qld	Vegetation structure. Habitat loss and alteration.	Catterall *et al.* (1998)
Multiple species	Site, Patch	Brisbane, Qld	Patch area. Habitat heterogeneity. Vegetation structure and density (particularly understorey density).	Grover and Slater (1994)
Multiple species	Long-term	Townsville, Qld	No changes in overall species richness. Significant changes in species composition.	Jones and Wieneke (2000)

Table 1. *Continued*

Species	Ecological level/s	Location	Key findings and habitat features	Reference
			Changes in species distributions attributed to changes in vegetation structure and composition over time (species-specific preferences) and associated Inter-species interactions.	
Multiple species	Patch	Sydney, NSW	Habitat heterogeneity.	Parsons *et al*. (2003)
Multiple species	Site	Sydney, NSW	Vegetation composition. Inter-species interactions.	Parsons and Major (2004)
Multiple species	Site, Patch, Landscape	Perth, WA	Habitat complexity and vegetation structure – native plants, not exotics. Patch isolation and habitat fragmentation. Urban matrix and resource availability within suburbs. Fire management, vehicular mortality and predation	Recher (2004)
Multiple species	Patch	Perth, WA	Vegetation structure – maintain complex understorey. Ground cover. Resource availability from residential gardens.	Recher and Serventy (1991)
Multiple species	Patch Qld	Brisbane,	Vegetation structure – retain old growth canopy trees. Vegetation composition – remnant vegetation more important than revegetated patches.	Sewell and Catterall (1998)
Multiple species	Site	Goode Beach, WA	Vegetation composition and structure. Inter-species interactions.	Smith (2002)
Multiple species	Site	Melbourne, Vic.	Vegetation composition and structure. Habitat condition (development disturbance).	White *et al*. (2005)
Multiple species	Site, Landscape	Wollongong, NSW	Wetland pollution. Habitat heterogeneity – especially maintain wetlands. Vegetation structure and heterogeneity. Habitat connectivity and buffers. Disturbances from human recreational activities and pets.	Wood (1993)
Multiple species	Site, Patch, Landscape	Melbourne and Geelong, Vic.	Patch size. Density of urban development.	Yeoman and MacNally (2005)
Multiple species†	Site, Patch	Perth, WA	Small, isolated patches (1 ha) important for urban birds – including migratory species. Vegetation composition (native remnants vegetation better than exotic plantings). Species-specific responses.	Cooper (1995)
Multiple species†	Patch, Landscape	Sydney, NSW	Patch area (and edge effects): approx. 4 ha threshold for generalist/urban tolerant species and approx. 50 ha for fragmentation-sensitive species. Functionalconnectivity between habitat patches.	Drinnan (2005)

Multiple species†	Historical	Perth, WA	Compositional changes since European settlement. Combination of habitat loss and fragmentation, altered fire regimes, introduced exotic species, wetland modification.	How and Dell (1993)
Multiple species†	Historical	Adelaide, SA	Species composition varies significantly over time. Habitat loss and fragmentation. Vegetation composition and structure. Edge effects. Inter-species interactions. Species-specific responses.	Tait *et al.* (2005)
Mammals				
Long-nosed bandicoot *Perameles nasuta*	PVA	Sydney, NSW	Urbanization threats to adult mortality more immediately important than managing habitat availability (although effects are additive).	Banks (2004)
Long-nosed bandicoot *Perameles nasuta*	PVA	North Head, NSW	Vegetation structural complexity and habitat heterogeneity.	Chambers and Dickman (2002)
Long-nosed bandicoot	Site	Sydney, NSW	Vegetation structural complexity and habitat heterogeneity. Mortalities due to vehicle collisions and predation by exotic species.	Scott *et al.* (1999)
Eastern barred bandicoot *Peremeles gunnii*	Site	Hamilton, Vic.	Vegetation structural complexity and habitat heterogeneity. Utilize both natural and artificial materials for shelter.	Dufty (1994)
Northern brown bandicoot *Isoodon macrourus*	Site, Patch, Landscape	Brisbane, Qld	Functional connectivity between habitat patches. Patch area. Habitat quality (especially ground cover density).	FitzGibbon *et al.* (submitted)
Koala *Phascolarctos cinereus*	Landscape	Koala Coast, Qld	Habitat loss and fragmentation. Habitat connectivity essential, especially between large patches. Connectivity between urban remnants and ex-urban remnant bushland.	Dique *et al.* (2004)
Koala *Phascolarctos cinereus*	Patch, Landscape	Noosa Shire, Qld	Habitat loss and habitat quality. Patch area. Density of sealed roads.	McAlpine *et al.* (2005)
Koala *Phascolarctos cinereus*	Site, Patch, Landscape	Qld and NSW	Combination of environmental variables across three spatial levels. Presence and abundance of food trees most important overall.	McAlpine *et al.* (in press)

Table 1. *Continued*

Species	Ecological level/s	Location	Key findings and habitat features	Reference
Koala *Phascolarctos cinereus*	Landscape	Port Stephens, NSW	Remnant habitat spatial configuration and connectivity. Road density. Fire frequency and intensity. Relative importance of these factors varies spatially.	Rhodes *et al.* (2006)
Koala *Phascolarctos cinereus*	Patch, Landscape	Noosa, Qld	Habitat loss and fragmentation.	Seabrook *et al.* (2003)
Koala *Phascolarctos cinereus* Landscape	Site, Patch, NSW	Warringah Shire, Habitat quality, especially food tree density.	Habitat loss. Patch connectivity. Management of mortalities due to pet predation and vehicle collisions. Mitigation of dispersal barriers such as fences and walls.	Smith and Smith (1990)
Koala *Phascolarctos cinereus*	Site, Landscape	Sydney, NSW	Habitat loss and connectivity. Vegetation composition and substrate. Fire regimes, vehicle and dog mortalities and, weed invasions.	Ward and Close (2004)
Platypus *Ornithorhynchus anatinus*	Site	Melbourne, Vic.	Utilize both natural waterways and drainage channels. Burrow location influenced by physical attributes of banks (concave profile preferred over convex profiles) and associated riparian vegetation density and structure.	Serena *et al.* (1998)
White-striped freetail bat *Tadarida australis*	Site	Brisbane, Qld	Hollow bearing tree characteristics (e.g. height, diameter, senescence). Surrounding local vegetation (i.e. tree density and undergrowth).	Rhodes and Wardell-Johnson (2006)
Squirrel glider *Petaurus norfolcensis*	PVA	Brisbane, Qld	Habitat loss. Patch isolation and area. Functional connectivity between suitable patches. Habitat quality (both patches and connecting vegetation corridors). Road density.	Goldingay and Sharpe (2004)
Squirrel glider *Petaurus norfolcensis*	Site, Patch, Landscape	Brisbane, Qld	Vegetation composition and structure. Remnant habitat area and altitude. Habitat isolation and connectivity.	Rowston *et al.* (2002)

Various (gliders and possums)	Site	Wyong and Lake Macquarie, NSW	Vegetation structure, composition and age. Fire frequency and Inter-species interactions. Species-specific responses.	Smith and Murray (2003)
Multiple species	Historical	Melbourne, Vic.	Species-specific responses. Habitat loss and fragmentation. Patch connectivity and habitat quality. Predation by introduced species.	van der Ree (2004)
Multiple species†	Historical	Adelaide, SA	Habitat loss and fragmentation. Vegetation structure. Inter-species interactions. Species responses vary. Species composition varies significantly over time.	Tait *et al.* (2005)
Multiple species†	Historical	Perth, WA	Combination of habitat loss and fragmentation, altered fire regimes, introduced exotic species, wetland modification.	How and Dell (1993)
Multiple species†	Patch, Landscape	Perth, WA	Habitat fragmentation.	How and Dell (2000)
Multiple species†	Site, Patch	Perth, WA	No native mammals found in study patch (1 ha) although representatives from other groups were.	Cooper (1995)
Herpetofauna				
Estuarine crocodile *Crocodylus porosus*	Site	North-east coastline, Qld	Riparian vegetation clearing anthropogenic developments. Secondary impacts: motor boat disturbance, commercial netting and individual removals.	Kofron and Smith (2001)
Multiple skink species	Site, Patch	Cumberland Plain, NSW	Edge effects influence species' distributions within patch.	Anderson and Burgin (2002)
Multiple lizard species	Site, Patch, Landscape	Hobart, Tas.	Vegetation structure and composition (native plants better than exotics). Patch geology and aspect. One species influenced by patch size; none by habitat fragmentation.	Jellinek *et al.* (2004)
Multiple reptile species†	Historical	Perth, WA	Combination of: habitat loss and fragmentation, local-level habitat degradation, altered fire regimes and wetland modification. Species-specific responses.	How and Dell (1993)
Multiple reptile species	Patch	Perth, WA	Combination of large and small remnants important. Large remnants especially important for urban snakes. Species-specific responses.	How and Dell (1994)

Table 1. *Continued*

Species	Ecological level/s	Location	Key findings and habitat features	Reference
Multiple reptile species†	Patch, Landscape	Perth, WA	Patch area important for all reptiles except skinks. Small remnants (as small as 1 ha) important for reptiles – although need to manage for fire and predator exclusion. Annual variation in lizard assemblages. Species-specific responses.	How and Dell (2000)
Multiple amphibian species†	Patch, Landscape	Sydney, NSW	Patch area: thresholds at approx. 4 ha for generalist/urban tolerant species and approx. 50 ha for intolerant species. Edge effects. Functional connectivity between habitat patches.	Drinnan (2005)
Multiple herpetofauna species†	Site, Patch	Perth, WA	Small, isolated patches (1 ha) – no large reptiles although historically present in the area; but important for small reptiles and amphibians. Remnant habitat.	Cooper (1995)
Multiple herpetofauna species†	Historical	Adelaide, SA	Reptile species composition (not richness) varies significantly over time. Substrate type and vegetation structure. No native amphibian losses since European settlement. Species-specific responses.	Tait *et al*. (2005)
Multiple herpetofauna species	Historical	Sydney, NSW	Decrease in species richness for both reptiles and amphibians. Large reptiles (e.g. goannas) locally extinct in urban remnant patches. Amphibians influenced by degradation of water quality. Arboreal amphibians more negatively impacted than terrestrials. Species-specific responses. Secondary impacts such as predation, altered fire regimes and human intervention influence both reptile and amphibian species.	White and Burgin (2004)
Invertebrates				
Ghost crab *Ocypode cordimana*	Site	Sydney, NSW	Fewer burrows on urban beaches than non-urban beaches. Human activity and dune modification affects species distribution – not yet clearly understood.	Barros (2001)

Western Jewel butterfly *Hypochrysops halyaetus*	Site	Perth, WA	Vegetation composition and structure. Habitat condition – prefer degraded, post-fire habitats. Inter-species interactions (mutual ant partner).	Dover and Rowlingson (2005)
African rhinoceros beetle *Temnorhynchus retusus*	Site	Sydney, NSW	Exotic vegetation has supported successful invasion and establishment.	Krell and Hangay (1998)
Multiple arthropod species	Site	Perth, WA	Tree age. Tree species (native better than exotics).	Bhullar and Majer (2000)
Multiple arthropod species	Site, Patch, Landscape	Sydney, NSW	Habitat fragmentation. Patch size. Habitat condition and altered fire regimes. Proximity to urban matrix.	Gibb and Hochuli (2002)
Multiple ant species	Site	Brisbane, Qld	Habitat heterogeneity. Inter-species interactions.	Burwell and Grimbacher (2005)
Multiple snail species	Review	Sydney, NSW	Small remnant vegetation patches as important as large ones. Vegetation type, habitat loss and fragmentation and habitat condition. Species-specific responses.	Clark (2004)
Multiple insect species	Site	Sydney, NSW	Vegetation diversity.	Emery and Emery (2004)
Multiple insect species	Patch	Sydney, NSW	Patch size. Inter-species interactions.	Hochuli *et al.* (2004)
Multiple butterfly species	Review	Various	Vegetation composition (especially exotic weeds). Inappropriate fire regimes.	New and Sands (2002)
Aquatic				
Multiple estuarine fish species	Site, Landscape	Botany Bay, NSW	Anthropogenic activities significantly alter fish habitats. Able to use significantly modified urban estuarine habitats in the absence of dispersal barriers (connectivity).	Gibbs (2004)
Multiple epilithic diatoms	Landscape	Melbourne, Vic.	Water quality (electrical conductivity) and drainage connections.	Newall and Walsh (2005)
Multiple amphipod species	Landscape	Melbourne, Vic.	Urban density and storm water drainage connections. Sealed roads and associated run-off also threaten species survival.	Walsh *et al.* (2004)
Multiple mcrofauna species	Landscape	Sydney, NSW	Adjacent habitat type and land use.	Yerman and Ross (2004)

Studies are grouped according to: birds, mammals, herpetofauna (reptiles and amphibians), invertebrates and aquatic. Ecological levels are assigned according to definitions provided in Table 2. Studies that were not spatially explicit are classified as: PVA (population viability analysis), long-term (field study repeated over ≥ 10 years), historical (comparison of historical records to present species distribution patterns) or, review (of current knowledge base).

†Indicates studies of multiple taxa that are repeated in each relevant section of this table, with key findings discussed relative to each specific taxon.

Table 2. Examples of habitat characteristics operating at the three ecological levels

Ecological level	Habitat characteristics
Site/Local (<1 ha)	Vegetation composition and structure. Ground cover type and proportion. Soil compaction. Nutrient levels.
Patch (1–100s ha)	Size and shape. Perimeter : area ratio (edge effects). Distance to landscape features (e.g. patch, river, road). Time since isolation.
Landscape (>100 ha)	Total habitat area (habitat loss). Number of habitat patches (habitat fragmentation). Degree of connectivity between patches. Density of land-use types (e.g. roads, residential areas, parks).

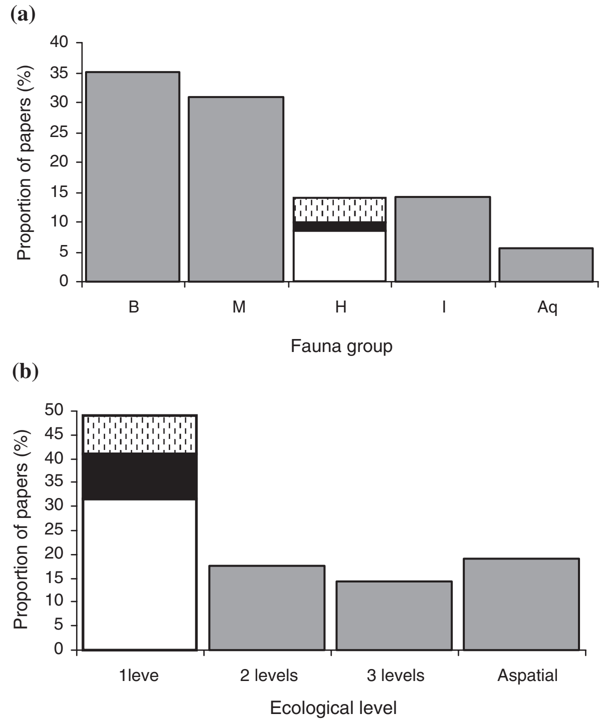

Fig. 1. Proportion of fauna groups and ecological levels examined across 63 urban fauna studies (see Table 1). (a) Relative proportion of fauna groups: B, birds; M, mammals; H, herpetofauna; I, invertebrates; Aq, aquatic. Herpetofauna column shows the relative number of studies that examined: reptiles (white area), amphibians (black area) and both reptiles and amphibians (dashed area). (b) Relative proportion of ecological levels (see Table 2): one level, two levels, three levels or, aspatial (no explicit level examined). The single-level column shows the relative number of studies that examined: site level (white area), patch level (black area) and landscape level (dashed area). Aspatial includes population viability analysis, long-term, historical and review studies as indicated in Table 1.

individual local communities may be characterized by either low species richness with high abundance or, high species richness with low abundance of individual species (Wood 1993). The increase in abundance of some bird species is attributed to their ability to utilize plentiful and novel resources (e.g. food and nesting locations) and habitats that occur in human-modified environments (Jones & Wieneke 2000; Catterall 2004). Such species usually comprise matrix-occupying assemblages, which dominate the built urban matrix and are comprised of both introduced species and native species (Jones & Wieneke 2000; Catterall 2004; Tait *et al.* 2005). These matrix-occupying assemblages are dominated by behaviourally aggressive, medium-bodied and large-bodied species such as, Australian magpies (*Gymnorhina tibican*), butcherbirds (*Cracticus* spp.), currawongs (*Strepera* spp.) noisy miners (*Manorina melanocephala*), and lorikeets (*Trichoglossus* spp.) (Jones & Wieneke 2000; Fitzsimons *et al.* 2003; Jones 2003; Catterall 2004; Wood & Recher 2004). This pattern of domination differs from the general trend observed in cities of the Northern Hemisphere where exotic and small-bodied natives tend to dominate the urban matrix (*sensu* Jones & Wieneke 2000). Much of the recent ecological research conducted on matrix-occupying species has investigated diet and behavioural adaptations to the urban environment, as well as human–avian conflict management issues (Jones & Everding 1991; Smith & Carlile 1993; Major *et al.* 1996; Fulton & Ford 2001; Hasebe & Franklin 2003; Ross 2004).

Some research has also investigated the influence of habitat on the distribution and abundance of Australian avian matrix-occupiers, showing that despite their dominance within the built environment, avian matrix-occupiers are rarely ubiquitous across the urban matrix, with distributions being influenced by *in situ* habitat factors such as vegetation composition and structure. Lorikeets, for example, appear to prefer well-established streetscapes planted with flowering native tree species (Fitzsimons *et al.* 2003), while Australian magpies thrive in highly disturbed, vegetated areas with little canopy cover such as well-watered residential lawns, managed parks and sporting ovals (Wood & Recher 2004). Noisy miners, in contrast, tend to dominate moderately disturbed 'edge' habitats with neither dense nor predominantly cleared vegetation cover (e.g. Catterall 2004; Tait *et al.* 2005).

In situ habitat factors have also been shown to be important for determining the presence and distribution of matrix-sensitive species, which in Australia are often small-bodied, insectivorous and nectarivorous bird species (White *et al.* 2005). Most studies that have investigated *in situ* habitat relationships agree that conserving, and potentially increasing, urban avian richness in habitat patches is primarily dependent on creating and maintaining structurally complex and floristically diverse habitats, with native plant species being recommended over exotic species (e.g. Recher & Serventy 1991; Cooke *et al.* 2002; Parsons *et al.* 2003; French *et al.* 2005; White *et al.* 2005). Sewell and Catterall (1998) further recommended that the retention of remnant vegetation habitats (more so than revegetation of native species) was central to the successful recovery and maintenance of insectivorous bird species in urban areas.

Both patch- and landscape-level variables have also been found to influence the presence of birds within urban landscapes. Kavanagh (2004) recommended that the conservation of various urban owl species necessitates the retention and protection of large areas of contiguous bushland. Similarly, Yeoman and MacNally (2005) concluded that patch size, rather than vegetation structure, influenced the avifauna of coastal moonah (*Melaleuca lanceolata*) woodlands in the Melbourne and Geelong regions of Victoria, although the density of urban development also appeared to affect bird species richness. Similarly, other studies have reported the influence of various combinations of multilevel habitat factors such as, patch size and area, spatial configuration, connectivity and isolation of patches, patch context and habitat heterogeneity and also, *in situ* vegetation structure and composition (e.g. Wood 1993; Cooper 1995; Catterall 2004; Recher 2004; Drinnan 2005). The relative influence of these factors, however, appears to vary between species. Bentley and Catterall (1997), for instance, found that both spatial and habitat characteristics influenced avian assemblages overall, although spatial characteristics such as fragmentation, isolation and the matrix were especially important for habitat-specialist species, whereas, migrant and habitat-generalist species were influenced more by site characteristics such as the structural complexity of vegetation (see also Wood 1993; Cooper 1995; Catterall 2004; Drinnan 2005; Tait *et al.* 2005).

The influence of interspecies interactions, associated with environmental variables, is also a contributing factor to species' distribution and abundance across urban areas. For example, Major *et al.* (1996) found that pied currawong (*Strepera graculina*) populations increased significantly as vegetation density decreased, which in turn increased their ability to predate the nests of willie wagtails (*Rhipidura leucophrys*), reducing the long-term local viability of willie wagtail populations in urban areas. Smith (2002) suggested that in Goode Beach, Western Australia, red wattlebirds (*Anthochaera carunculata*) became the dominant large honeyeater species in areas where vegetation structure and composition was suitable for their nesting requirements. This domination coupled with their inherent aggressive behaviour contributed to the disappearance of smaller-bodied bird species from the same areas. Catterall (2004) reported invasions of flocks of behaviourally aggressive noisy miners adjacent to moderately disturbed forest edges excluded smaller-bodied birds from these areas, despite the presence of suitable habitats for such species (see also Low 2002; Parsons & Major 2004).

The cumulative effect of species-specific responses to other species and environmental variables results in urban avifauna assemblages that differ significantly from non-urban and preurban assemblages. What is more, as urban areas are in a continual state of flux (habitat destruction, degradation and restoration), so too are the associated avian assemblages. As the time since development increases, avian assemblages tend to become more distinct from preurban and nonurban assemblages, yet more similar to those in other urban environments (Jones & Wieneke 2000; Chance & Walsh 2006). Studies of such long-term changes in Australian urban avifauna assemblages are less common in the literature, with notable exceptions occurring in Perth (e.g. Recher & Serventy 1991; Smith 2002; Recher 2004; Wood & Recher 2004), Adelaide (Tait *et al.* 2005) and Townsville (Jones & Wieneke 2000). Given the restricted number of studies with a long-term focus, coupled with the inherent differences between sites in terms of biophysical and climatic influences, it is unclear whether observed trends are consistent across different urban environments (Jones & Wieneke 2000). This lack of historical knowledge, coupled with species-specific responses to urban environmental change, makes it particularly problematic to predict changes in avifauna populations living within Australia's expanding urban environments.

Mammals

Native mammals, particularly medium-sized species, are widely considered in Australia to be the fauna group most detrimentally affected by habitat changes resulting from urbanization and associated secondary impacts such as introduced species predation, interspecies competition and mortality from vehicle collisions (How & Dell 1993; Tait *et al.* 2005). Very few mammal species become human commensals, with exceptions of exotic species, such as the house mouse (*Mus musculus*), rabbit (*Oryctolagus cuniculus*) and red fox (*Vulpes vulpes*), and the native brush-tail possum (*Trichosurus vulpecula*). To effectively conserve rich and viable urban mammal assemblages it is essential that species–habitat relationships are clearly understood for a range of species with different habitat requirements and dispersal abilities. To date, much of the research conducted on urban mammalian assemblages has examined various aspects of species' diet and behaviour (e.g. Markus & Hall 2004), with significantly fewer studies specifically investigating multilevel habitat relationships within the dynamic urban environment.

The most commonly studied mammal species are those that are easily observed and identified, as well as those that elicit an emotive public response. Accordingly, possum and glider species (e.g. Smith & Murray 2003; Goldingay & Sharpe 2004; Matthews *et al.* 2004), koalas *Phascolarctos cinereus* (e.g. Lunney *et al.* 2002; Dique *et al.* 2004; Ward & Close 2004; McAlpine *et al.* 2005) and, bandicoot species (e.g. Dufty 1994; Chambers & Dickman 2002; Banks 2004) are the most frequently studied Australian urban mammals. More cryptic, rare or survey intensive species, such as dunnarts (*Sminthopsis* spp.), antechinus (*Antechinus* spp.), native rodents (e.g. *Rattus fuscipes*, *Xeromys myoides*), and volant species (bats) have received significantly less research focus. This bias is a particular concern for many of Australia's native marsupials and rodents, which are often both behaviourally cryptic and unrecognized or disliked by the public.

Terrestrial mammal species and, to a lesser extent, gliding species, have a lower probability of survival in urban environments due to their limited locomotion and dispersal abilities which make them either unable or unwilling to traverse the urban matrix and transport networks between often highly fragmented and isolated remnant patches (Dickman & Doncaster 1987, 1989; How & Dell 1993; Goldingay & Sharpe 2004; Tait *et al.* 2005). Individuals dispersing between remnant vegetation patches face anthropogenic barriers such as walls, fences and roads, as well as increased risk of predation from exotic species (e.g. cats *Felis catus*, dogs *Canis familiaris*, red foxes *V. vulpes*) or collisions with vehicles (Andrews 1990; Smith & Smith 1990; Barratt 1997; Forman 1999; Lunney *et al.* 2002; Dique *et al.* 2003; Banks 2004).

As with avifauna, attaining a comprehensive understanding of the habitat relationships of mammal assemblages in urban areas is particularly challenging. This challenge stems from the diverse range of habitat and disturbance factors, operating at multiple ecological levels, which impact species' distribution, abundance, and species-specific responses to habitat change and predation pressures. How and Dell (2000), for example, suggested that mammals in general are most influenced by habitat fragmentation yet, McAlpine *et al.* (2005) concluded habitat loss is more important than habitat fragmentation and road density for koala populations living in semiurban landscapes of south-east Queensland, Australia. Within their home range, although, koalas prefer particular Eucalyptus species, especially those occurring on fertile soils (e.g. Smith & Smith 1990; Moore *et al.* 2004; Ward & Close 2004). Bandicoots, however, prefer spatially heterogenous and structurally complex habitats to support foraging and shelter requirements (e.g. Dufty 1994; Scott *et al.* 1999; Chambers & Dickman 2002). For northern brown bandicoots (*Isoodon macrourus*) living in Brisbane, Queensland, Australia, FitzGibbon *et al.* (submitted) showed the combined influence of patch-level characteristics such as patch size and, functional connectivity between patches at the landscape level were important. Functional connectivity was identified as the most important factor for conservation actions targeting bandicoot populations. For glider species living in Brisbane, however, it is recommended that mitigating the impacts of habitat loss and fragmentation at the landscape level is the highest management priority, followed by habitat condition and edge effects at the local level (Goldingay & Sharpe 2004).

Rhodes *et al.* (2006) have further demonstrated that the relative importance of environmental factors may also vary for individual species, depending on the level of observation. They found that habitat loss and fragmentation, connectivity, patch size, vegetation composition and road density all influenced urban koala population dynamics in Port Stephens Shire, New South Wales. However, at the site level, tree species composition was the primary factor, while the amount of habitat and its connectivity were important at the landscape level. Such knowledge has implications for targeting fauna management actions and determining the levels of government responsible for these actions (D. Lunney, pers. comm. 2005).

Determining effective management strategies for urban mammal populations is further complicated by the lack of knowledge regarding population trends over time. Very few studies have explicitly considered population trends and viability, while those that have tried to address this problem have been limited by the consistency of historical records (e.g. How & Dell 1993; van der Ree 2004; Tait *et al.* 2005). To achieve effective long-term conservation of mammals in urban areas, it is essential that urban researchers broaden their current focus to include multiple species; especially those currently underrepresented in the scientific literature, and determine the influence and relative importance of environmental variables across multiple ecological levels. These factors must also be examined within a temporal context in order to facilitate accurate predictions of population responses to ongoing urban development and associated environmental change.

Reptiles and amphibians

Reptiles and amphibians may be collectively referred to as herpetofauna, although the taxon exhibit significantly different responses to urbanization and associated environmental changes. Of the papers reviewed, 14% focused urban herpetofauna species, with reptile species examined more frequently than amphibians (Fig. 1a). This may be a consequence of more reptile species (than amphibians) being easily observed in urban landscapes, the cryptic nature of many amphibians and, the concomitant difficulties associated with amphibian surveys (Hazell 2003). At present, there are major knowledge gaps in the understanding of the habitat requirements of both reptile and, particularly, amphibian populations within urban environments. For instance, it is apparent that certain herpetofauna species are able to adapt to urban environments, while others are restricted to remnant vegetation patches or disappear locally. However, this pattern of persistence and loss appears to vary regionally between urban environments. Large reptile species, particularly snakes, have been repeatedly reported as the most detrimentally impacted reptile species in both Perth and Sydney (e.g. How & Dell 1994, 2000; Cooper 1995). Yet, Fearn *et al.* (2001) documented the abundance of carpet pythons (*Morelia spilota*) in highly disturbed urban areas, reporting on the removal of 258 'nuisance' pythons from Brisbane and Ipswich (Queensland) over a 6-year period. Both reptile and amphibian assemblages in Sydney have experienced losses of reptile species since European settlement (White & Burgin 2004), yet Tait *et al.* (2005) reported only reptile, not amphibian, species have declined in Adelaide despite significant and widespread habitat alterations and water quality degradation.

As with birds and mammals, there is a paucity of information regarding the relative importance of habitat factors operating at multiple ecological levels for herpetofauna assemblages. It appears that the relative importance of habitat factors varies between reptiles and amphibians, as well as between species of each group (e.g. How & Dell 2000; Anderson & Burgin 2002; Jellinek *et al.* 2004). For example, according to Jellinek *et al.* (2004) lizards were influenced more by *in situ* vegetation structure and composition rather than patch size (except for one species). Whereas Drinnan (2005) found patch size was especially influential for amphibian species. White and Burgin (2004), however, suggest that frogs are impacted primarily by changes in water cycling and quality. Drinnan (2005) further suggested that habitat thresholds existed for amphibian species, with threatened and urban-sensitive species requiring significantly larger habitat patches (>50 ha) for survival than matrix-sensitive species that occupied much smaller patches (approx. 4 ha).

The current knowledge base clearly lacks a sound grasp of the relative importance of habitat factors measured at a range of ecological levels and the presence of critical habitat retention thresholds for individual reptile and amphibian species and assemblages. There is also a need to specifically examine and compare temporal variations in herpetofauna assemblages within and among urban environments across Australia (How 1998). Management actions based on the current limited knowledge base may fail to address critical environmental factors and so fall short in achieving their long-term conservation outcomes. Clearly, much more research is required to better understand both reptile and amphibian population dynamics in urban areas and how these dynamics vary across multiple ecological levels.

Invertebrates

Invertebrates are recognized by the scientific community as being the largest and most diverse fauna group, referred to as 'the other 99%' (Ponder & Lunney 1999; Stanisic 2005). However, they are one of the least understood groups, both in non-urban and urban landscapes. Because invertebrates play a significant role in the functioning of ecosystems as decomposers, parasites, pollinators and prey for many higher order species (Bhullar & Majer 2000), it is essential that the impacts of urbanization on invertebrates are explicitly understood. A synthesis of current research knowledge shows that both small and large remnant vegetation patches (Gibb & Hochuli 2002; Clark 2004; Hochuli *et al.* 2004), vegetation diversity (Emery & Emery 2004; Burwell & Grimbacher 2005), and habitat condition (Gibb & Hochuli 2002; New & Sands 2002; Dover & Rowlingson 2005) are critical factors for invertebrate conservation. Other factors important for individual species include: altered fire regimes (Gibb & Hochuli 2002; New & Sands 2002; Dover & Rowlingson 2005) and interspecies interactions (Hochuli *et al.* 2004; Burwell & Grimbacher 2005; Dover & Rowlingson 2005). Hochuli *et al.* (2004), for example, documented that invertebrate herbivore composition varied with remnant patch size, with abundance increasing in smaller patches because of a lower density of predatory and parasitic species that are sensitive to habitat fragmentation. This interaction, in turn, resulted in smaller native vegetation patches, in general, experiencing increased insect herbivory compared with large patches where predatory and parasitic species act to maintain herbivorous insect populations at a sustainable level. The resulting loss of habitat condition is likely to have further implications for the compositions of higher order species such as birds, mammals and reptiles that are particularly sensitive to changes in habitat condition.

As for other fauna groups, the impacts of urbanization on invertebrate communities are highly species-specific. For example, New and Sands (2002) recommended that the conservation of urban butterfly species required improving the condition of degraded urban habitats, specifically by addressing weed and fire issues. Dover and Rowlingson (2005), conversely, reported that improving habitat condition would negatively influence the already threatened western jewel butterfly (*Hypochrysops halyaetus*), as this species appeared to prefer degraded habitats, particularly those degraded by fires. Subsequently, it was suggested that this particular butterfly species may benefit from urbanization, and the commonly associated degraded habitats, as long as the species' mutual ant partner is also present (Dover & Rowlingson 2005). Similar interspecies interactions have been observed for other invertebrates, although this is sometimes due to species exclusion rather than species mutualism. Heterick *et al.* (2000), for example, concluded that the composition of native ant species in suburban Perth gardens varied inversely to the presence of exotic ant species, with few native species able to coexist in gardens dominated by introduced ant populations. Burwell and Grimbacher (2005) reported similar impacts on native ant assemblages at one site in Brisbane as the result of habitat domination by the introduced coastal brown ant (*Pheidole megacephala*).

Temporal variations in invertebrate assemblages have received significantly less examination, although Bhullar and Majer (2000) reported that older, native (especially locally endemic) trees lining Perth's streets hosted both increased abundance and diversity of arthropod species, compared with recently planted native and exotic species. However, the underlying mechanisms driving these variable arthropod responses remain unclear. Such knowledge has important implications for local government management decisions, especially considering the flow-on effect of invertebrate presence influencing invertebrate predators at higher trophic levels. None of the other invertebrate studies reviewed considered temporal dimensions and so the influence of time on invertebrate species dynamics remains unclear.

It is obvious that immediate attention must be paid to both investigating and comprehending the impacts of urbanization on insect communities and, the concomitant interspecies relationships and invertebrate impacts on the condition of remnant patches and the population dynamics of other invertebrate and vertebrate species. By understanding such relationships, urban planners and conservation managers will be better able to make conservation decisions that target and benefit a range of species and species groups.

Aquatic

Aquatic ecosystems and assemblages are often overlooked in urban ecology studies in favour of the more dominant terrestrial systems, despite the overall concession by researchers that aquatic ecosystems are undeniably impacted by urbanization. Aquatic fauna have been shown to be particularly sensitive to: altered environmental flows, increased water pollution, turbidity and sediment levels, exotic species introductions, altered vegetation presence and composition (e.g. sea grasses and mangroves) and, built structures such as piers, harbours and dams (e.g. Hough 1995; Dow & Dewalle 2000; Gibbs 2004).

Similar to their terrestrial counterparts, certain urban aquatic species are able to adapt and persist in the modified environments better than others. Gibbs (2004), for instance, concluded that many fish species were able to utilize significantly modified urban estuarine habitats, provided other factors such as water flow, are effectively managed. Comparatively, Newall and Walsh (2005) reported that the built environment, particularly urban storm water drain designs, had significant negative impacts on diatom assemblages. Walsh *et al.* (2004) reported similar influences of urban development and storm water drainage connections, on the distribution of an already threatened stream-dwelling amphipod (*Austrogammarus australia*). Walsh *et al.* (2004) further commented on the role of sealed roads in urban areas in degrading amphipod habitat (water quality) by altering storm water run-off and transporting urban pollutants into waterways. Yerman and Ross (2004) examined the influence of different landscape types and uses on the composition of mangrove macrofauna communities in Sydney, concluding that mangrove forests adjacent to natural saltmarshes support higher macrofauna diversity than do mangroves situated next to man-made parks or bund walls.

The limited number of studies on aquatic fauna–habitat relationships (Fig. 1a) highlights a paucity of information on aquatic ecosystems. The current knowledge base provides limited, often suppositional, insights into urbanization impacts on aquatic habitats and the associated responses of their fauna inhabitants. An important initial step for addressing this issue is to alter the way in which urban researchers, public members and urban managers, alike, view aquatic ecosystems and fauna. There is a need to integrate them into the urban ecosystems/fauna viewpoint, rather than treating them as a separate entity.

PRINCIPLES

Urbanization and its impacts on fauna populations must be closely examined and understood before urban planners and managers can hope to successfully achieve long-term conservation goals in urban areas. Currently, Australia's conservation actions often fall short of their intended long-term goals due to decision-making processes that are ill-informed by sound scientific research. There are numerous gaps in Australia's urban ecology knowledge base, with certain groups and species being considerably less understood than others. To address these issues we suggest the following five guiding principles when designing and conducting research into the ecology of Australia's urban fauna. By doing so, future research in this field will produce a more comprehensive knowledge foundation upon which to base conservation and management decisions and thereby help urban planners and managers make better decisions.

Principle 1

Urban ecology studies need to adopt a hierarchical landscape approach that explicitly considers the structure of the urban landscape and the influence of the quality and quantity of habitat elements that constitute that landscape.

The urban environment is a complex mosaic of landscape elements dominated by the built environment and interspersed with remnants of natural ecosystems and open space. Remnant ecosystem patches provide habitat for many native fauna species, and vary with respect to shape, size, condition, connectivity/isolation and disturbance regime. Urban landscapes are in a continual, and often rapid, state of flux as a result of human land use pressures. Accordingly, urban fauna populations that inhabit these landscapes are dynamic, and sensitive to changing environmental conditions. Of the research papers reviewed, 49% focused on the impact of environmental factors operating at a single ecological level, multilevel studies were examined in 32% of cases, and the remaining 19% were aspatial (Fig. 1b). Of the single-level studies, more than half (65%) were conducted at the local level (Fig. 1b). This bias limits our ability to determine the ecological level that most influences populations, which in turn limits our ability to make recommendations about priority and cost-effective actions for conservation.

Increasingly, urban researchers are demonstrating that urban fauna respond to a combination of habitat variables occurring at multiple ecological levels (e.g. How & Dell 1993; Grover & Slater 1994; Gibb & Hochuli 2002; Rowston *et al.* 2002; Catterall 2004; McAlpine *et al.* 2005). Consequently, studies conducted at a single ecological level (e.g. Dufty 1994; Fitzsimons *et al.* 2003; Hochuli *et al.* 2004; Yerman & Ross 2004) can explain only part of the overall impact of urbanization and may indeed obscure or exaggerate regional declines that are now occurring for many species (Wiens 1994; Hobbs 1999). This does not mean that single-level habitat attributes are unimportant, rather that it is necessary to consider the structure of the whole landscape and the inherent hierarchy of habitat influences when predicting the effects of urbanization on native biota and choosing conservation actions (McGarigal & McComb 1995; Hokit *et al.* 1999; Dorner *et al.* 2002; McAlpine & Eyre 2002). Studies should also recognize that the perceived permeability of the urban matrix differs between species and is not always considered unsuitable (Opdam *et al.* 2003). Studies that classify urban landscapes as binary (i.e. suitable habitat or unsuitable habitat) risk misinterpreting the influence of urban landscape structure on species occurrence and abundance, and their interactions with other organisms. It is imperative that urban ecology researchers adopt a spatially explicit approach that specifically considers the scale of movement of the target species, and how it perceives and utilizes the dynamic habitat heterogeneity of urban landscapes (Pearson *et al.* 1996; White *et al.* 1999; Hostetler & Holling 2000; Debinski *et al.* 2001; McAlpine *et al.* 2002).

Principle 2

Urban fauna studies should explicitly test *a priori* predictions of the relative importance of habitat amount, configuration and condition, the presence of critical habitat retention thresholds, and the interaction between these factors.

Critical issues for many Australian local government agencies responsible for urban biodiversity conservation are: how much habitat is enough to sustain viable fauna populations? how should this habitat be spatially arranged in the landscape? and what is the relative importance of habitat amount, configuration and condition? These questions are important for prioritizing investment in the conservation and restoration of urban biodiversity. Therefore, understanding the relative importance of these factors for various fauna species (terrestrial and aquatic, vertebrate and invertebrate) is essential for informing the decision-making process and investment prioritization. For example, in Brisbane City, a common dilemma for local government urban planners and conservation managers is whether to focus efforts and resources on restoring the quality of habitats (condition), or on increasing the area of habitat and its connectivity (S. McLean, pers. comm. 2004). This decision is often specific to a particular species, assemblage or landscape/ecosystem in a particular region. If a landscape has experienced extensive habitat loss, and the remaining habitat is below a critical threshold, then increasing the amount of habitat and its connectivity may deliver the greatest conservation outcome. Conversely, if the remaining habitat within the urban landscape is above a critical threshold and is located in a few large patches, then managing habitat quality for species may prove more beneficial for achieving long-term conservation goals. These management issues are further complicated in urban landscapes by the effect of roads, human disturbance pressures (e.g. vandalism, high fire frequencies) and the high density of exotic predator species.

Improving the effectiveness of urban conservation strategies therefore is reliant on being able to prioritize the importance of the amount of habitat, its configuration and condition, while minimizing the negative impacts of roads, predators and human activity. The hypothetical curve depicted in Fig. 2 represents how knowledge about the relative importance of environmental variables could be used to assist the decision-making process prioritizing conservation actions and investments to ensure effective biodiversity outcomes. The effectiveness of such investments firstly depends on urban researchers explicitly testing the relative importance of, and interactions between, these critical habitat factors.

Principle 3

Urban ecology studies need to consider the responses of multiple species to urban habitat conditions and dynamics.

Current urban biodiversity management decisions are too often based on recommendations accrued from studies of a single species or a small group of species. However, species have varying habitat requirements and sensitivities to urban landscape change (Table 1). A single/few species approach therefore is limited in its ability to conserve the full complement of species in the landscape. If maintaining species diversity is the ultimate goal, then landscapes should not be planned and managed based on the requirements of a single or limited selection of species. Often research resources are only available to survey a single species or taxa (e.g. birds). The findings of these studies need to be integrated with similar designed studies in order to develop an integrated, multispecies approach to urban biodiversity conservation and restoration.

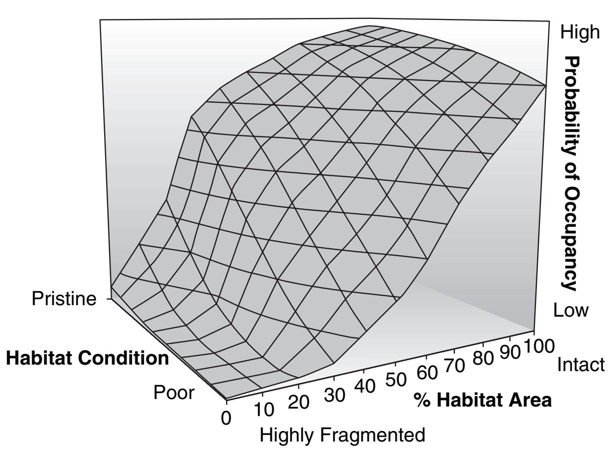

Fig. 2. Hypothetical curve of the relationships between habitat area, habitat condition (quality) and the probability of a species being present.

An alternative approach considers multiple species ecological 'profiles' that classify a range of different species based on similarities in their responses to landscape structure and change (Opdam *et al.* 2002). The development of comprehensive ecological profiles is a major, yet necessary, challenge that will facilitate urban planning and conservation management decisions that effectively target the habitat requirements of several species and taxa, rather than those specific to a single species or taxa. Such an approach is complicated but particularly pertinent in urban areas because of fauna population fluctuations in response to the extreme, dynamic and continually changing urban environment.

Principle 4

Urban ecological studies need to consider the temporal dimension as well as the spatial dimension of urban landscapes.

Urban landscapes have a temporal as well as a spatial component (*sensu* Marucci 2000) Following clearing or other major disturbances, the remaining habitats often experience decline in condition to a state of lower habitat quality. The response of fauna populations may also occur over long time periods, with certain species exhibiting a time lag of decades or centuries in their responses (Tilman *et al.* 1994; Hanski 1998; Possingham & Field 2001; Tait *et al.* 2005). In Australia's urban landscapes, it is particularly important to study the long-term dynamics of fauna populations in order to predict long-term population responses to urban developments and plan to mitigate the impacts of associated habitat alterations and secondary pressures. For example, many Australian bird and mammal species are long-lived and consequently, non-viable populations may persist for many years in the urban landscape before suddenly disappearing. Yet, very few of the studies reviewed explicitly considered the temporal aspect. Static studies cannot determine population viability and may mistakenly consider a population as being viable. As a consequence, valuable conservation resources may be invested inappropriately. Further, changes in species compositions and distributions across urban habitats, in response to urban land use changes, may also be more accurately predicted using temporal patterns. Jones and Wieneke (2000), for example, demonstrate distinct compositional and distributional shifts in Townsville bird communities over a 16-years period in response to habitat succession and modification, such as transitions from open grassy areas, to recently vegetated areas, to well-established areas, and vice versa.

Understanding the mechanisms by which species to respond to given disturbances is important for predicting the long-term outcome for urban fauna populations. Incorporating a temporal dimension in urban ecology research will help produce information that will enable urban planners and managers to make effective decisions regarding the impact of prospective development actions on the long-term viability of urban fauna populations.

Principle 5

Urban ecological research must be effectively communicated to urban planners and conservation managers so that recommendations are adopted and integrated into urban planning, management, conservation and restoration strategies.

Within Australia, urban conservation goals are limited by a lack of collaborative research and management (*sensu* Underwood 1995; Liu & Taylor 2002). In order to preserve urban biodiversity, planners, managers and developers must be equipped with appropriate scientific knowledge on which to base sound conservation decisions and actions. Such decisions are often resource (time and money) limited. A critical goal for researchers is to provide 'decision tools' and planning guidelines that facilitate the prioritization of conservation actions as well as the identification of cost efficient management alternatives. Furthermore, urban ecology researchers should aim to address priority issues for urban managers and planners and take the responsibility for clearly communicating their findings and recommendations in a format that is easily understood by decision makers. In addition, when the multiple-use of habitats is mandated, the successful preservation and restoration of urban habitats for biodiversity conservation rely on a cooperative, multidisciplinary approach (Johnson 1995). As such, researchers are further encouraged to instigate collaborative projects that incorporate a variety of disciplines (e.g. sociology, ecotourism) and key stakeholders (e.g. landholders, politicians, architects and developers) (e.g. Niemelä 1999a; Collins *et al*. 2000; Grimm *et al*. 2000; Musacchio & Wu 2004). Doing so will promote the integration of scientific recommendations into decision-making processes and subsequent panning management, conservation and restorations strategies.

CONCLUSIONS

The process of urbanization causes significant and ongoing alterations to natural landscape compositions and ecosystem processes. It is axiomatic that such habitat alterations impact the composite fauna communities and inhibit long-term persistence. Ironically, it seems the inherent dynamic nature of cities creates and maintains a complex mosaic of habitat niches, many of which are unique to urban areas, which in turn support a high diversity of fauna species, including rare and threatened species (Niemelä 1999a,b). The future conservation of Australia's urban fauna depends heavily on collaborative research projects that integrate multiple ecological levels of habitat influence and multiple species, as well as temporal variation, in investigating the relationships existing between urban environments and their resident fauna populations. The principles outlined in this paper provide the scientific basis for designing urban fauna studies to address the right questions and help meet the information needs of urban planners and conservation mangers. Without such knowledge, poorly targeted urban fauna conservation actions will continue and populations will decline further under increasing development and disturbance pressures, resulting in a reduced quality of life for all city dwellers.

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