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Quantifying taxon-specific habitat connectivity requirements of urban wildlife using structured expert judgement

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ABSTRACT

Urban planning which enhances native biodiversity in and around cities is needed to address the impacts of urbanisation and conserve urban biodiversity. The “Biodiversity Sensitive Urban Design” (BSUD) framework incorporates ecological knowledge into urban planning to achieve positive biodiversity outcomes through improved urban design and infrastructure development. BSUD includes principles to direct strategic design and placement of connected wildlife habitat. However, effective BSUD implementation requires defining and quantifying the landscape-scale habitat connectivity needs of a range of taxon groups within urban contexts. The aim of our study was to use expert elicitation to address these gaps in landscape-scale habitat connectivity currently limiting the capacity of urban planning. We estimated habitat connectivity needs for seven representative taxon groups in urban environments, including ideal habitat, habitat constraints, barriers to movement, and movement thresholds that determine habitat connectivity. In using expert elicitation to quantify habitat connectivity requirements for urban biodiversity, our study provides insights on both the usefulness of expert elicitation to inform urban habitat connectivity planning generally, and the functional habitat connectivity requirements of our focal taxon groups specifically. Overall, we consider our expert-derived estimates of connected habitat to be a highly useful set of baseline data for habitat and connectivity modelling and urban planning for a range of taxon groups.

1. Introduction

Urbanisation threatens biodiversity through habitat loss and fragmentation, and the modification of resource availability, disturbance regimes, local climate, and species assemblages within what habitat remains (McKinney, 2008; McDonald et al., 2008, 2020; Seto et al., 2012; Garrard et al., 2018; Selinske et al., 2022). However, the urban environment is important for biodiversity conservation, with many native species (including rare and threatened species) having population strongholds (Maclagan et al., 2018) or persisting entirely within urban landscapes (Ives et al., 2016; Garrard et al., 2018; Soanes and Lentini, 2019). Urban planning which aims to minimise the impacts of urbanisation and enhance native biodiversity in and around cities is therefore urgently needed (Garrard et al., 2018; Scheele et al., 2018; Huang et al., 2018). ‘Biodiversity Sensitive Urban Design’ (BSUD) presents a framework for better incorporating ecological knowledge into urban planning to promote biodiversity and mitigate the impacts of urbanisation through improved urban design and infrastructure development (Garrard et al., 2018).

The BSUD framework sets out five principles: (1) maintain and introduce habitat, (2) facilitate dispersal, (3) minimise threats and anthropogenic disturbances, (4) facilitate natural ecological processes, and (5) improve potential for positive human–nature interactions (Garrard et al., 2018). The first two principles of BSUD intend, among other things, to direct more strategic design and placement of connected wildlife habitat in urban landscapes (Garrard et al., 2018). However, Kirk et al. (2018) identified two key factors that currently limit the capacity of urban design to achieve habitat connectivity outcomes: (1) the assumption that connected habitat defined by structural elements (e.g., patch dimensions, vegetation composition, and spatial continuity) provides appropriately for target wildlife in the absence of defining functional constraints (e.g., physical, physiological, or behavioural barriers to successful use, movement, or dispersal), and (2) a lack of empirical information to describe taxon-specific ideal habitat requirements and constraints at the relevant spatial scale to inform evidence-based urban design for target wildlife.

Addressing these limitations to effective BSUD implementation requires defining and quantifying the landscape-scale connectivity requirements for a range of taxon groups within urban contexts. The ‘City Biodiversity Index’ – a Convention on Biological Diversity endorsed tool to monitor urban biodiversity – measures ecological connectivity as the relationship between the total area of habitat available and the degree to which it is functionally (dis)connected, either by distance (e.g., small birds will be unable to disperse where distance between tree cover exceeds their movement capacity (Tremblay, and St. Clair, C.C., 2009)) or by physical or behavioural barriers to movement (Chan et al., 2014; Deslauriers et al., 2018; Kirk et al., 2018, 2023). While recent studies have highlighted the value of using this approach for spatially mapping and measuring habitat connectivity in BSUD (e.g., Kirk et al., 2018, 2021), the input data often remains coarse in terms of what constitutes habitat (e.g., presence of trees only without consideration of preferred spacing and composition), and taxon-specific movement thresholds and movement barriers (Kirk et al., 2023). Applying BSUD to achieve ecological connectivity outcomes requires a greater taxon-specific understanding of what constitutes functional connected habitat to underpin these connectivity maps, models, and measures.

Robust empirical data on the functional connectivity requirements of most species within urban environments are preferable, however are severely lacking when imminent decisions are required (Burgman, 2016). Expert judgement is increasingly used to inform decisions where empirical data are insufficient or unobtainable due to funding limitations for systematic ecological surveys and monitoring (Legge et al., 2018). A range of methods have been developed to minimise inherent bias and uncertainty, and to account for wide variances in knowledge (Martin et al., 2012). One such method is the ‘IDEA’ protocol (standing for ‘Investigate’, ‘Discuss’, ‘Estimate’, and ‘Aggregate’) which is a structured elicitation approach designed to improve the accuracy and quantitative rigor of expert judgements (Hanea et al., 2017; Hemming et al., 2018). The IDEA protocol is routinely used in government policy settings (e.g., forecasting changes in biosecurity risk (Wittmann et al., 2015)) and in ecological and conservation contexts (e.g., Geyle et al., 2021; Camac et al., 2021). However, to our knowledge, this form of structured expert elicitation has not yet been used to address data gaps in taxon-specific habitat connectivity requirements in urban environments.

The aim of our study was to use the IDEA protocol of expert elicitation to address gaps in landscape-scale habitat connectivity data which limit the capacity of urban planning to adopt the BSUD principles of “maintain and introduce habitat” and “facilitate dispersal”. We used the city of Canberra in the Australian Capital Territory (ACT) as a case study to quantify habitat connectivity needs for seven taxon groups—invertebrate and vertebrate species spanning terrestrial, arboreal, aquatic, and aerial habitats— of representative fauna present in that urban environment. Taxon-specific experts quantitatively estimated ideal habitat, habitat constraints, barriers to movement, and movement thresholds that determine habitat connectivity. In using expert elicitation to quantify habitat connectivity requirements for urban biodiversity, our study provides insights on both the usefulness of the IDEA protocol to inform urban habitat connectivity planning generally, and the functional habitat connectivity requirements of our focal taxon groups specifically.

2. Methods

All procedures were performed in compliance with relevant laws and ACT Government guidelines including the ACT Public Service Values and workplace health, safety and wellbeing, and compliance requirements of the Territory Records Act 2002 and Public Sector Management Act 1994. Prior and informed consent of all experts was obtained and adhered to confidentiality requirements, with privacy rights of all participants observed.

2.1. Study area

Our study was conducted for Canberra, ACT, an inland city in temperate south-eastern Australia. Canberra has a population of 455,900 which has been growing at a rate of 2.3 % per year since 2011, faster than any other Australian city during that time (Alexandra et al., 2017; Alexandra and Norman, 2020; ABS, 2022). While the total urban area of Canberra is approximately 800 km^2, the developed urbanised footprint is only around half of this, with the remaining area consisting of urban green spaces and an extensive urban reserve network of remnant native vegetation (ACT Government, 2018). As a result, the city is colloquially known as the 'Bush Capital' and has the second lowest population density of any major Australian city (~1000 people per km^2 (ACT Government, 2018; ABS, 2022)). Canberra population densities are already increasing under a planning strategy that seeks to limit urban spread through prioritising development within the existing urban footprint, however new urban growth areas are also being established (ACT Government, 2018). The planning strategy seeks to grow Canberra in a way that protects and maintains the biodiversity values of the city.

Canberra is built in an area of the ecologically diverse Southern Tablelands region west of the Great Dividing Range that was once dominated by box-gum grassy woodlands and natural temperate grasslands. The Ngunnawal people are the Traditional Custodians of the land and waters of the ACT, and for tens of thousands of years actively manipulated the woodlands, grasslands, and waterways in the region, shaping the structure and function of these ecosystems. Some large intact remnants of critically endangered woodland and grassland remain in and around Canberra, but most have been substantially modified by land clearing, urbanisation, livestock grazing, invasion by weeds and feral animals, and the loss of Indigenous management following European colonisation. Many natural creeks, tributaries and associated riparian vegetation that were present throughout Canberra are now highly modified, with most of these areas now existing as concreted drains with reduced biodiversity and species abundance (Gomes and Wai, 2020). Urbanisation presents an ongoing threat to the extent, condition, and connectedness of these ecosystems in the region, and greater understanding of the habitat connectivity needs of the native wildlife that rely on these areas within the city is crucial for sustainable urban policy, planning, and management (Ikin et al., 2015; Rayner et al., 2015; Hale et al., 2015).

2.2. Selection of representative taxon groups

We selected seven taxon groups for which to quantify the landscape-scale habitat connectivity requirements of fauna within urban Canberra. We decided to use a taxon group approach which considers species that have relative ecological similarities and share broad dispersal abilities and habitat requirements (as opposed to an individual species approach) (e.g., Kirk et al., 2018). We included seven taxon groups to best capture the breadth of ecosystem associations, habitat needs, and movement abilities of most fauna in urban Canberra, particularly ACT threatened species. These groups of species were: (1) grassland reptiles, (2) native bees, (3) small–medium terrestrial mammals (hereafter small–medium mammals), (4) small woodland birds (hereafter woodland birds), (5) riparian reptiles and mammals, (6) amphibians, and (7) small freshwater fish (see Table 1 for taxon group definitions, justification, and final list of species considered). While there are other taxon groups that could have been considered (e.g., arboreal mammals, water birds, tree-hollow using fauna, soil-dwelling fauna), we considered the selected fauna as broadly informative for taxa not explicitly assessed. For example, we selected four taxon groups that are associated with box-gum grassy woodlands that vary widely in their dispersal capacity and specific habitat requirements (i.e., native bees, small–medium mammals, woodland birds, and amphibians), presuming that these adequately captured the variability in connected habitat needed for other non-assessed woodland-associated species (e.g., native bees broadly represent other insect pollinators). Three taxon groups were associated with natural temperate grasslands (i.e., grassland reptiles, native bees, and amphibians), and three taxon groups were associated with aquatic zones and riparian vegetation (i.e., riparian reptiles and mammals, amphibians, and small freshwater fish).

We refined our considered species within each taxon group to a final agreed list prior to quantifying their habitat connectivity requirements (Table 1). Initial broad species lists for each taxon group were established based on existing systematic lists relevant to the ACT (e.g., small woodland birds as identified by Fraser et al., 2019; amphibians as identified by Westgate et al., 2015; all other groups as described on the citizen-science platform Canberra Nature Map https://canberra.naturemapr.org/). During expert elicitation workshops, we then discussed the relative value of including or excluding particular species from each taxon group for our assessment. Native species were included where they were considered strongly representative of the group in urban areas and were (a) common but potentially threatened by increased urbanisation, (b) present but listed as vulnerable in the ACT, (c) established following translocation to the ACT, or (d) absent or rare in the ACT urban areas but could potentially re-establish in the future (e.g., through reintroductions or assisted migration; Buckmaster et al., 2010). Species were excluded if they were considered not representative of the group because of (a) unique habitat requirements or dispersal capacities, (b) having a natural or predicted distribution which did not include the urban extent of the ACT, (c) requiring direct management interventions for persistence, or (d) were absent or rare in the ACT with re-establishment deemed extremely unlikely.

2.3. Selection of habitat connectivity metrics

The most robust measures of functional connectivity (e.g., effective mesh size for City Biodiversity Index, see Deslauriers et al., 2018) quantify the potential of a given landscape to provide unfragmented or unobstructed habitat for particular wildlife by spatially mapping habitat and barriers to movement (Deslauriers et al., 2018; Kirk et al., 2023). To be informative for such measures, metrics that define taxon-specific habitat connectivity need to be both ecologically meaningful and translate into spatial data layers that are location-specific and readily available (Kirk et al., 2023). These restrictions mean some ecologically meaningful metrics that are not readily spatialised, such as noise pollution, are not considered here. We selected 30 metrics to represent landscape-scale, functional habitat connectivity for our seven taxon groups (Table 2) that were ecologically important (Doerr et al., 2010, 2014) and had the potential to align with spatial data inputs to underpin robust measures of functional connectivity (Kirk et al., 2018, 2023). They included metrics that represented (1) ideal habitat requirements ($n = 8$), (2) habitat constraints ($n = 13$), (3) barriers to movement ($n = 6$), and (4) movement thresholds ($n = 3$).

We selected eight ideal habitat requirement metrics to define elements of the physical environment that can promote or inhibit the presence of a taxon group (e.g., preferred distance between mature trees, maximum tolerable distance from a permanent waterbody, etc.). While not included explicitly in previous connectivity indices (see Chan

Table 1
Definition, species list, and justification (reasons for inclusion) for the seven taxon groups assessed for connected habitat requirements through expert elicitation in Canberra, Australian Capital Territory (ACT). Bolded species are either #endangered or critically endangered, †vulnerable, ‡regionally conservation dependant, ^locally rare, or *absent from the ACT lowlands but may occur in the future via assisted or unassisted means. Species scientific names can be found in Supplementary Material.

Taxon group and definition	Species considered	Justification
Grassland reptiles: reptile species that have a strong association to grasslands.	Blue-tongued lizard Eastern brown snake **Grassland earless dragon#** **Pink-tailed worm-lizard†** **Striped legless lizard†** Three-toed skink	We considered here characteristic grassland species (predominantly grassland specialists), using them as a surrogate group to ensure 'Natural Temperate Grassland' structure and functionality was protected within the urban extent.
Native Bees: all native species of the clade Anthophila (Order Hymenoptera).	All native bee species occurring within the ACT (approximately 150 species).	Native bees are major pollinators within the urban extent and so were considered broadly representative of other insect pollinating orders (Hymenoptera, Diptera, Lepidoptera, Coleoptera).
Small–medium terrestrial mammals: mammals within the critical weight range (35–5500 g) that are predominantly terrestrial (excluding arboreal mammals such as possums, and volant mammals including bats).	Agile antechinus **Brush-tailed phascogale*** Bush rat Common dunnart **Eastern bettong‡*** Eastern chestnut mouse Long-nosed bandicoot **New Holland mouse†** Short-beaked echidna **Southern brown bandicoot#*** Yellow-footed antechinus	Species considered within this group were currently present (but may be absent from urban areas, e.g., Buckmaster et al., 2010) or likely to occur within the urban extent of the ACT (e.g., [eastern] southern brown bandicoot; eastern bettong; and brush-tailed phascogale). Spotted-tailed and eastern quolls were considered likely to benefit from similar habitat conditions but were not considered in the expert elicitation.
Small woodland birds: smaller bird species (<40 g) of the ecologically and functionally identifiable Temperate South-eastern Mainland Australia ecoregion sub-community of the *Australian Temperate and Subtropical Woodland Bird Community* (Fraser et al., 2019).	Brown-headed Honeyeater Brown Treecreeper† Buff-rumped Thornbill Diamond Firetail Eastern Yellow Robin Fuscous Honeyeater Grey Fantail Leaden Flycatcher Mistletoebird Painted Button-Quail Rufous Whistler Scarlet Robin† Southern Whiteface Speckled Warbler Striated Pardalote Striated Thornbill Superb Fairy-Wren Tree Martin Weebill White-browed Scrubwren White-throated Gerygone Yellow-rumped Thornbill	Smaller species in the broader woodland bird community are most vulnerable to the threatening processes of the urban landscape (e.g., harassment by noisy miners, simplification of woodland structure). We included species that were increasing and declining, using different parts of the woodland forest column, were woodland-dependent, and already occurring the urban extent of the ACT.
Riparian reptiles and mammals: semi-aquatic species which have specific riparian or aquatic habitat requirements.	Eastern long-necked turtle Eastern water dragon Gippsland water dragon Platypus Rakali Red-bellied black snake Tiger snake	Reptile and mammal species considered within this group were currently present within the urban areas of the ACT and had specific riparian or aquatic habitat requirements for population persistence.
Amphibians: any native frog, froglet, or toadlet.	**Bibron's toadlet*** Broad-palmed rocket frog Common eastern froglet Eastern banjo frog Eastern sign-bearing froglet **Green and golden bell frog †*** Stony Creek frog Peron's tree frog Smooth toadlet Spotted marsh frog Striped marsh frog **Sudell's frog^** Verreaux's tree frog	Species in this taxon group included those currently occurring within or near urban areas within the ACT using data generated from the citizen-science Frogwatch ACT and Region Program (Westgate et al., 2015). Species which were considered candidates for reintroduction to the urban area were also included.
Small freshwater fish: freshwater fish with <10 cm total length or fork length.	Australian smelt **Bald carp gudgeon*** Flathead gudgeon Mountain galaxias **Southern pygmy perch*** Western carp gudgeon	Experts considered aquatic habitat within the urban extent of the ACT to only be suitable for small species, rather than larger species (e.g., Murray cod). As a result, the species list includes smaller species found in small stream environments, and species which transit between lake and large river core habitat. Two species, bald carp gudgeon (*Hypseleotris* sp.) and southern pygmy perch (*Nannoperca australis*), were included as potential candidates for introduction to the ACT.

et al., 2014; Deslauriers et al., 2018; Kirk et al., 2023) we also included 13 habitat metrics which constrained the spatial area, vegetation composition, or physical environment of available habitat. We did this to better estimate minimum spatial habitat requirements, environmental tolerances, and what experts deem to be unsuitable habitat (e.g., the preference of grassland reptiles for native species dominance in ground-layer vegetation; Antos and Williams, 2015). We selected the six metrics reflecting barriers to movement to define where capacity to disperse between patches would be disrupted (i.e., reduce the movement threshold of a taxon group, e.g., maximum crossable extent of paved surface, tolerable traffic flow during active periods, maximum crossable height of vertical structure; Merkens et al., 2023; Table 2). We selected three movement thresholds to define typical movement capacity in the absence of barriers to understand where distance to the next patch of suitable habitat itself became the barrier to movement.

Not all metrics were relevant for all taxon groups (confirmed through expert elicitation, e.g., minimum water depth of core habitat was only relevant for aquatic associated taxon groups). We assessed functional connectivity using a minimum of 16 metrics (applicable to woodland birds; where none of our barriers to movement metrics were relevant due to the ability of these species to fly) and a maximum of 27 metrics (applicable to riparian reptiles and mammals; where terrestrial and aquatic habitat use meant almost all metrics were relevant) (see Table 2 for full details). Where metrics were considered only relevant for some but not all species within a taxon group (e.g., not all small woodland birds require specific ground-layer vegetation conditions), the metric was retained to capture the needs of more specialised (and therefore at-

Table 2
List of ideal habitat requirements, barriers, habitat constraints and movement threshold metrics, their description, and whether they were assessed for each of the seven taxon groups ("GR" grassland reptiles; "NB" native bees; "SM" small-medium mammals; "WB" woodland birds; "RM" riparian reptiles and mammals; "AM" amphibians; "FF" small freshwater fish). Metrics were presented as questions asked throughout the expert elicitation process. The applicability of each metric varied among the seven taxon groups as either being not relevant (and therefore not assessed = blank), assessed as relevant for some species of the group ("grey text"), and assessed as relevant to all species in the group ("regular text"). Ideal habitat metrics only were also determined to be a more important (but not critical) habitat element for the group ("underlined text"), or an essential (critical) habitat element for the group ("**bold and underlined text**").

	Metric	Description	Assessed taxon groups						
Ideal habitat requirements	Preferred distance between tree canopies (m)	Preference in terms of tree spacing and canopy density.	**GR**	NB	**SM**	**WB**	RM	AM	FF
	Preferred distance between mature trees (m)	Proxy for preference in terms of access to features associated with mature trees such as fallen limbs, or tree hollows.	GR	NB	**SM**	WB	RM	AM	
	Preferred distance between mid-storey canopies (m)	Preference in terms of mid-storey spacing and canopy density.	GR	NB	SM	WB			
	Preferred distance from ground layer vegetation (m)	Preference in terms of proximity to ground layer vegetation, spacing between vegetation patches	**GR**	NB	SM	WB	RM	AM	
	Minimum height of ground layer vegetation (cm)	Preference in terms of ground layer vegetation structure and management (e.g., mowing regime).	**GR**		SM	WB	RM	AM	
	Maximum height of ground layer vegetation (cm)	Preference in terms of ground layer vegetation structure and management (e.g., grazing regime).	**GR**		SM	WB	RM	AM	
	Preferred distance between emergent vegetation (m)	Preference, for aquatic and riparian taxa, in terms of the distance between clumps of emergent vegetation.					RM	AM	FF
	Maximum distance which can be travelled from permanent waterbody (m)*	Requirements in terms of access to permanent surface water. *Represents a structural habitat requirement for aquatic species.					**RM**	AM	FF
Habitat constraints	Minimum width of core habitat patch (m)	The minimum dimension of a patch of suitable size to facilitate permanent residency.	GR	NB	SM	WB	RM	AM	FF
	Minimum suitable core habitat depth (m)	For aquatic habitat, the minimum depth of water required to facilitate permanent residency.					**RM**	AM	FF
	Minimum width of movement corridor habitat (m)	The minimum dimension of a patch of suitable size to support movement between 'core' habitat areas, but not permanent residency.	GR	NB	SM	WB	RM	AM	FF
	Minimum suitable corridor habitat depth (m)	For aquatic habitat, the minimum depth of water required to facilitate movement between 'core' habitat areas, but not permanent residency.					RM		FF
	Percentage of trees which need to be native (%)	The proportion of trees which need to be native to facilitate habitat use.	GR	NB	SM	WB	RM	AM	FF
	Percentage of native mid-storey vegetation (%)	The proportion of shrubs which need to be native to facilitate habitat use.	GR	NB	SM	WB			
	Percentage of native ground layer vegetation (%)	The proportion of ground layer vegetation which needs to be native to facilitate habitat use.	GR	NB	SM	WB	RM	AM	
	Percentage of native emergent vegetation (%)	The proportion of emergent vegetation, in aquatic environments, which needs to be native to facilitate habitat use.					RM	AM	FF
	Maximum tolerable night-time light levels (Lux)	The level of artificial light conducive to habitat use.	GR	NB	SM	WB	RM	AM	FF
	Maximum tolerable surface temperature (°C)	The maximum surface temperature conducive to habitat use.	**GR**	NB			RM	AM	
	Maximum tolerable ambient temperature (°C)	The maximum ambient temperature conducive to habitat use.	**GR**	NB	SM	WB	RM	AM	
	Maximum tolerable water temperature (°C)	The maximum water temperature conducive to habitat use.					**RM**	**AM**	**FF**
	Minimum tolerable water temperature (°C)	The minimum water temperature conducive to habitat use.					**RM**	**AM**	**FF**
Barriers to movement	Maximum crossable extent of paved surface (m)	The maximum extent of paved surface which does not represent a physical barrier to movement, including concrete drains.	**GR**		SM		RM	AM	FF
	Maximum crossable height of vertical structure (m)	The maximum height of a vertical structure (e.g., building, wall or fence) which can be crossed in the absence of a suitable gap.	**GR**		SM		**RM**	**AM**	**FF**
	Minimum passable gap dimensions (m)	The minimum gap dimensions required to facilitate movement through an otherwise impenetrable vertical barrier.	GR		SM		**RM**	**AM**	**FF**
	Maximum crossable extent of waterbody (m)	The maximum extent of a waterbody which does not represent a physical barrier to movement.	GR		SM			AM	
	Tolerable traffic flow during active period (vehicles/hr)	The maximum tolerable level of vehicle traffic (including boats) which does not represent a physical or behavioural barrier to movement during the taxon's active period.	GR		SM		RM	AM	
	Tolerable pedestrian traffic flow during active periods (pedestrians/hr)	The maximum tolerable level of pedestrian access (including swimmers) which does not represent a physical or behavioural barrier to movement during the taxon's active period.	GR		SM		RM		
Movement thresholds	Typical movement distance within established home range/territory (m)	The capacity for movement within a home range or territory (used to buffer known species records to determine likely occupied habitat).	GR	NB	SM	WB	RM	AM	FF
	Typical capacity for movement outside of suitable habitat (m)	The capacity to move from areas of suitable habitat to other nearby patches, in the absence of a physical or behavioural barrier.	GR	NB	SM	WB	RM	AM	FF
	Typical dispersal distance when seeking new home range/territory (m)	The landscape scale requirements for connected habitat to facilitate the full display of life history traits.	GR	NB	SM	WB	RM	AM	FF

risk) species. All metrics considered were compatible with existing spatial data layers (or layers able to be compiled) to enable habitat connectivity mapping from these data in the future (e.g., Kirk et al., 2018).

2.4. Applying the IDEA protocol for structured expert elicitation

We used the IDEA protocol for conducting structured, iterative expert elicitation to quantify each of the relevant metrics for each of our seven taxon groups (see Hanea et al., 2017; Hemming et al., 2018; Courtney Jones et al., 2023). This protocol involved four main steps: (1) *INVESTIGATE*: recruit a diverse group of experts for each taxon group to answer questions with initial quantitative 4-point estimate responses (i.e. best estimate, lower limit and upper limit, and a measure of confidence [or a degree-of-belief] in the accuracy those estimates; Speirs-Bridge et al., 2010); (2) *DISCUSS*: convene a workshop with experts to discuss their initial estimates to the questions, clarify their meaning, share reasoning and evidence behind initial estimates, and resolve differences in interpretation of the application of habitat metrics; (3) *ESTIMATE*: enable experts to provide a revised and final estimate to each question that considers the workshop discussion which clarified the taxon group species, existing knowledge, sources of uncertainty, and encouraged cross-examination of reasoning and evidence in context of habitat connectivity within the ACT (Courtney Jones et al., 2023); and (4) *AGGREGATE*: mathematically aggregate experts' final estimates to determine the average best, lower limit and upper limit for each taxon group for each metric (Table 2).

We recruited experts during a two-month period leading up to a series of taxon group-themed workshops held online in September and October 2021. A total of 59 experts were consulted throughout the study (i.e., contributed to the collective knowledge, discussions, and interpretation of results) with 47 of those providing estimates ($n = 8$ for woodland birds, $n = 7$ for amphibians, $n = 5$ for native bees, $n = 5$ for small freshwater fish, $n = 12$ for grassland reptiles, $n = 10$ for small–medium mammals, $n = 4$ for riparian reptiles and mammals [noting that four experts contributed to two taxon group estimates each]). Experts were identified based on both local-based experience and taxon-specific knowledge and were selected to represent a breadth of expertise for each taxon group. Experts included (a) academic researchers and post-graduate students involved in ecological research on relevant taxa, (b) management agency staff involved in field ecology, surveys, and management on relevant taxa within the ACT, and (c) ecological consultants, citizen-scientists, naturalists, or museum and zoo staff with extensive experience with the relevant taxa. We selected a diverse expert panel to capture a broad base of knowledge and perspectives, so as to yield accurate aggregated judgements rather than that of a single well-credentialled expert (Page, 2008a, 2008b). In this instance, Traditional Ecological Knowledge was not included within the expert elicitation process as it was not considered a culturally safe practice for Knowledge holders, particularly given the extractive knowledge approach used in expert elicitation (Thomas, 2021).

Each taxon group workshop ran for between 4 and 6 working hours, where moderators (SKCJ and MS) lead experts through each metric sequentially, discussing the initial estimates and support for those estimates, the interpretation of each question and relevance of the metric for the taxon group, and ensured all experts were fully informed and prepared to complete their revised estimates after the workshop. A later review of metrics assessed the relative relevance and importance of each metric for each taxon group (Table 2). Despite the majority decisions from such discussion, in 14 % of all taxon-specific metrics assessed (21/149) one or more experts felt they either could not (i.e., low familiarity with the metric) or should not (i.e., disagreed with the relevance of the metric) submit final estimates. We presented questions in an order that followed the workflow described by Kirk et al. (2023), starting by estimating "ideal habitat" features without defined spatial parameters (e.g., "what are the structural features of continuous, unfragmented habitat?"), and estimating the taxon-specific habitat constraints, barriers to movement and movement thresholds second (e.g., "what is the minimum size/composition/distance between habitat that is still considered connected?", see Supplementary Material).

2.5. Summary statistics

Expert-derived data can be aggregated with or without weighting (Hanea et al., 2017; Hemming et al., 2018, 2020). While there are some species-level habitat association data that could be used to calibrate and weight expert estimates had we taken a species-level approach, no such calibration data were available at the taxon group-level at which our estimates were made. Therefore, we used equally weighted aggregation using arithmetic means for all data (Hemming et al., 2022). We estimated the means of the best, lower, and upper estimate for each metric for each taxon group in which it was assessed. We also calculated standardised 80 % credible intervals surrounding the best estimate for each assessed metric using expert-reported confidence levels (Hemming et al., 2018). We calculated these intervals for each estimate using linear extrapolation that considered the confidence reported by the experts (see Adams-Hosking et al., 2016 and Hemming et al., 2018 for equations). Where experts reported 0 % confidence, their individual confidence was truncated to 1 % to enable calculation, and all credible intervals were averaged for each taxon group by metric combination (Adams-Hosking et al., 2016; Hemming et al., 2018). Using the four-step elicitation method (i.e., the expert specifying their confidence) and subsequent standardisation of credible intervals reduces overconfidence in expert-derived data by presenting a confidence-informed measure of certainty surrounding the mean (Speirs-Bridge et al., 2010; Hemming et al., 2018). In the absence of independent empirical data on which to calibrate our expert-derived estimates, no other data summarisation, transformation, or analyses were undertaken. Individual estimates were removed from analysis where no response was provided, or where associated written comments clearly indicated an inconsistent interpretation of the metric compared to other participants. All data summarisation was performed using R version 4.1.2 (R Core Team, 2022).

3. Results

We used the IDEA protocol to estimate 30 metrics to represent landscape-scale, functional habitat connectivity for seven taxon groups (16–27 metrics per taxon group). They included metrics representing (1) ideal habitat requirements (eight metrics), (2) habitat constraints (13 metrics), (3) barriers to movement (six metrics), and (4) movement thresholds (three metrics). We present averaged best estimates (± 80 % credible intervals) and lower/upper estimates for each habitat connectivity metric assessed (Table 3).

3.1. Grassland reptiles

We estimated functional habitat connectivity requirements for grassland reptiles across 23 relevant metrics. Ideal habitat comprised a largely continuous grassy understory with a preferred grass height range of 10–19 cm, and with several hundreds of metres between trees or shrubs. Core habitat was estimated as requiring a minimum width of 204 m (or 38 m for a movement corridor) and high native ground cover (best estimate = 72 %, although they could tolerate as low as 19 %). As largely diurnal species, grassland reptiles were considered tolerant of high night-time light levels, and high temperatures assuming refugia habitat was available. Grassland reptiles were considered unlikely to cross paved surfaces >5 m wide or vertical structures >0.2 m high. Many grassland reptiles were estimated as having very low movement capacity outside of ideal habitat (<10 m), although larger species considered as part of this group (e.g., eastern brown snake) increased the average to 37 m. Movement within home ranges or dispersal to a new home range was considered low (best = 58–69 m).

Table 3

Summary of expert-derived functional habitat connectivity requirements for seven taxon groups representative of urban ecosystems *in Canberra, Australian Capital Territory*. Averaged 'Best' (± 80 % credible intervals),and lower and upper (L–U) estimates are presented (as reported) for all metrics, as well as the number of expert estimates (n) used to calculate statistics provided for each metric.

Metric		Grassland reptiles	Native bees	Small-medium mammals	Woodland birds	Riparian reptiles and mammals	Amphibians	Small freshwater fish
Ideal habitat								
Preferred distance between tree canopies (m)	Best	114 (42–1008)	40 (6–634)	11 (0–80)	41 (4–217)	28 (2–108)	23 (2–703)	11 (0–563)
	L–U (n)	48–858 (8)	7–320 (5)	2–49 (10)	7–155 (8)	8–88 (4)	1–607 (7)	1–440 (5)
Preferred distance between mature trees (m)	Best	864 (65–2183)	143 (48–667)	23 (3–99)	75 (11–242)	60 (22−122)	58 (5–626)	
	L–U (n)	73–1826 (7)	55–510 (5)	9–61 (10)	24–189 (8)	28–100 (4)	5–957 (7)	
Preferred distance between mid-storey canopies (m)	Best	792 (39–1769)	42 (5–340)	7 (0–39)	37 (5–153)			
	L–U (n)	49–1480 (7)	9–300 (4)	1–29 (10)	8–113 (8)			
Preferred distance from ground layer vegetation (m)	Best	1 (0–7)	35 (1–192)	3 (0–14)	4 (0–80)	26 (0–38)	10 (1–1040)	
	L–U (n)	0–8 (10)	0–161 (5)	1–11 (10)	0–42 (7)	3–33 (4)	1–739 (7)	
Minimum height of ground layer vegetation (cm)	Best	10 (5–17)		27 (7–60)	11 (2–36)	25 (11–46)	23 (9–40)	
	L–U (n)	5–17 (11)		10–52 (10)	4–29 (7)	15–40 (4)	10–36 (7)	
Maximum height of ground layer vegetation (cm)	Best	19 (12–36)		51 (28–113)	26 (4–100)	50 (30–104)	56 (26–99)	
	L–U (n)	14–36 (11)		33–85 (10)	12–52 (8)	36–86 (4)	30–76 (7)	
Preferred distance between emergent vegetation (m)	Best					13 (1–40)	11 (2–40)	11 (2–119)
	L–U (n)					6–25 (4)	3–27 (7)	2–84 (5)
Maximum distance which can be travelled from permanent waterbody (m)*	Best					38 (5–528)	304 (88–2358)	
	L–U (n)					8–383 (4)	111–2021 (7)	
Habitat constraints								
Minimum width of core habitat patch (m)	Best	204 (74–390)	151 (54–602)	113 (25268)	378 (32–3805)	9 (4–30)	90 (2–216)	5 (2–48)
	L–U (n)	75–298 (11)	66–600 (5)	49–1273 (10)	73–2075 (8)	5–24 (4)	22–177 (7)	3–33 (5)
Minimum suitable core habitat depth (m)	Best					2.3 (1.3–5.0)	0.6 (0.2–1.2)	1.4 (0.2–3.9)
	L–U (n)					1.5–4.0 (4)	0.3–0.9 (7)	0.3–3.5 (5)
Minimum width of movement corridor habitat (m)	Best	38 (9–153)	37 (3–235)	65 (7299)	28 (4–146)	4 (3–16)	10 (1–29)	2 (1–39)
	L–U (n)	11–131 (11)	5–168 (5)	18–171 (10)	9–91 (8)	4–13 (3)	3–26 (7)	1–26 (5)
Minimum suitable corridor habitat depth (m)	Best					1.0 (0.3–1.8)		0.6 (0.0–2.5)
	L–U (n)					0.4–1.6 (4)		0.2–2.0 (5)
Percentage of trees which need to be native (%)	Best	48 (21–68)	79 (19–99)	81 (35–96)	73 (32−100)	63 (31−112)	49 (4–90)	100 (9–100)
	L–U (n)	24–73 (6)	14–100 (5)	45–94 (10)	32–90 (8)	38–98 (4)	9–88 (7)	12–100 (5)
Percentage of native mid-storey vegetation (%)	Best	51 (10–81)	76 (21–99)	63 (22–96)	18 (3–53)			
	L–U (n)	16–82 (5)	18–100 (5)	30–96 (10)	8–89 (8)			
Percentage of native ground layer vegetation (%)	Best	72 (19–97)	68 (8–100)	75 (28–94)	66 (6–96)	63 (31–95)	53 (0−100)	
	L–U (n)	20–96 (11)	8–98 (5)	35–94 (10)	13–94 (8)	40–90 (4)	1–91 (7)	
Percentage of native emergent vegetation (%)	Best					47 (17–94)	54 (11–99)	100 (15–100)
	L–U (n)					26–93 (4)	23–85 (7)	20–100 (5)

(*continued on next page*)

Table 3 (*continued*)

Metric		Grassland reptiles	Native bees	Small-medium mammals	Woodland birds	Riparian reptiles and mammals	Amphibians	Small freshwater fish
Maximum tolerable night-time light levels (Lux)	Best	22 (0–1235)	5 (0–24)	4 (2–30)	7 (0–21)	1 (0–1)	5 (0–126)	1 (0–12)
	L–U (n)	2–718 (7)	2–212 (5)	2–21 (8)	2–22 (7)	0.1–0.6 (2)	0–80 (7)	0.0–8.2 (5)
Maximum tolerable surface temperature (°C)	Best	43 (30–61)	34 (20–57)			37 (31–47)	26 (16–35)	
	L–U (n)	32–58 (11)	34–78 (3)			33–43 (3)	19–33 (7)	
Maximum tolerable ambient temperature (°C)	Best	36 (28–42)	40 (34–53)	41 (34–49)	38 (28–48)	39 (26–42)	29 (18–40)	
	L–U (n)	30–41 (11)	36–48 (5)	35–46 (10)	31–43 (8)	32–44 (3)	21–36 (7)	
Maximum tolerable water temperature (°C)	Best					27 (23–34)	23 (20–31)	25 (16–36)
	L–U (n)					24–32 (4)	21–31 (7)	16–31 (5)
Minimum tolerable water temperature (°C)	Best					5 (1–8)	8 (3–14)	6 (2–16)
	L–U (n)					2–7 (4)	4–12 (7)	3–12 (5)
Barriers to movement								
Maximum crossable extent of paved surface (m)	Best	5 (1–28)		17 (5–73)		16 (1–44)	34 (6–146)	13 (0–60)
	L–U (n)	2–25 (11)		7–50 (9)		4–31 (4)	12–108 (7)	0–55 (5)
Maximum crossable height of vertical structure (m)	Best	0.2 (0.0–0.7)		1 (0–4)		0.7 (0.1–1.0)	0.5 (0.0–4.4)	0.1 (0.0–0.3)
	L–U (n)	0.1–0.9 (11)		0.4–3.3 (9)		0.6–0.9 (4)	0.0–3.0 (7)	0.0–0.2 (5)
Minimum passable gap dimensions (m)	Best	0.1 (0.0–0.1)		0.3 (0.1–0.9)		0.3 (0.2–0.3)	0.1 (0.0–0.1)	0.2 (0.0–0.5)
	L–U (n)	0.0–0.2 (11)		0.1–0.7 (10)		0.2–0.3 (4)	0.0–0.1 (7)	0.1–0.4 (5)
Maximum crossable extent of waterbody (m)	Best	0.8 (0.5–13.3)		14 (3–52)			28 (11–206)	
	L–U (n)	0.4–7.6 (11)		6–590 (9)			14–196 (7)	
Tolerable traffic flow during active period (vehicles/h)	Best	8 (4–30)		9 (2–27)		7 (0–20)	14 (1–64)	
	L–U (n)	3–27 (9)		3–28 (9)		2–13 (4)	4–43 (7)	
Tolerable pedestrian traffic flow during active periods (pedestrians/h)	Best	15 (0–46)		10 (1–71)		71 (2–149)		
	L–U (n)	3–35 (11)		3–42 (9)		9–103 (4)		
Movement thresholds								
Typical movement distance within established home range/ territory (m)	Best	58 (13–237)	213 (26–751)	611 (9–2164)	395 (58–1156)	1625 (554–3835)	54 (4–607)	30 (0–340)
	L–U (n)	19–173 (9)	22–800 (5)	87–1620 (10)	158–813 (8)	800–3250 (4)	14–436 (7)	7–226 (5)
Typical capacity for movement outside of suitable habitat (m)	Best	37 (2–344)	205 (13–602)	106 (26–1058)	960 (85–16,758)	233 (11–767)	89 (2–313)	35 (6–554)
	L–U (n)	2–208 (9)	33–540 (5)	34–699 (10)	180–9503 (8)	75–700 (4)	9–350 (7)	13–340 (5)
Typical dispersal distance when seeking new home range/ territory (m)	Best	69 (8–869)	133 (0–965)	794 (4–5928)	760 (67–13,352)	1375 (150–5258)	517 (22–3118)	88 (3–1074)
	L–U (n)	18–467 (9)	15–680 (5)	110–3730 (10)	210–7375 (8)	400–4000 (4)	76–2450 (7)	11–820 (5)

3.2. Native bees

We estimated functional habitat connectivity requirements for native bees across 17 relevant metrics. Ideal habitat for native bees consisted of trees, midstory and/or ground-layer vegetation, generally in an open arrangement, with variable distances between each being preferred. Estimated habitat was constrained to areas with a minimum width of 151 m for core habitat or 37 m for a movement corridor. High nativeness of all strata was also seen as beneficial (best estimates = 68–79 %, although some species could tolerate as low as 8 % native cover). Native bees were considered tolerant of temperatures ≥40 °C where thermal refugia was available. There was low confidence in whether native bees tolerated only low or moderate night-time light levels (80 % credible interval of best estimate = 0–24 Lux). Movement of native bees were impacted by large expanses of pavement or water, but not by vertical structures or traffic. Native bees were deemed to have moderate capacity for movement outside of ideal habitat (best estimate = 205 m, although upper estimate was 602 m), roughly equivalent to typical foraging ranges within a habitat patch (best = 213 m).

3.3. Small–medium mammals

We estimated functional habitat connectivity requirements for small–medium mammals across 22 relevant metrics. Ideal habitat was estimated as having more dense vegetation across all strata than any other taxon group, with shrubs and trees being considered the more important or essential habitat elements for most species considered (best estimates of 7 and 11 m for preferred distances between shrubs and trees, respectively). Core habitat was estimated as requiring a minimum width of 113 m (or 65 m for a movement corridor) with high levels of nativeness being preferred for all vegetation strata, particularly for trees where the best estimate was 81 % native with the low estimate also relatively high at 35 %. Small–medium mammals were considered only tolerant of low night-time light levels (best estimate = 4 Lux). All barriers to movement assessed were considered relevant, with the group unlikely to cross paved surfaces >17 m, vertical structures >0.3 m, or traffic areas of >9 vehicles or > 10 pedestrians per hour during the taxon groups' active period. This group was assessed as having a high capacity for movement within ideal habitat, including moving a best estimate of 794 m when dispersing to a new territory, but were unlikely to move >106 m through unsuitable habitat.

3.4. Woodland birds

We estimated functional habitat connectivity requirements for woodland birds across 16 relevant metrics. Ideal habitat was estimated as having moderate tree density, with a complex mid- and/or understory comprised of shrubs or long grasses (best estimates = 41 m and 37 m for preferred distances between tree and midstory canopies). Minimum width requirements for core habitat were the largest for any taxon group (best estimate = 378 m for core habitat, and 28 m for a movement corridor). Experts agreed native vegetation would likely represent ideal habitat but exotic vegetation could also be used if it provided appropriate structure (best estimates = 18–73 % native vegetation). Woodland birds were considered tolerant of temperatures <38 °C if thermal refugia was available, although prolonged heatwaves were considered likely to impact this species group particularly during breeding periods. Experts considered the group to have reasonable tolerance to artificial night-time light, based on the persistence of many species in urban areas. Small woodland bird movement was not impacted by any barriers assessed and they were considered capable of moving substantial distances across unsuitable habitat (best estimate = 960 m with an upper estimate of 16.8 km).

3.5. Riparian reptiles and mammals

We estimated functional habitat connectivity requirements for riparian reptiles and mammals across 27 relevant metrics. Ideal habitat was variable due to the breadth of species considered, but was generally associated with the riparian zone within 38 m of permanent water. The combined aquatic and riparian habitat supported emergent vegetation, moderately spaced trees, and ground-layer vegetation with a preferred grass height of 25–50 cm. Habitat was estimated as being constrained mostly by the depth (best estimate = 2.3 m) and width (best estimate = 9 m) of the associated waterbody. Corridor habitat could be narrower (4 m waterbody width) and shallower (1.0 m depth). Habitat was not necessarily constrained by vegetation nativeness (best estimates = 63 %) but was constrained by water temperatures outside of a 5–27 °C best estimate range. Barriers to movement included paved surfaces >16 m, vertical surfaces >0.7 m, or traffic areas of >7 vehicles or > 71 pedestrians per hour, however since these averages reflect a diverse group, they do not reflect smaller barriers identified by experts during the discussion which would impact some species (e.g., smooth vertical barriers for eastern long-necked turtles are likely <10 cm). The average capacity for movement for this taxon group was high, including moving an upper estimate of 5.2 km when dispersing to a new territory, but their capacity to move outside of suitable habitat was best estimated around 233 m.

3.6. Amphibians

We estimated functional habitat connectivity requirements for amphibians across 26 relevant metrics. Ideal habitat was estimated as being within a few hundred metres of water which contained emergent vegetation (distance from water best estimate = 304 m), with moderately spaced trees and ground-layer vegetation also present to varying degrees in the broader landscape (reflecting divergent habitat requirements of different species within this group). Best estimates for preferred grass height were 23–56 cm. Core habitat was estimated as being constrained to a minimum width of 90 m (or 10 m for a movement corridor) and a minimum water depth of 0.6 m. Amphibians were not necessarily constrained by vegetation nativeness (best estimates = 49–53 %) but were the least tolerant of high surface and ambient temperatures of any taxon group. Most barriers to movement assessed were considered relevant, with the group unlikely to cross paved surfaces >34 m, vertical surfaces >0.5 m, or waterbodies >28 m. Amphibians were estimated as having moderate–low movement capacity outside of ideal habitat (best = 89 m), although their capacity to disperse through suitable habitat was much higher (best estimate = 517 m, to <3.1 km).

3.7. Small freshwater fish

We estimated functional habitat connectivity requirements for small freshwater fish across 18 relevant metrics. Ideal habitat was confined to permanent water, with moderately spaced emergent vegetation and trees in the associated riparian environment (best estimates of 11 m for preferred distances between each of those elements). Core habitat was estimated as being constrained to a minimum width of 5 m (or 2 m for a movement corridor) and a minimum water depth of 1.4 m (or 0.6 for a movement corridor). Experts reported best habitat conditions for this group with estimates of 100 % for both native emergent vegetation and trees. Small freshwater fish were estimated to have the lowest tolerance of night-time light levels of any taxon group, and water temperatures outside of a 6–25 °C best estimate range. High movement barriers submerged paved surfaces >13 m long and exposed vertical structure >0.1 m high. Their typical movement within a home range or territory was estimated to be the same as their capacity to move outside of suitable habitat (both best estimates ~30–35 m).

4. Discussion

We used the IDEA protocol of expert elicitation to address gaps in landscape-scale habitat connectivity data that can limit the capacity of urban planning to adopt BSUD principles. Using the city of Canberra in Ngunnawal Country (ACT) as a case study, we found that the IDEA protocol was effective in this application – taxon-experts were able to estimate metrics describing connected habitat for the taxon-groups, the estimates were ecologically meaningful and generally consistent with empirical knowledge around habitat connectivity requirements from species within the groups (where it existed), and the consultative process was generally useful in determining the relevancy of metrics for specific groups (see examples below). However, there were also difficulties and limitations of the approach. This included difficulty identifying 'best' estimates for individual metrics at the taxon-group level where different species within the group were expected to have quite different habitat requirements or movement capabilities. Overall, we consider our expert-derived estimates of connected habitat to be a highly useful set of baseline data for habitat and connectivity modelling and urban planning for a range of taxon groups. Below we discuss the strengths and limitations of how our taxon-specific connected habitat estimates were determined for, and their potential use in, urban planning and BSUD.

4.1. Applicability of the IDEA protocol to estimate habitat connectivity metrics

The connected habitat estimates we derived by applying the IDEA protocol for expert elicitation were, in general, both ecologically meaningful and aligned with expert expectations. These estimates contribute to the identified gaps in data for biodiversity-sensitive urban design - namely that the lack of taxon group-level habitat connectivity data at the relevant spatial scale (Kirk et al., 2018) has been addressed by defining habitat preferences with greater precision than is typically used in describing habitat connectivity. For instance, our expert elicitation process derived a minimum and maximum grass height, required percentage of native vegetation, and minimum width for core or corridor habitat areas for grassland reptiles. This contrasts with the habitat description characterised simply by "a grassy ground-cover free of trees" used in a similar application by Kirk et al. (2018). The combination of these estimates also accurately described the specialised requirements of grassland reptiles when compared to empirical data (Antos and Williams, 2015; Howland et al., 2016). Metrics that we assessed also describe well the other taxon groups that are known to be more diverse and adaptable in their connected habitat needs. For example, connected habitat for small–medium mammals was estimated as not only including the presence of tree canopies and midstory cover, but importantly, that preferred distances between those habitat elements are required to provide functionally connected habitat for the majority of species considered. All taxon groups had nuance in the specific spatial arrangement - for example native versus exotic composition, or tolerance of particular habitat constraints - that were estimated quantitatively (e.g., tree spacing, tolerance of artificial light) using the IDEA protocol. Important qualitative elements (e.g., the relative heterogeneity or 'clumped' distribution of structural habitat elements) was also captured through the '*DISCUSS*' step of the IDEA protocol.

The breadth of metrics that could be collaboratively estimated through the IDEA protocol is a major strength for addressing data gaps in urban planning. Habitat connectivity modelling largely relies on a limited number of metrics, such as is in Kirk et al. (2018) where ecological connectivity was determined for taxon groups from 4 to 5 structural metrics, 1–2 barrier metrics, and a single dispersal metric. By using expert elicitation, we have generated quantitative estimates that describe taxon group habitat connectivity using 16–27 metrics (mean = 21 metrics) that consider the functional dimensions of connectivity by estimating up to eight ideal habitat metrics, 13 habitat constraint metrics, six barriers to movement metrics, and four movement threshold metrics. Generating such a breadth of data to inform connectivity metrics is particularly important for taxon groups with complex and diverse habitat needs, such as amphibians that require both terrestrial and aquatic environments (Becker et al., 2007). Further, our approach and breadth of metrics enabled determination of the impact of anthropogenic processes on connectivity. For example, Kirk et al. (2018) determined roads with >5 m width as a barrier to amphibian movement, whereas our approach separated two considerations of how paved roads presented a barrier to movement (i.e., crossable extent of paved surface versus impact of traffic volume) and estimated amphibians were able to cross much larger road (viz. "paved surfaces" best estimate = 34 m) when traffic flow during active periods was low (<14 vehicles per hour during active periods). By using the IDEA protocol, we have established a large collection of quantitative estimates to describe habitat connectivity for a range of taxon groups in more detail and with greater context-dependency than is typical in urban planning context.

Using the IDEA protocol to generate ecologically meaningful habitat connectivity estimates was not without limitations, with some metrics proving more difficult to estimate than others. Some of the difficulty that arose was due to lumping multiple species together based on broad habitat use, but without being able to represent the diversity of habitat usage between individual species. This constraint was most apparent for our riparian reptiles and mammals group, where the species considered broadly require riparian and/or aquatic habitat elements, but vary widely on the relative importance of each. For example, defining a minimum width of core habitat required consideration of both aquatic habitat (more relevant for platypus and turtles) and associated terrestrial riparian habitats (more relevant for water dragons and snakes). Depending on the specific subject matter expertise of the experts, responses often focused on one or the other, rather than the combined requirements for the full taxon group. Careful revision of expert estimates to identify variability in metric interpretation by experts, coupled with more precise refinement of species comprising the taxon groups themselves (e.g., adopting a process of identifying 'dispersal guilds' as described by Lechner et al., 2017) could improve our methodology.

Wide tolerances among species within a taxon group created difficulties in providing representative estimates, and contributed to broad confidence bounds for many metrics in this study. Typically, in applying the IDEA protocol, the upper and lower estimates provided by experts represent 'plausible bounds' around the 'best' estimate and may reflect something akin to a 95 % confidence interval. In this application however, the upper and lower bounds were adopted to reflect the variability between, or tolerances within, species comprising the taxon group. For example, while experts unanimously agreed that native-dominated vegetation was preferrable in all habitats, all taxon groups were considered able to tolerate non-native dominated vegetation to some extent (Threlfall et al., 2016, 2017). As such, in many instances this meant the lower and upper estimates for 'percent native' vegetation metrics were close to the full 0–100 % range across different taxon groups. Providing a best estimate for these metrics generally reflected one of three values: (a) the mid-point of the full breath of tolerance within a taxon group (e.g., amphibians), (b) the maximum value indicating that 100 % native vegetation will always be 'best' (e.g., small freshwater fish), or (c) a native-skewed estimate indicating native vegetation was likely better than exotic within the full breath of compositional tolerance (e.g., all other groups). The way in which estimates were provided as 'best', 'upper', and 'lower' in this study was based on our acknowledgement that estimating the single 'true' value for metrics at the taxon group-level (i.e., across a range of species) would be less ecologically meaningful than representing the within-group variability. To prevent overly broad metric estimates in future, researchers could select species groupings which share greater ecological dependencies (such as association with a vegetation community). Additionally, deciding whether to use the upper and lower estimates to capture variability among species (as we did in estimating tolerance bounds) or to capture the plausible range of the true value should be carefully considered.

Using the IDEA protocol enabled us to estimate metrics for which there is almost no research (e.g., tolerable levels of artificial light, or traffic volumes) with a similar level of confidence to metrics with considerably more knowledge (e.g., those related to structural habitat requirements). For instance, the credible interval around metrics with ACT-specific empirical studies (e.g., minimum grass height for grassland reptiles, Howland et al., 2016) were comparable to metrics where there were no species- or taxon-specific literature available (e.g., tolerable levels of artificial light; Gaston et al., 2012). However, our application of the IDEA protocol did not resolve issues around metric relevance for some taxon groups, which resulted in some experts not contributing estimates, thereby decreasing our sample size for some metric-taxon group combinations. This was most evident for the grassland reptile metrics related to preferred distances between tree canopies, mature trees, and midstory canopies. All experts agreed that the presence of trees and shrubs would inhibit these grassland specialists (Antos and Williams, 2015; Howland et al., 2016), however some experts contributed estimates for large distances between trees or shrubs to represent a sufficiently 'treeless' landscapes, while others provided no response, deeming tree spacing to be irrelevant for the group. The exclusion of 'no response' data may have artificially reduced the confidence limits around metrics where collectively there was greater uncertainty. Previous studies have adopted the confidence score to reflect experts' confidence that their 'best' estimate falls within their upper and lower bounds (as opposed to how confident they are that their estimate is correct) which may be a way to encourage expert responses in future studies. Since we adopted upper and lower estimates to reflect the breadth of suitable habitats in this study, such an approach was not appropriate here. This example highlights the importance of ensuring a consistent interpretation around individual metrics within the expert group, either prior to experts providing initial estimates, or during the '*DISCUSS*' step. Clarifying the relative value of including or excluding metrics will avoid the need for subsequent qualitative descriptions of expert intent.

4.2. Capacity of estimated ecological connectivity metrics to inform spatial urban planning

We investigated whether using the IDEA protocol could generate data inputs that could be used to directly describe or model habitat connectivity to support urban planning and BSUD. Given the strengths and minimal limitations we have identified for generating ecologically sensible estimates, we consider our data is most useful in extending and refining what defines ecological connectivity in an urban setting, thereby enabling for more precise and taxon-specific connectivity modelling and mapping in the future.

We have estimated habitat connectivity over a broader set of metrics than is typically considered in habitat connectivity assessments. However, a smaller set of metrics in previous studies may reflect limited access to accompanying spatial modelling inputs at a suitable resolution, rather than authors not considering other metrics to be important. For example, connected habitat models may consider the presence of trees only without consideration of preferred spacing and composition because that information is not available (Kirk et al., 2018, 2023). This means many of our estimated metrics may only be useful as descriptions for urban planning (e.g., ACT Government, 2023), rather than contributing directly to spatial modelling. Whereas Kirk et al. (2018) presents small bird connectivity in an urban environment based on presence-absence data for four vegetation metrics with accompanying spatial data, we present small bird connectivity as elicited quantitative threshold data for 11 vegetation metrics, alongside minimum width of core and movement corridor habitat patch. These additional metrics will be useful for wildlife managers to conceptualise and advise on connected habitat, and will ideally contribute to predictive habitat and fragmentation mapping where associated spatial layers are available. Where possible, however, using the IDEA protocol to increase the number of metrics considered will limit overestimates of connected habitat (through greater incorporation of limiting aspects like urban heat or light, impacts of human presence and density) and also underestimates (through incorporating more nuance in important elements like the interaction of road width and traffic volume), thereby providing more representative connected habitat model outputs overall.

A final strength of the IDEA protocol is that in estimating lower and upper bounds for metrics, there is flexibility to explore different scenarios and contexts in habitat connectivity modelling and mapping (Hanea et al., 2017; Hemming et al., 2018). This contrasts with the classical approach of obtaining a single data input through behavioural aggregation of experts (O'Hagan et al., 2006; Hanea et al., 2017), where habitat would be considered connected or disconnected based on the 'best' value only for any particular habitat metric. For example, connectivity for woodland birds in Kirk et al. (2018) was modelled using a median dispersal distance of 1.5 km. Our best estimate for typical dispersal distance when seeking a new territory (13.4 km) for the same taxon group meant the results from our expert elicitation were not dissimilar to those used in Kirk et al. (2018). However, the upper bounds provided by experts in our study determined that some small woodland birds are potentially capable of moving up to three-times further than the distance described as the best estimate, meaning connectivity or the minimum requirements for dispersal for some species in the group is likely to be underestimated by adopting only the 'best' reported value in habitat connectivity models.

5. Conclusion

Maintenance of habitat connectivity through the conservation of habitat and wildlife corridors across urban landscapes is important for promoting biodiversity, including for many threatened species which occur within urban extents (Ives et al., 2016; Garrard et al., 2018; Soanes and Lentini, 2019). Identifying, retaining and restoring habitat and wildlife corridors to facilitate dispersal within urban landscapes requires species- or taxon-specific knowledge of their ecological connectivity requirements including movement abilities, habitat preferences, and potential barriers to dispersal (Kirk et al., 2018). Using the habitat connectivity estimates we quantified through an expert-elicitation process, there is a clear opportunity to identify congruency among taxon group requirements to establish urban planning and BSUD approaches that have positive effects for a range of taxa (ACT Government, 2023). For example, multiple species groups shared a preferred tree spacing of 11–41 m, and hence the conservation of such structural elements within core habitats (≥328 m wide) or corridors (≥39 m wide) will support habitat connectivity for all terrestrial groups except grassland reptiles. The lack of congruency between grassland reptile habitat and that of other taxon groups in this study highlights the importance of identifying taxon group-level dependencies where differing ecosystems overlap or co-occur. Specific to this case study in Canberra, this will involve understanding the requirements of aquatic and riparian associated fauna (i.e., amphibians, riparian reptile and mammals, and freshwater fish), woodland associated fauna (i.e., native bees, small–medium mammals, woodland birds, and amphibians), and grassland-associated fauna (i.e., native bees, grassland reptiles, small–medium mammals, and amphibians) and identifying a spatially explicit conservation network which adequately provides for the protection and restoration of connected habitat to meet the needs of all. Combining information across taxon groups in this way to produce maps of functional connectivity to inform future urban planning offers an opportunity to identify gaps in connectivity for targeted restoration and validate estimates through targeted monitoring. Using our approach, expert estimates can harness congruency among taxon groups to maximise co-benefits and identify where additional conservation measures are required to conserve habitats which are not shared by multiple species assemblages (Gordon et al., 2009).

The IDEA protocol provided quantitative information on taxon-specific habitat requirements and constraints in data-deficient contexts and enabled robust consideration of functional constraint data (e.g., behavioural barriers) in our definitions of connected habitat. This enabled us to address the two limitations of applying BSUD identified by Kirk et al. (2018, 2021, 2023). Through reviewing the applicability of the IDEA protocol and assessing expert estimates, we identified that taxon-group variability and an occasional lack of consistency around metric relevance or interpretation limited the clarity around how to best interpret and apply estimates for habitat connectivity. We have discussed how these limitations can be addressed in future uses of expert elicitation in similar contexts. Applying these data to the calculation of connectivity indices (e.g., the City Biodiversity Index) would benefit from further investigation and validation of scenario-based assumptions through field-based assessments of species distribution (Kirk et al., 2018), as well as the creation of relevant spatial layers. This approach can also be used to estimate metrics related to within area habitat suitability and threats, not just connectivity. The application of the IDEA protocol to provide greater detail around habitat connectivity metrics in this study is anticipated to represent broad benefits for urban planning and developing BSUD frameworks in cities into the future.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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