BIOLOGICAL REVIEWS
Cambridge Philosophical Society

Biol. Rev. (2023), **98**, pp. 1530–1547.
doi: 10.1111/brv.12964

Hypotheses in urban ecology: building a common knowledge base

Sophie Lokatis[1,2,3,4,*], Jonathan M. Jeschke[1,2,3], Maud Bernard-Verdier[1,2,3], Sascha Buchholz[5], Hans-Peter Grossart[2,6], Frank Havemann[7], Franz Hölker[1,2,3], Yuval Itescu[1,2,3], Ingo Kowarik[3,8], Stephanie Kramer-Schadt[3,8,9], Daniel Mietchen[1,2,3,10], Camille L. Musseau[1,2,3], Aimara Planillo[3,9], Conrad Schittko[3,8], Tanja M. Straka[3,8] and Tina Heger[1,2,3,11]

[1] *Institute of Biology, Freie Universität Berlin, Königin-Luise-Str. 1-3, Berlin 14195, Germany*
[2] *Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Müggelseedamm 310, Berlin 12587, Germany*
[3] *Berlin-Brandenburg Institute of Advanced Biodiversity Research, Königin-Luise-Str. 2-4, Berlin 14195, Germany*
[4] *German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Puschstr. 4, Leipzig 04103, Germany*
[5] *Institute of Landscape Ecology, University of Münster, Heisenbergstr. 2, Münster 48149, Germany*
[6] *Institute of Biochemistry and Biology, Potsdam University, Maulbeerallee 2, Potsdam 14469, Germany*
[7] *Institut für Bibliotheks- und Informationswissenschaft, Humboldt-Universität zu Berlin, Dorotheenstraße 26, Berlin 10117, Germany*
[8] *Institute of Ecology, Technische Universität Berlin, Rothenburgstr. 12, Berlin 12165, Germany*
[9] *Leibniz Institute for Zoo and Wildlife Research (IZW), Alfred-Kowalke-Str. 17, Berlin 10315, Germany*
[10] *Institute for Globally Distributed Open Research and Education (IGDORE), Gothenburg, Sweden*
[11] *Technical University of Munich, Restoration Ecology, Emil-Ramann-Str. 6, Freising 85350, Germany*

ABSTRACT

Urban ecology is a rapidly growing research field that has to keep pace with the pressing need to tackle the sustainability crisis. As an inherently multi-disciplinary field with close ties to practitioners and administrators, research synthesis and knowledge transfer between those different stakeholders is crucial. Knowledge maps can enhance knowledge transfer and provide orientation to researchers as well as practitioners. A promising option for developing such knowledge maps is to create hypothesis networks, which structure existing hypotheses and aggregate them according to topics and research aims. Combining expert knowledge with information from the literature, we here identify 62 research hypotheses used in urban ecology and link them in such a network. Our network clusters hypotheses into four distinct themes: (*i*) Urban species traits & evolution, (*ii*) Urban biotic communities, (*iii*) Urban habitats and (*iv*) Urban ecosystems. We discuss the potentials and limitations of this approach. All information is openly provided as part of an extendable *Wikidata* project, and we invite researchers, practitioners and others interested in urban ecology to contribute additional hypotheses, as well as comment and add to the existing ones. The hypothesis network and *Wikidata* project form a first step towards a knowledge base for urban ecology, which can be expanded and curated to benefit both practitioners and researchers.

Key words: conceptual network, ecological theory, hypothesis network, knowledge visualisation, map of science, research synthesis, urban biology, Wikidata.

CONTENTS

* Author for correspondence (Tel.: +49 30 838 57294; E-mail: sophie.lokatis@fu-berlin.de).

I. INTRODUCTION

(1) Urban ecology

'*to truly advance the discipline of urban ecology requires the creation of new hypotheses and the identification of confirmed generalizations*' McDonnell & Niemelä (2011, p. 12)

Urban ecology is a multifaceted research field that ties together research traditions and methods from a wide range of backgrounds and disciplines. Over the past century, it has been adopted and expanded by researchers from fields as diverse as the social sciences, natural sciences and engineering (McDonnell & Niemelä, 2011; Weiland & Richter, 2011; Wu, 2014). While urban ecology used to be underrepresented in textbooks and journals of ecology (Forman, 2016), it is now recognised as an important research field for ecologists, evolutionary biologists and others. With urban systems being responsible for 60–80% of natural resource consumption (Peter & Swilling, 2012; UN-Habitat, 2017, 2020), and substantially impacting every other ecosystem on the globe, urban ecology has become a key research field in tackling the sustainability crisis (Rosenzweig *et al.*, 2010; Sachs *et al.*, 2019; Spiliotopoulou & Roseland, 2020; Tanner *et al.*, 2014). A number of journals cover the intersection of ecology with urban planning, urban biodiversity conservation and urban socio-economy, such as *Landscape and Urban Planning* (founded in 1974), *Urban Ecosystems* (1997), *Urban Forestry and Urban Greening* (2002) and the *Journal of Urban Ecology* (2015).

Urban ecology has different meanings to different researchers and stakeholders, a circumstance that is rooted in the history of the field, the unstandardized use of the term 'urban' (McIntyre, Knowles-Yanez & Hope, 2008; MacGregor-Fors, 2011; McDonnell & Hahs, 2008; Sukopp, 2008) and different meanings of the term 'ecology' (Schwarz & Jax, 2011). For example, Sukopp (1998) divided urban ecology into a solution-oriented branch with a research agenda to make cities more habitable and sustainable from the perspective of humans, focusing, for example on nature-based solutions and green infrastructure; and a natural-science branch that studies the natural world within cities, including environmental, biological, evolutionary and ecological patterns and processes, and treating human influences as ecological factors. Both branches are interdisciplinary; the first with a focus on urban planning and the second taking the perspective of natural scientists. They have partly been developed in concert, and the Berlin School provides an example for linking ecological studies with approaches to conserve and develop cities for the benefit of humans (see Kowarik, 2020; Popkin, 2022).

A framework introduced by Pickett *et al.* (1997) and put forward by Grimm *et al.* (2000) differentiates between ecology *of* cities and ecology *in* cities. Here, ecology *in* cities focuses on the distribution, abundance and interactions of non-human populations in the context of the diverse influences and impacts that urbanisation poses on them (Grimm *et al.*, 2000). The ecology *of* cities has a broader scope: it integrates ecology in cities with research from a social and environmental science perspective, with the aim of studying and understanding cities as ecosystems from an interdisciplinary perspective, including how they 'process energy or matter relative to their surroundings' (Grimm *et al.*, 2000, p. 574), but also looking at cities as social-ecological systems. Going even further, Des Roches *et al.* (2021) proposed to integrate evolutionary biology into the investigation of urban social–ecological systems, and McPhearson *et al.* (2016*b*) envisioned a 'science of cities' which comprises the ecology *in*, *of* and *for* cities in order to: 'motivate new and advanced cross-city comparative ecology, to develop more unified conceptual frameworks to advance urban ecology theory, and to synthesise core urban ecology research principles to guide future research in the field' (McPhearson *et al.*, 2016*b*, p. 198).

What researchers mean by urban ecology tends to be shaped by their disciplinary background and the research school they come from (Dooling, Graybill & Greve, 2007).

It is a common narrative that urban ecology in Europe focused on what Grimm *et al.* (2000) described as ecology *in* cities, while urban ecology in the anglophone literature was shaped by the sociological adaptation of the term 'ecology' to urban settings by the Chicago School of urban ecology in the 1920s (Wu, 2014), adopting an ecosystem-centred perspective with a focus on humans as key agents from the start (ecology *of* cities). Yet, this view is at least in part the result of barriers in communication. For example, there is a vast amount of urban-wildlife literature in the USA (Magle *et al.*, 2012) that even though not explicitly termed urban ecology can be viewed as ecology *in* cities; and there is the holistic ecosystem-centred research in Europe put forward in the late 1960s and culminating in the meticulous analyses of ecosystem flows of the metropolitan region of Brussels (Danneels, 2018; Kowarik, 2020) that can certainly be regarded as ecology *of* cities. International exchange between researchers from different schools of urban ecology grew stronger in the 1990s, along with important research schools arising around the globe, with a particular emphasis on research schools in Asia and Australia. Nowadays, research schools from all continents are collaborating with each other (Breuste & Qureshi, 2011), with collaborations spanning continents [e.g. the Urban Wildlife Information Network (UWIN); the Comparative Urban Research Training (CURT) network; the Global Urban Soil Ecological Education Network (GLUSEEN); and the Urban Biodiversity and Design (Urbio) network] and barriers in communication being less of an issue. Albeit not a new approach (e.g. Stearns & Montag, 1975; Sukopp, Numata & Huber, 1995), researchers all over the world now focus increasingly on combining natural-science urban ecology and solution-focused urban ecology, since a combined, integrative perspective is needed to tackle omnipresent challenges, such as building sustainable cities and conserving biodiversity outside of nature reserves (Collins *et al.*, 2000; Ramadier, 2004; Wolfram, Frantzeskaki & Maschmeyer, 2016).

(2) Mapping urban ecology

'*I sense that humans have an urge to map – and that this mapping instinct, like our opposable thumbs, is what makes us human*' – Katharine Harmon, cited in Börner (2010, p. 10)

Maps of research fields can visually guide us through the complex structure of science. They can guide scientists from both within and outside the field as well as policy makers, practitioners and others interested in the topic. This is particularly important in our current era, which is characterised by a rapid growth in data and publications. It is important to recognise that data and publications do not automatically translate into knowledge and understanding (e.g. Jeschke *et al.*, 2019), and that research in rapidly growing fields can become 'relatively ineffective and inefficient, as existing evidence is often not found, collaboration opportunities are missed, and research is too often conducted in pursuit of dead ends' (Jeschke *et al.*, 2021, p. 6). There is thus a strong need for synthesis tools that can intuitively provide orientation to research fields. Maps can serve as such tools and are becoming increasingly popular to structure active research fields (e.g. Enders *et al.*, 2020; Klavans & Boyack, 2009; Leydesdorff, Carley & Rafols, 2013). As outlined above, urban ecology is a particularly active field (see also Bai *et al.*, 2018; Wolfram *et al.*, 2016), and the pace of urban growth as well as the urgency of acting fast require sound and accessible synthesis tools. Ideally, such tools should enable dynamic, community-based evidence assessment.

Our aim here is to take initial steps towards a community-built knowledge base for urban ecology that can later be expanded and also interlinked with other disciplines. We use hypotheses as focal entities to build a map of urban ecology. Such an approach has the advantage that the mapped hypotheses can be linked with empirical evidence in the future. For the field of invasion biology, conceptual maps based on hypotheses were developed by Enders, Hütt & Jeschke, (2018) and Enders *et al.* (2020) and then combined with empirical evidence (Jeschke & Heger, 2018; Heger *et al.*, 2021) to create interactive maps of this research field (see http://www.hi-knowledge.org). When selecting a hypothesis from the map, it is possible to see how well it is supported and to identify research gaps. Ideally, the evidence for each hypothesis in such a map will grow continuously; an idea that has been proposed as community-built 'evidence revolution' (Nakagawa *et al.*, 2020).

For the current study, we took the following initial steps towards such a community-built knowledge base. First, we combined expert knowledge with information from the literature to identify key hypotheses in urban ecology; these will be the focal units of our map. Second, we structured the hypotheses in a network based on their attributes, identified important groups of hypotheses (clusters in the network) and propose this clustered network as a preliminary map of hypotheses in urban ecology. Third, we discuss the list and network of hypotheses in urban ecology and propose follow-up steps towards a community-curated knowledge base for urban ecology. To realise this goal, we invite other researchers to join us and contribute other relevant hypotheses, collectively to build a growing and evidence-linked map of urban ecology.

II. METHODS

(1) Identifying relevant hypotheses in urban ecology

We compiled hypotheses from urban ecology based on a combination of expert knowledge within our group and literature searches. A challenge for searching in literature databases like the *Web of Science* was that the term 'hypothesis' is (*i*) often not spelled out when hypotheses are formulated or (*ii*) is used for null-hypotheses and other statistical tests, which meant that this approach was not feasible. Therefore, we combined literature searches with an expert-based approach. Our goal was not to collect all existing hypotheses in the field of urban ecology, but to identify a set of relevant hypotheses that can serve as a starting point for a community-built knowledge base of urban ecology and can be expanded in the future.

Our approach to identify relevant hypotheses in the field of urban ecology consisted of the following steps. First, 74 hypotheses were identified from textbooks and *via* literature searches in the *Web of Science* and *Google Scholar*, including searching for the key words 'urban', 'city OR cities', 'ecology', 'hypothes*', 'theory', 'prediction', and back-tracing literature cited within key references (S. L., J. M. J., T. H.). Second, 11 additional experts in the field working on different aspects of urban ecology (M. B.-V., S. B., H.-P. G., F. Ha., Y. I., I. K., S. K.-S., C. L. M., A. P., C. S., T. M. S.) were asked to contribute further hypotheses that they considered relevant to urban ecology. The resulting list included 149 potentially relevant hypotheses (including synonymous hypotheses and concepts that other experts do not consider hypotheses or not relevant to urban ecology). Third, we identified synonymous hypotheses and merged them, agreed on a definition of 'hypothesis' (see next paragraph) and on which of the proposed hypotheses are actually relevant for urban ecology. We also cross-compared the identified hypotheses with the studies by Parris (2018), Forman (2016), as well as Cadenasso & Pickett (2008) and Pickett & Cadenasso (2017), who previously provided collections of theories, hypotheses and/or principles in urban ecology. This step resulted in 115 hypotheses. Fourth, we discussed and agreed on which of these hypotheses are overarching hypotheses *versus* lower-level sub-hypotheses. For example, the *Ideal urban dweller* hypothesis is an overarching hypothesis (see online Supporting Information, Data S1). It states that there are specific traits that make species successful in urban ecosystems. Several sub-hypotheses can be specified, depending on the taxonomic focus or type of change (see 'Sub-hypotheses' sheet in Data S1). For example, a sub-hypothesis focusing on animals is that urban dwellers have a higher cognitive performance than urban avoiders (Sol, Lapiedra & Ducatez, 2020). In this final step, we identified 53 sub-hypotheses and 62 overarching hypotheses; full lists of all sub-hypotheses and overarching hypotheses are provided in Data S1. The overarching hypotheses were mapped as a network (see Section II.2).

A basic methodological question is what exactly is regarded as a 'hypothesis'. Betts *et al.* (2021) define a hypothesis as 'an explanation for an observed phenomenon' (p. 5763), and a research question as 'a statement about a phenomenon that also includes the potential mechanism or cause of that phenomenon' (p. 5763). Scientists often tend to use the term 'hypothesis' in a broader sense, for ideas or predicted outcomes that can be tested and/or discussed. We here decided to define a hypothesis as an assumption that is based on a formalised or non-formalised theoretical model of the real world and can deliver one or more testable predictions (Heger *et al.*, 2021; after Giere, Bickle & Mauldin, 2005). Further, an important question is whether the prediction of a pattern is regarded as a hypothesis as well. While Pickett, Kolasa & Jones (2010) argue for regarding predictions of patterns as hypotheses as well, other authors have a much stricter view (Betts *et al.*, 2021). Here, we explicitly include non-explanatory, descriptive hypotheses, and suggest that they also contribute to ecological knowledge about cities. The identification of patterns can lead to valuable predictions and stimulate further research on underlying causal relationships. For example, for the *Earlier phenology* hypothesis, which states that seasonal life cycles tend to start earlier in the urban core than in rural surroundings (Roetzer *et al.*, 2000), several predictions can be formulated on how urbanisation influences phenology, e.g. by increased and/or more constant temperatures or concentrated light pollution.

A summary of the identified hypotheses is provided in Table 1 [the full data file is provided in Data S1 and as an open *Wikidata* project (https://www.wikidata.org/wiki/Wikidata:WikiProject_Ecology/Task_Force_Urban_Ecology)]. Where, to our knowledge, no accepted name for a given hypothesis currently exists, we provide a suitable name. The open *Wikidata* file is a 'living' project and can be expanded by including additional hypotheses or information, e.g. on additional taxonomic groups that a hypothesis has been applied to, the addition of sub-hypotheses, and empirical support of the hypotheses and respective sub-hypotheses.

We differentiate between (*i*) hypotheses that are specific to urban environments (i.e. they can only be tested in an urban environment) and have not been derived from more general ecological hypotheses, thus are unique to research in urban ecology; (*ii*) 'urbanised' hypotheses that exist in a more general or analogous form outside of urban ecology, but have been adapted to urban systems; and (*iii*) general hypotheses from another research field that have not been specifically adapted to urban systems but are nonetheless highly relevant there (e.g. the street barrier effect, as the high density of streets in cities can lead to strong constraints on species' movement; Mader, 1984).

To structure the hypothesis network, we characterised each hypothesis based on its focal entity or topic (i.e. whether it addresses species traits, trait evolution, niche shift, species abundance, community composition, species interactions, habitat quality, or ecosystem functioning and services), and the hypothesised drivers of change [artificial light at night, anthropogenic noise, climatic change (e.g. heat islands), chemical pollution, nutrients, fragmentation, habitat loss and isolation, invasive alien species and other novel organisms (*sensu* Jeschke, Keesing & Ostfeld, 2013), novel community composition and structure, and human presence and intervention]. A decision about which attribute to assign to each hypothesis was reached by a consensus approach: each hypothesis was assessed by two authors. If there was no agreement, a third author reassessed the respective hypotheses and consensus was reached *via* in-depth discussion among these three authors. The attributes assigned in this way were then shared with all other authors for feedback and final consensus. These assignments are provided for each hypothesis in Data S1.

Table 1. Information on the 62 hypotheses in urban ecology included in this study. Names for hypotheses are either taken from the literature or new names are proposed here (indicated by *). 'Label' refers to the abbreviation for each hypothesis used in Fig. 2. 'Cluster' indicates where each hypothesis is located: Cluster I, Urban species traits & evolution; II, Urban biotic communities; III, Urban habitats; IV, Urban ecosystems. 'Type' refers to the research field in which a hypothesis was formulated: Urban, urban ecology; Urbanised, hypotheses originally formulated in a related field other than urban ecology, but adapted to urban environments; Related field, research field other than urban ecology (if the hypothesis was originally formulated outside of urban ecology).

Hypothesis	Label	Cluster	Definition	Key reference(s)	Type
Acoustic adaptation*	AA	I	Animals that communicate acoustically adapt their vocalisations to the local conditions to optimise signal transmission.	Morton (1975)	Related field
Biodiverse cities*	BC	II, IV	Cities can sustain and promote biodiversity.	Walters (1970), Kühn *et al.* (2004)	Urban
Biodiversity-wealth*	BW	III	The socio-economic status of urban residents is positively related to the biodiversity in their neighbourhoods.	Kinzig *et al.* (2005)	Urban
Cities as entry points	CEP		Cities are entry points for introduced non-native species.	Pyšek *et al.* (2010); Potgieter & Cadotte (2020)	Urban
Credit card	CC	II	Low variability in resource abundance and reduced predation allow higher population densities in urban areas through the persistence of many weak competitors who remain in poor body condition, are less reproductively successful, and would not otherwise survive.	Shochat (2004)	Urban
Decay paradigm	DP	III	Species richness declines within patches of remnant native habitat isolated within an urban matrix; habitat-dependent (such as 'forest interior') species are expected to suffer a progressive series of local extinctions over time.	Catterall *et al.* (2010)	Urbanised
Earlier phenology	EP	I	Seasonal life cycles tend to start earlier in the urban core than in rural surroundings.	Roetzer *et al.* (2000)	Urbanised
Ecological trap	ET	I, III	Habitats preferred over other, higher quality habitats that are low in quality for reproduction or survival may not sustain a population.	Schlaepfer *et al.* (2002); Battin (2004)	Related field
Enemy release	ER	II	The absence of enemies is a cause of invasion success.	Keane & Crawley (2002)	Related field
Environmental filter	EF		Urban habitats filter communities as a function of their traits.	Aronson *et al.* (2016)	Urbanised
Epigenetic adaptation*	EA	I	Epigenetic mechanisms can explain why some organisms are more successful in urban than non-urban areas.	Isaksson (2015)	Urbanised
Food-web reshaping*	FWR	II	Urban food webs largely lack weak interactions, but the partly disassembled food webs retain a greater density of species interactions (e.g. greater connectance).	Start *et al.* (2020)	Urban
Generalists *vs.* specialists*	GVS		Generalist species are more frequent in urban areas than specialist species.	Sorace & Gustin (2009)	Urbanised
Genetic signatures*	GS	I	'Genetic signatures of urban eco-evolutionary feedback can be detected across multiple taxa and ecosystem functions.' (Alberti, 2015, p. 116)	Alberti (2015)	Urban
Green roofs	GR	III	Green roofs promote urban biodiversity.	Oberndorfer *et al.* (2007); Williams *et al.* (2014)	Urban
Habitat diversity	HD	III	Biodiversity in urban areas is high due to habitat diversity.	Pyšek (1989)	Urbanised
Habitat isolation	HI	III	More isolated habitat islands have lower species richness.	MacArthur & Wilson (1967)	Related field

(Continues on next page)

Table 1. *(Cont.)*

Hypothesis	Label	Cluster	Definition	Key reference(s)	Type
Herbivore proliferation*	HP	II	Herbivores may become hyperabundant in urban areas, sometimes leading to pest outbreaks.	Raupp *et al.* (2010)	Urban
High propagule pressure in cities*	PHC		A higher proportion of alien taxa in captivity and cultivation leads to an increased propagule pressure in cities.	Kühn *et al.* (2017); Potgieter & Cadotte (2020)	Urbanised
Home range reduction*	HRR	I, III	Many species maintain smaller home ranges in urban areas.	Mannan & Boal (2000); Atwood *et al.* (2004); Wright *et al.* (2012)	Urban
Human commensalism	HC	I	Species that live in close proximity to humans are more successful in invading new areas than other species.	Jeschke & Strayer (2006)	Related field
Hyperabundance due to anthropogenic food*	HAF	I, II, III	An increase in the proportion of anthropogenic food with urbanisation leads to an increase in the abundance of prey as well as mid-sized animals (e.g. mesopredators).	Fischer *et al.* (2012)	Urban
Ideal urban dweller*	IUD	I	There are specific traits that make species successful in urban ecosystems.	Evans *et al.* (2011); Adler & Tanner (2013, p. 202)	Urban
Increased boldness	IB	I	Animals tend to become bolder in urban than non-urban areas.	Knight *et al.* (1987); Uchida *et al.* (2019)	Urban
Intermediate disturbance	ID	III	Biodiversity is high in sites that show intermediate levels of disturbance and decreases with no and high levels of management.	Grime (1973); Connell (1978, p. 1303)	Related field
Landscape of fear	LOF	I, II	Animals adjust their behaviour and activity to avoid humans spatio-temporally.	Brown *et al.* (1999); Laundré *et al.* (2010); Bleicher (2017)	Related field
Light at night – social interaction*	LSI	I, II	Light pollution alters the social interactions and group dynamics of animals.	Kurvers & Hoelker (2015)	Related field
Matrix species	MS	II, III	Urban habitat remnants are more sensitive to the penetration of matrix species than less disturbed suburban or rural remnants.	Tóthmérész *et al.* (2011)	Urban
Microbiota exposure	ME	II, IV	Urbanisation reduces exposure of humans to environmental microbiota, leading to higher allergy risks and negative effects on immune function.	Ruiz-Calderon *et al.* (2016); Parajuli *et al.* (2018)	Urban
Non-native species hypothesis* aka Invader species	IS		Non-native species richness increases with urbanisation.	Sukopp (1969); Kunick (1974); Kowarik (1988); Blair (2001)	Urban
Non-native substitution*	NNS	II	Non-native plants in urban areas can sometimes substitute the loss of resources provided by native plants.	Berthon *et al.* (2021)	Urbanised
Novel communities	NC	II	Urban environments have novel communities that do not exist in natural environments.	Perring *et al.* (2013*a*)	Urban
Plant host switching	PHS	I, II	The abundance of alien plants in the urban core encourages native arthropods (herbivores, pollinators) to switch from native to alien host(s).	Shapiro (2002); Raupp *et al.* (2010)	Urban
Population pressure hypothesis	PPH	III	Urban habitats serve as sinks for rural dispersers. Continuous gene flow between a rural source and an urban sink population prohibits pronounced genetic differentiation.	Gloor *et al.* (2001)	Urban
Predator proliferation	PP	II	Predator densities and/or predation rates are higher in urban than non-urban areas.	Fischer *et al.* (2012) based on Sorace (2002); Eötvös *et al.* (2018)	Urban
Predator relaxation	PR	I, II	Predator density, prey mortality and/or prey fearfulness are lower in urban than non-urban areas.	Tomialojc (1982); Gering & Blair (1999)	Urban

(Continues on next page)

Table 1. *(Cont.)*

Hypothesis	Label	Cluster	Definition	Key reference(s)	Type
Prey specialisation	PS	I, II	'The diet of carnivorous mesopredators will be increasingly dominated by a few species with urbanisation. These prey species will be hyperabundant within cities. The predation rate on prey species that are not hyperabundant will decline with urbanisation.' (Fischer *et al.*, 2012, p p. 816)	Fischer *et al.* (2012)	Urban
Rapid adaptation	RA	I	Rates of evolutionary change are greater in urban systems.	Alberti *et al.* (2017*b*); Johnson & Munshi-South (2017)	Urbanised
Resilience of urban hybrid systems*	RUH	II, IV	'Resilience in urban ecosystems is a function of the patterns of human activities and natural habitats that control and are controlled by both socio-economic and biophysical processes operating at various scales'. (Alberti & Marzluff, 2004, p. 242)	Alberti & Marzluff (2004)	Urban
Shift toward non-migratory species*	SMS	I	Urbanisation favours non-migratory species.	McClure (1989)	Urban
Species richness – HPD*	SRH		Species richness is positively correlated with human population density.	Luck (2007)	Related field
Species-area relationship	SAR	III	Species richness and diversity increase with habitat size.	MacArthur & Wilson (1967)	Related field
Street barrier effect	SBE	III	Streets act as dispersal barriers.	Mader (1984)	Related field
Street corridor effect	SCE	III	Streets act as dispersal corridors.	Seabrook & Dettmann (1996); James & Stuart-Smith (2000); von der Lippe & Kowarik (2007)	Related field
Suburban peak*	SP	III	Species richness is highest in sub-urban areas; it is lower in urban centres and the (rural) periphery.	Blair (2001)	Urban
Synanthropic species	SS		The number of synanthropic species increases along the rural–urban gradient.	Klausnitzer (1987, p. 106); Guetté *et al.* (2017)	Urban
Thermal tolerance increase	TTI	I	Thermal tolerance increases with urbanisation.	Diamond *et al.* (2018)	Urban
Urban avoiders	UA	I	Urban avoiders have a reduced ability to adapt, compete and/or reproduce in cities.	Blair (1996)	Urban
Urban biodiversity hot spots*	UHS	II, III, IV	Cities are often located in areas of high biodiversity, and urbanisation is disproportionally higher in areas with high biodiversity.	Kühn *et al.* (2004); Luck (2007); Ives *et al.* (2016)	Urban
Urban biotic homoge nisation	UBH		Species composition of different cities will become more and more similar as urbanisation increases.	Blair (2001); McKinney (2006); Groffman *et al.* (2014)	Urbanised
Urban core herbivore decline*	UCH	II	The abundance of alien plants in the urban core tends to reduce the richness and abundance of native herbivore insects incapable of using non-native plants.	Raupp *et al.* (2010)	Urbanised
Urban density-diversity paradox*	UDD		Diversity typically increases as the number of individuals increases in biological communities. Urban environments, however, tend to be characterised by lower biodiversity than wildlands despite high population densities.	Shochat *et al.* (2010); Saari *et al.* (2016)	Urban
Urban eco-evolutionary mechanisms*	UEE	I	'Through urbanisation, humans mediate the interactions and feedbacks between evolution and ecology in subtle ways by introducing changes in habitat, biotic interactions, heterogeneity, novel disturbance, and social interactions.' (Alberti, 2015, p. 116)	Alberti (2015)	Urban

(Continues on next page)

Table 1. *(Cont.)*

Hypothesis	Label	Cluster	Definition	Key reference(s)	Type
Urban ecosystem convergence	UEC	II, IV	All ecosystems types respond to urban land use in a convergent manner (in other words: urban ecosystems are convergent regardless of the original ecosystem they replaced).	Pouyat *et al.* (2002)	Urban
Urban ecosystems as source of innovation*	USI	I	'The hybrid nature of urban ecosystems – resulting from co-evolving human and natural systems – is a source of "innovation" in eco-evolutionary processes.' (Alberti, 2015, p. 117)	Alberti (2015)	Urban
'Urban effect' on invasion	UEI		The number of non-native species moving through each invasion stage (transport, introduction, establishment, spread) is higher in urban areas than in natural environments.	Potgieter & Cadotte (2020)	Urban
Urban fragmentation	UF	I, III	Urbanisation, specifically the fragmentation of habitats, leads to a loss of genetic variation within and increased differentiation between populations.	Miles *et al.* (2019)	Urbanised
Urban habitat analogues*	UHA	I	Native species can switch to urban habitats.	Thellung (1919); Lundholm & Richardson (2010)	Urbanised
Urban mesopredator release*	UMR	II	'The abundance of large-bodied predators will decline with urbanisation, whereas the abundance of mesopredators will increase.' (Fischer *et al.*, 2012, p. 816)	Crooks & Soulé (1999); Fischer *et al.* (2012)	Urbanised
Urban sexual traits*	UST	I	In urban environments, species show shifts in several traits related to sexual selection (particularly in their coloration, acoustic signals including songs and calls, hormones, pheromones, mating behaviour).	Sepp *et al.* (2020)	Urban
Urbanisation ecosystem functioning*	UEF	II, IV	Urbanisation leads to a reduction in ecosystem functions and services.	Grimm *et al.* (2008)	Urban
Urbanisation tolerance	UT	III	Biodiversity loss in cities can be explained by a low tolerance of species to urbanisation.	Sol *et al.* (2014)	Urban

(2) Network and cluster analysis

The matrix of hypotheses and attributes was used to create a bipartite network; here, every hypothesis is linked to attributes (i.e. focal entities or topic related to a hypothesis, or drivers of change) and *vice versa*. No information is lost, as opposed to monopartite networks that use dissimilarity matrices of the interconnected nodes rather than the connections between hypotheses and attributes themselves, resulting in a network showing presence *versus* absence of links.

Typically, clusters in network analyses are created based on the similarity or connectivity of nodes, here hypotheses and attributes. Nodes are assigned to specific clusters, and each node is attributed to exactly one cluster. Here, we created a set of 24 clusters based on four regularly used node-based algorithms from R iGraph (GN, Fastgreedy, Walktrap and leading eigenvector, R version R 4.1.1). All four algorithms evaluate network partitioning into disjoint node communities or clusters by calculating modularity (see Newman & Girvan, 2004).

In a third step, these clusters were optimised by a memetic algorithm (PsiMinL) that clusters links instead of nodes and optimises each cluster separately (Havemann, Gläser & Heinz, 2017; Havemann, 2021) by iteratively adding or removing links. By setting the value of the resolution parameter r ($r < 1$), we can control the resolution of the set of clusters; a small value (closer to 0) results in many poorly distinct clusters, while a value close to 1 will result in few clusters with little overlap. Because the network analysed here is relatively small, we are confident that PsiMinL can find all relevant clusters possible for the chosen value for r (here $r = 1/3$) after a small number of evolutionary searches. The resulting optimised clusters have the advantage that nodes can be members of more than one cluster (see Enders *et al.*, 2020), and the resulting clusters also will be more robust, as the algorithm does not force nodes into clusters. A detailed description of the network analysis is provided in Appendix S1.

Membership of a hypothesis in a cluster is quantified as the percentage of links between attributes and a hypothesis, e.g. two out of three links leading to a node equals a membership of 67% in the respective cluster. A hypothesis (node) can be included in two clusters with 100% if they overlap one another.

III. RESULTS AND DISCUSSION

(1) Hypotheses in urban ecology

We identified 62 hypotheses in urban ecology (Table 1). Thirty-six hypotheses are uniquely or originally urban; 12 stem from related fields like invasion biology or biogeography, but are highly relevant to urban ecology; and 14 hypotheses exist in a general version and, here, are adapted to an urban setting ('urbanised'). This collection of hypotheses for urban ecology has a different scope and goes beyond previous compilations that have attempted to structure this field. The approach of Cadenasso & Pickett (2008) was theory driven, and their five principles aimed to ground urban ecology within scientific theory and provide suggestions for urban planning and landscape design. These five principles are: (*i*) 'urban areas are ecosystems', (*ii*) 'urban ecosystems are diverse', (*iii*) 'urban ecosystems are dynamic'; (*iv*) 'human and natural processes interact in cities' and (*v*) 'ecological processes remain important in cities' (Cadenasso & Pickett, 2008, p. 8). These principles were later extended by the same authors to 13 principles (Pickett & Cadenasso, 2012).

Taking a different approach, Forman (2016) published a compilation of 90 principles, based on six reviews on urban ecology. These contain more detailed and case-specific findings and generalisations from empirical research on urban ecosystems; for example, 'More buildings and tall structures create both more habitats and hazards for organisms.' (Forman, 2016, p. 1657). Parris (2018) recently published a collection of theories, paradigms and hypotheses from general ecology that have been shown to apply in urban systems.

Similar to Forman (2016) and Parris (2018), and unlike Cadenasso & Pickett (2008) and Pickett & Cadenasso (2017), we used a bottom-up approach to structure the field of urban ecology. While there are shared aims between these studies and ours, focusing on hypotheses has two large benefits: (*i*) in contrast to principles, hypotheses and hypothetical generalisations imply that what they describe or predict is still under scientific inquiry, and possibly questioned and tested in numerous instances; (*ii*) hypotheses can be directly linked to empirical evidence in a future step (see Fig. 1), thereby distinguishing between well-supported and highly questioned hypotheses, and allowing the identification of research gaps.

Given the unique nature of urban ecosystems, an interesting question is whether general ecological theory can be directly applied to urban ecology (Parris, 2018). Urban ecosystems differ profoundly from natural ones, and ecologists have identified many differences between urban and non-urban systems, arguing that ecological theory has at least to be adapted (Niemelä, 1999), if not profoundly expanded (Collins *et al.*, 2000; Alberti, 2008; McPhearson *et al.*, 2016*a*), for urban systems. Still, ecological theory has been repeatedly applied to urban settings (Parris, 2018). Of the 62 hypotheses listed in Table 1, 14 have been adapted from general ecological theory to urban systems (23%), and 12 (19%) are from related fields. These hypotheses from fields like evolutionary biology or general ecology are highly relevant in urban settings, and thus a vital part of urban ecology. Take, for example, the *enemy release* hypothesis which is well known in invasion ecology (Enders *et al.*, 2018) and explains the invasion success of species in the absence of (co-evolved) enemies in novel settings. As urban ecosystems have been shown to be rich in non-native species (e.g. Kowarik, 2008), and even hypothesised to act as distribution hubs for species invasions into rural regions (von der Lippe & Kowarik, 2008) as well as to other cities worldwide (Potgieter & Cadotte, 2020), urban ecology and invasion biology are closely connected research fields. Therefore, hypotheses formulated for invasion biology can often be applied to urban settings. As a wide variety (if not most) of general ecological theory also can be applied in urban settings (see Parris, 2018), our selection here is far from

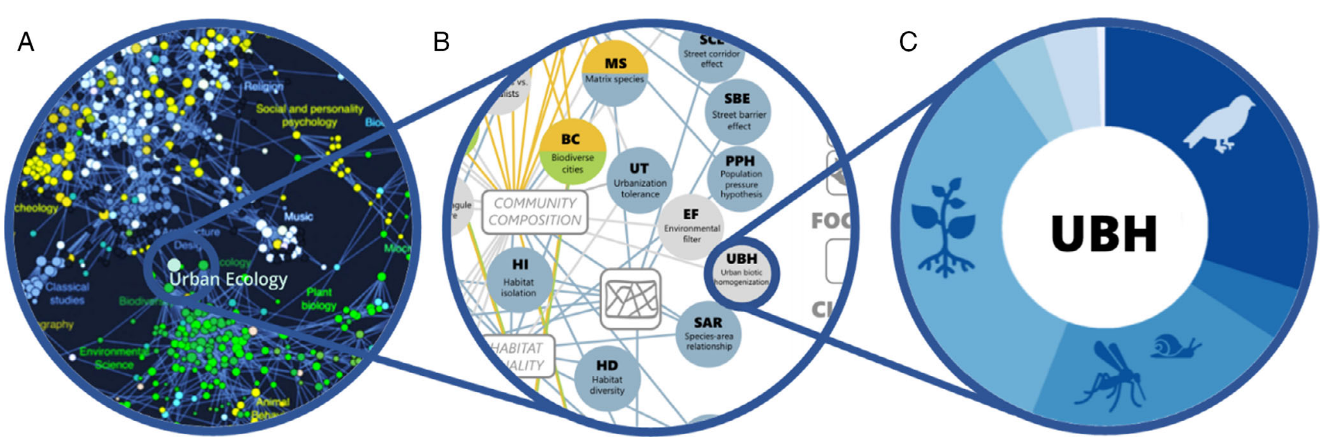


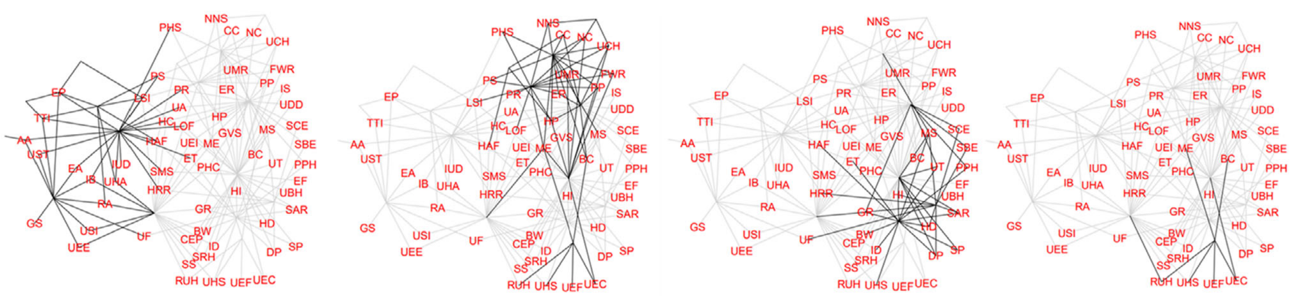
Fig. 1. The network of hypotheses in urban ecology (B) can be interlinked with hypotheses (or other knowledge entities) from other fields and positioned within a broader network of science (A; modified from Bollen *et al.*, 2009). Each hypothesis can be connected with empirical evidence, or with meta-information on the research related to a hypothesis (C; modified from Lokatis & Jeschke, 2022). Here, the proportion of taxonomic groups for which biotic homogenisation has been studied in an urban context is shown.

exhaustive. Accompanying the rapid loss of the untouched, pristine nature (Watson *et al.*, 2016; Potapov *et al.*, 2017) that has been studied by classical ecology (Inkpen, 2017), urban ecosystems are nowadays only one among many strongly transformed ecosystem types, and can even be regarded as trial systems for studying effects of multiple global changes (Lahr, Dunn & Frank, 2018). For Johnson & Munshi-South (2017, p. 1), the global network of cities might even be 'the best and largest-scale unintended evolution experiment'. So instead of asking if and in what form classical ecological theory can be applied to urban systems, the inverse question might become increasingly important in the future (Forman, 2016): can research from urban ecology help us to understand other anthropogenically shaped ecosystems?

(2) A first map of hypotheses in urban ecology

Maps are a powerful tool to visualise knowledge. Envisioning an 'atlas of science' that uses mapping technology to connect the different branches of science, we here propose a first map of urban ecology. This map can be connected to other fields (Fig. 1A) and serve as a reference point for researchers from urban ecology and other disciplines (Fig. 1B). Using hypotheses as nodes for the network opens the possibility that each hypothesis can be connected with empirical evidence and meta-information about a particular hypothesis (Fig. 1C).

To provide a visualisation of knowledge in urban ecology, we applied a semi-automated approach to map all 62 hypotheses and the 16 assigned attributes listed in Table 1 in a bipartite network (Appendix S1; Fig. 2). Of the seven clusters identified in a network analysis (see Table S1 in Appendix S1), the four best separated clusters were retained (clusters I–IV). These clusters were named according to the hypotheses and attributes they contain (Figs 2, 3), and will be described in detail below. Cluster L0–L1 is the complementary cluster to cluster I and is thus redundant, and three clusters (L5, L6 and L7, see Table S1 in Appendix S1) were not retained because they were rather small and not as well separated as the other clusters (see Appendix S1). Several hypotheses are part of more than



I Urban species traits & evolution		%
Acoustic adaptation	AA	100
Earlier phenology	EP	100
Epigenetic adaptation	EA	100
Genetic signatures	GS	100
Ideal urban dweller	IUD	100
Increased boldness	IB	100
Rapid adaptation	RA	100
Thermal tolerance increase	TTI	100
Urban eco-evolutionary mechanisms	UEM	100
Urban ecosystems as source of innovation	USI	100
Urban habitat analogues	UHA	100
Urban sexual traits	UST	100
Light at night – social interaction	LSI	50
Prey specialization	PS	50
Shift towards non-migratory species	SMS	50
Urban avoiders	UA	50
Urban fragmentation	UF	50
Hyperabundance due to anthrop. food	HAF	40
Human commensalism	HC	33
Home range reduction	HRR	33
Plant host switching	PHS	33
Ecological trap	ET	25
Predator Relaxation	PR	25
Landscape of fear	LOF	20

II Urban biotic communities		%
Biodiverse cities	BC	100
Credit card	CC	100
Enemy release	ER	100
Food-web reshaping	FWR	100
Herbivore proliferation	HP	100
Microbiota exposure	ME	100
Non-native substitution	NNS	100
Novel communities	NC	100
Predator proliferation	PP	100
Urban core - herbivore decline	UCH	100
Urban ecosystem convergence	UEC	100
Urbanization ecosystem functioning	UEF	100
Urban mesopredator release	UMR	100
Plant host switching	PHS	67
Prey specialization	PS	50
Resilience of urban hybrid systems	RUH	50
Urban biodiversity hot spots	UHS	33
Matrix species	MS	25
Predator relaxation	PR	25
Hyperabundance due to anthrop. food	HAF	20
Landscape of fear	LOF	20
Light at night – social interaction	LSI	17

III Urban habitats		%
Decay paradigm	DP	100
Green roofs	GR	100
Habitat diversity	HD	100
Habitat isolation	HI	100
Matrix species	MS	100
Population pressure hypothesis	PPH	100
Species-area relationship	SAR	100
Street barrier effect	SBE	100
Street corridor effect	SCE	100
Suburban peak	SP	100
Urbanization tolerance	UT	100
Urban fragmentation	UF	50
Biodiversity-wealth	BW	33
Intermediate disturbance	ID	33
Urban biodiversity hotspots	UHS	33
Ecological trap	ET	25
Home-range reduction	HRR	33
Hyperabundance due to anthrop. food	HAF	20

IV Urban ecosystems		%
Resilience of urban hybrid systems	RUH	100
Urban ecosystem convergence	UEC	100
Urbanization ecosystem functioning	UEF	100
Biodiverse cities	BC	33
Urban biodiversity hotspots	UHS	33
Microbiota Exposure	ME	20

Urban
Urbanized
Related field

Fig. 2. 62 hypotheses in urban ecology grouped into clusters identified by a link clustering algorithm. The best separated and meaningful clusters are shown here and were subsequently named Urban species traits & evolution, Urban biotic communities, Urban habitats and Urban ecosystems. Cluster membership of all hypotheses attributed to a cluster are listed below each cluster. Cluster membership values indicates the proportion of links leading to a hypothesis that belong to that cluster. Coloured circles indicate whether a hypothesis has been formulated within urban ecology (blue), adapted to urban ecology ('urbanised', blue-outlined yellow), or is a general hypothesis from a related field (yellow). Links that belong to a cluster are black, other links are grey. Note that not all hypotheses were allocated into one of the four clusters, and that some appear in more than one cluster.

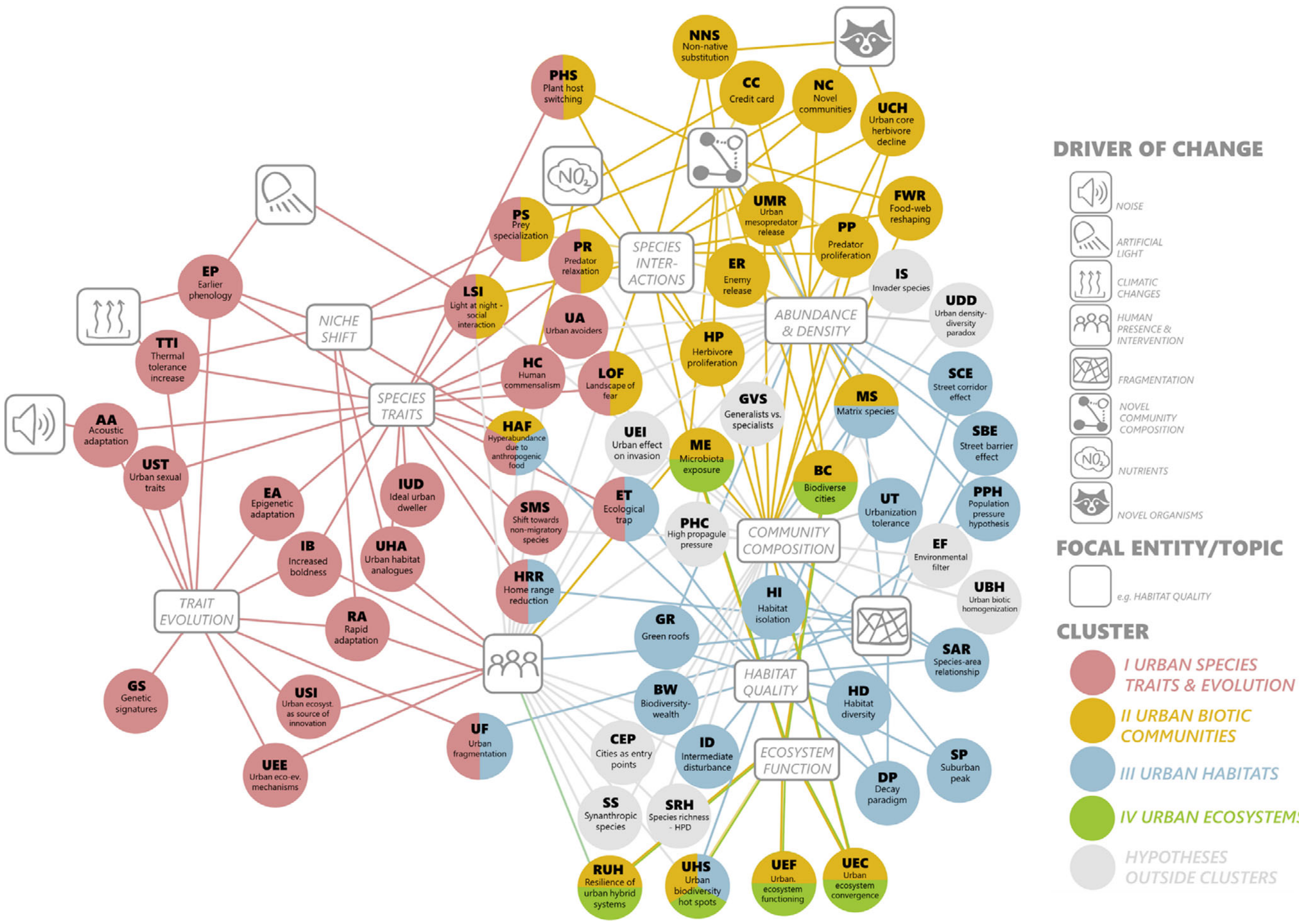


Fig. 3. Bipartite network of 62 hypotheses (circles) and 16 attributes (grey boxes at the intersection of several links showing focal entities/topics and drivers of change), which were used to characterise and group the hypotheses. Four clusters that emerged when applying a link clustering algorithm (see Appendix S1) are shown: Urban species traits & evolution (red), Urban biotic communities (yellow), Urban habitats (blue) and Urban ecosystems (green). Full circles belong to a single cluster, divided circles indicate that a hypothesis has shared membership between two or more clusters. Hypotheses within a white circle do not belong to any of the clusters.

one cluster, and ten hypotheses are not part of any of the four named clusters (Fig. 3). Cluster IV is nested within cluster II, but was retained as it is well separated and informative. It is a feature of such analyses that clusters share overlapping links and nodes (Fig. 1).

(*a*) *Cluster I: urban species traits & evolution*

Cluster I (Urban species traits & evolution) comprises 24 hypotheses; 12 hypotheses have 100% membership (i.e. all links leading to a hypothesis belong to that cluster) and 12 hypotheses have a membership of ≤50% (Fig. 2). Attributes of this cluster can be separated into the focal entities or topics: species traits, trait evolution and niche shift (all 100% cluster membership); and into the drivers of change: artificial light, noise, climatic change (all 100% cluster membership) and human presence and intervention (23%) (Fig. 3). Although this cluster has some overlap with Urban biotic communities (cluster II) and Urban habitats (cluster III), it has the lowest normalised node-cut Psi-value among the identified clusters, indicating that it was the best separated cluster.

A major focus of the hypotheses in this cluster is to predict and explain which traits characterise species that inhabit urban areas, and how they adapt to urban environments. The study of species that live close to human settlements dates back to studies on birds, mammals and blowflies in the 1950s (see Povolný, 1962; Nuorteva, 1963, 1971), and far earlier for plants (Linkola, 1916; reviewed by Sukopp, 2008). A central idea in this cluster is the *Ideal urban dweller* hypothesis, which posits that specific traits make species successful in urban ecosystems. This is a very general statement that we chose to treat as an overarching hypothesis that can be specified into a range of descriptive hypotheses focusing on a specific taxonomic group or urban setting, and which implicitly assumes that there is a set of traits characterising an ideal urban dweller (or other positions on the urban affinity spectrum; Wolf *et al.*, 2022). This might be higher cognitive performance or increased capability to learn (Sol *et al.*, 2020), an enhanced movement capacity (Santini *et al.*, 2019), or greater dietary flexibility (Palacio, 2020; Scholz *et al.*, 2020; Planillo *et al.*, 2021). Hypotheses like *acoustic adaptation*, *earlier phenology*, *increased boldness*, *thermal tolerance increase* and *shift towards non-migratory species* link evolutionary changes to physical stressors in urban environments or the presence of humans. *Epigenetic adaptation*, *genetic signatures*, *rapid adaptation* and *urban eco-evolutionary mechanisms* are hypotheses about general evolutionary processes that are expected in urban settings.

(*b*) *Cluster II: urban biotic communities*

The Urban biotic communities cluster includes 13 hypotheses with 100% membership and nine hypotheses with a membership between 17% and 67% (Fig. 2). Drivers of change within this cluster are: nutrients, novel organisms and novel community composition (all 100%) as well as human presence and intervention (5%); focal entities and topics include species interaction (100%), ecosystem functioning (100%) abundance & density (33%), and community composition (30%).

Hypotheses in the Urban biotic communities cluster focus on research questions investigating how urban food webs, communities and species assemblages differ from non-urban ones, and what features characterise urban species interactions (e.g. predation or competition). Four hypotheses that are clearly related to abundance and density, as well as community composition (i.e. *invader species*, *urban density-diversity paradox*, *urban effect on invasion* and *high propagule pressure in cities*) were not grouped within cluster II, but are in the vicinity of this cluster (Fig. 3). Nested completely within the Urban biotic communities cluster is the Urban ecosystems cluster (cluster IV) outlined below.

(*c*) *Cluster III: urban habitats*

The Urban habitats cluster includes 11 hypotheses with 100% membership and seven hypotheses with ≤50% membership (Fig. 2). The focal entities/topics for this cluster are: habitat quality (100%) as well as abundance & density and community composition (23% and 24%, respectively), and the drivers of change are fragmentation (100%), novel community composition (7%) and human presence and interaction (5% membership).

The central question of this cluster is which habitat characteristics influence populations, species and their interactions, and how urban habitats can be characterised. For example, a high diversity of habitats in urban areas has been linked to high overall biodiversity of cities (Pyšek, 1989; Sattler *et al.*, 2010; Helden & Leather, 2004), a hypothesis that is well known but often only implicitly tested. An example for a pair of contrasting hypotheses included in this cluster is the *street barrier effect*, which predicts that traffic routes reduce the mobility of urban wildlife (Rondinini & Doncaster, 2002; Riley *et al.*, 2014), and the *street corridor effect* (Seabrook & Dettmann, 1996; von der Lippe & Kowarik, 2007; Riley *et al.*, 2014), which describes the opposite, i.e. species or populations moving more easily along streets. The Urban habitats cluster is characterised by a larger proportion of hypotheses adapted or directly applied to urban systems from other research areas, especially biogeography, population ecology and conservation ecology.

(*d*) *Cluster IV: urban ecosystems*

Incorporating patterns and processes on the ecosystem level, the Urban ecosystems cluster comprises only six hypotheses, of which only three have a cluster membership of 100% (Fig. 2). These hypotheses focus on ecosystem functions or services. Three other hypotheses have a lower affiliation (20–33%). The attributes of this cluster are: ecosystem functioning (focal topic, 100% membership), human presence and intervention (driver of change, 5% membership) and community composition (focal topic, 3%).

Not all hypotheses dealing with ecosystems are included in this cluster (e.g. *urban ecosystems as source of innovation* belongs to cluster I), but it is still striking that so few of the hypotheses are concerned with ecosystem functions or services. Thus, while we expect that this part of the network will be extended in the future, e.g. by including research on microbial urban ecology, it might be fruitful to consider how work in urban ecosystems that is not hypothesis-oriented could be covered within a community-built knowledge base as proposed here.

(3) Critical reflections

The network presented here was built by combining expert knowledge with a network algorithm. While there are many possibilities for building networks, we chose to create a bipartite network with the advantage that the information about the assessed hypotheses is directly translated into a network structure, instead of relying on one of numerous possible measures of (dis)similarity. This approach is also flexible and easy to adjust for additions to the underlying data set, which we hope will happen in the near future. The resulting network represents a first step towards a knowledge map for urban ecology (see Fig. 1). It has to be noted, however, that by only building on explicitly formulated hypotheses, certain topics addressed in urban ecology might be underrepresented or even missing. Grogan (2005) found that less than half of a selection of articles from ecological journals explicitly used hypotheses. Nilsen, Bowler & Lind (2020) found this proportion to be only 19% in a random selection of articles from practitioner-orientated journals in conservation biology, applied ecology and wildlife management. We expect that this proportion is equally low in urban ecology, and also will vary profoundly among its sub-disciplines, due to its inherent multidisciplinarity. For example, we expect the content of the Urban ecosystems cluster to increase once more explicit hypotheses are included, because urban ecosystem models and analyses of material flow and processes in cities implicitly contain hypotheses. Whether it makes sense to formulate these hypotheses, and add them to our network, or whether it might be more constructive to adapt the network to include models, concepts or research questions remains to be discussed in the future.

As pointed out above, this network builds on a first list of key hypotheses identified by a group of experts that will need to be expanded with the help of the broader community of urban ecologists. Additional hypotheses will then probably also alter the structure of our network. For example, the Urban species traits & evolution cluster is currently well separated from all other clusters, with only a few hypotheses shared with the Urban biotic communities cluster (e.g. *plant host switching*) and the Urban habitats cluster (e.g. *ecological trap*, *urban fragmentation*). We expect that increasing the network resolution (i.e. including additional sub-hypotheses and adding new hypotheses) will probably strengthen the overlap between these clusters, as habitat fragmentation, community composition and novel organisms are also studied as important evolutionary factors (Shochat *et al*., 2006; Diamond & Martin, 2021; Winchell, Battles & Moore, 2020; Borden & Flory, 2021).

The collection of hypotheses and their clustering are a result of the joint contributions and expertise within our group. Our scientific work is currently predominantly carried out in Berlin (Germany), and even though many of us have close connections or backgrounds with other research schools and scientists around the world, we expect that other researchers would have selected different hypotheses and added their own perspectives to the creation of a hypothesis map in urban ecology. In the next and final section, we therefore discuss how the present selection and map of hypotheses can be expanded to incorporate a more diverse and less biogeographically and culturally biased view on hypotheses in urban ecology.

(4) Co-creating a knowledge base of urban hypotheses

The list of hypotheses that we mapped is not exhaustive, but can serve as a basis to formulate other hypotheses, to expand the map with additional (sub-)hypotheses from urban ecology, and to link it to other disciplines from within and outside urban ecology (see Fig. 1). We hope that the network can act as a starting point which other disciplines from urban ecology in the broader sense can expand, and rearrange, where appropriate. Knowledge gaps are known to be especially pronounced in the Global South and in areas with the highest urbanisation pressure, as well as on a global level, with most research still carried out locally (Young & Wolf, 2006; Shackleton *et al*., 2021). To synthesise existing theory and constantly update new findings, as well as to identify research gaps, it is necessary to compare and communicate between different research disciplines and stakeholders. As a first step, we provide our data file of hypotheses as an open expandable *Wikidata* file, that we envision to grow collaboratively in the future. As part of the *Wikidata* project, well-studied hypotheses can also be linked to meta-analyses and literature reviews, or to the body of relevant data and literature. Hypotheses can thus be assessed directly, as well as analysed from a meta-perspective, i.e. by generating bibliometric networks, and charts, as well as evidence maps, with the aim to identify gaps and biases in research. A *Wikidata*-based tool – Scholia – is available for such visualisations (Nielsen, Mietchen & Willighagen, 2017) and can provide an introductory overview of research areas like urban ecology. It has been adapted to support geospatial queries (Nielsen, Mietchen & Willighagen, 2018) and is currently being refined further to facilitate hypothesis-centric visualisations (Jeschke *et al*., 2021). We chose *Wikidata* as a platform, as it is free, open-access, community-run, user-friendly, well established and adheres to the FAIR-principles (Wilkinson *et al*., 2016, Waagmeester *et al*., 2020). Entries can be easily linked to entries from other platforms, and existing knowledge (in our case: hypotheses) can be linked to existing literature and data sets (Erxleben *et al*., 2014; Vrandečić & Krötzsch, 2014).

We advocate for a more frequent use of explicit hypotheses in urban ecology and invite future authors to expand our data file both by adding more or alternative hypotheses and by adding explanations to overarching and descriptive hypotheses. Additionally, this collection and mapping of hypotheses will greatly benefit from information on the validity or generality of the collected hypotheses and from linking of hypotheses with empirical data. In the future, we envision a more extensive knowledge base that includes related fields like urban ecology, restoration ecology (Heger *et al*., 2022) and invasion biology.

IV. CONCLUSIONS

(1) Urban ecology is a growing research field in which there are numerous different hypotheses that could benefit from applying new synthesis tools.
(2) A map of 62 hypotheses from urban ecology broadly clusters into four main themes: Urban species traits & evolution; Urban biotic communities; Urban habitats; and Urban ecosystems.
(3) We propose using this network as a basis for a community-built knowledge base of hypotheses in urban ecology, and introduce a *Wikidata* project for this purpose.
(4) Our map of hypotheses in urban ecology will hopefully foster knowledge exchange, help identify research gaps, and provide orientation and guidance for researchers and practitioners.

V. ACKNOWLEDGEMENTS

We thank Nadja Pernat for helpful discussions. We greatly appreciate the comments from two anonymous reviewers which profoundly improved the manuscript, as well as the thorough comments and edits by Alison Cooper on the final version. We also thank Alexandra Elbakyan and the Open Science community. Financial support was received from the Studienstiftung des deutschen Volkes (S. L.), the German Federal Ministry of Education and Research BMBF within the Collaborative Project 'Bridging in Biodiversity Science – BIBS' (funding number 01LC1501) (J. M. J., M. B.-V., S. B., H.-P. G., I. K., S. K.-S., A. P., C. L. M., T. H.), the VolkswagenStiftung (97 863) (J. M. J., M. B.-V., C. L. M., D. M., T. H.), the Deutsche Forschungsgemeinschaft DFG (HE 5893/8-1) (T. H., J. M. J.), and the Alexander von Humboldt Foundation (Y. I.). Open Access funding enabled and organized by Projekt DEAL.

VI. DATA AVAILABILITY STATEMENT

The dataset compiled for this article is available in the supplementary material of this article. A related wikidata-site can be found at https://www.wikidata.org/wiki/Wikidata:WikiProject_Ecology/Task_Force_Urban_Ecology.

VII. REFERENCES

References identified with an asterisk (*) are cited only within the supporting information.

*Adams, J. M., Fang, W., Callaway, R. M., Cipollini, D. & Newell, E. (2009). A cross-continental test of the enemy release hypothesis: leaf herbivory on *Acer platanoides* (L.) is three times lower in North America than in its native Europe. *Biological Invasions* **11**, 1005–1016.

Adler, F. R. & Tanner, C. J. (2013). *Urban Ecosystems: Ecological Principles for the Built Environment*. Cambridge University Press, New York.

*Ahn, Y. Y., Bagrow, J. P. & Lehmann, S. (2010). Link communities reveal multiscale complexity in networks. *Nature* **466**, 761–764.

Alberti, M. (2008). *Advances in Urban Ecology: Integrating Humans and Ecological Processes in Urban Ecosystems*. Springer, New York.

Alberti, M. (2015). Eco-evolutionary dynamics in an urbanizing planet. *Trends in Ecology & Evolution* **30**, 114–126.

*Alberti, M., Correa, C., Marzluff, J. M., Hendry, A. P., Palkovacs, E. P., Gotanda, K. M., Hunt, V. M., Apgar, T. M. & Zhou, Y. (2017*a*). Global urban signatures of phenotypic change in animal and plant populations. *Proceedings of the National Academy of Sciences USA* **114**, 8951–8956.

Alberti, M., Marzluff, J. & Hunt, V. M. (2017*b*). Urban driven phenotypic changes: empirical observations and theoretical implications for eco-evolutionary feedback. *Philosophical Transactions of the Royal Society B: Biological Sciences* **372**, 20160029.

Alberti, M. & Marzluff, J. M. (2004). Ecological resilience in urban ecosystems: linking urban patterns to human and ecological functions. *Urban Ecosystems* **7**, 241–265.

Aronson, M. F., Nilon, C. H., Lepczyk, C. A., Parker, T. S., Warren, P. S., Cilliers, S. S., Goddard, M. A., Hahs, A. K., Herzog, C. & Katti, M. (2016). Hierarchical filters determine community assembly of urban species pools. *Ecology* **97**, 2952–2963.

Atwood, T. C., Weeks, H. P. & Gehring, T. M. (2004). Spatial ecology of coyotes along a suburban-to-rural gradient. *The Journal of Wildlife Management* **68**, 1000–1009.

Bai, X., Elmqvist, T., Frantzeskaki, N., McPhearson, T., Simon, D., Maddox, D., Watkins, M., Romero-Lankao, P., Parnell, S., Griffith, C. & Roberts, D. (2018). New integrated urban knowledge for the cities we want. In *The Urban Planet: Knowledge Towards Sustainable Cities* (eds T. Elmqvist, X. Bai, N. Frantzeskaki, C. Griffith, D. Maddox, T. McPhearson, S. Parnell, P. Romero-Lankao, D. Simon and M. Watkins), pp. 462–482. Cambridge University Press, Cambridge.

Battin, J. (2004). When good animals love bad habitats: ecological traps and the conservation of animal populations. *Conservation Biology* **18**, 1482–1491.

Berthon, K., Thomas, F. & Bekessy, S. (2021). The role of 'nativeness' in urban greening to support animal biodiversity. *Landscape and Urban Planning* **205**, 103959.

Betts, M. G., Hadley, A. S., Frey, D. W., Frey, S. J. K., Gannon, D., Harris, S. H., Kim, H., Kormann, U. G., Leimberger, K., Moriarty, K., Northrup, J. M., Phalan, B., Rousseau, J. S., Stokely, T. D., Valente, J. J., *et al.* (2021). When are hypotheses useful in ecology and evolution? *Ecology and Evolution* **11**, 5762–5776.

Blair, R. B. (1996). Land use and avian species diversity along an urban gradient. *Ecological Applications* **6**, 506–519.

Blair, R. B. (2001). Birds and butterflies along urban gradients in two ecoregions of the United States: is urbanization creating a homogeneous fauna? In *Biotic Homogenization* (eds J. L. Lockwood and M. L. McKinney), pp. 33–56. Kluwer Academic/Plenum Publishers, New York.

Bleicher, S. S. (2017). The landscape of fear conceptual framework: definition and review of current applications and misuses. *PeerJ* **5**, e3772.

Bollen, J., Van de Sompel, H., Hagberg, A., Bettencourt, L., Chute, R., Rodriguez, M. A. & Balakireva, L. (2009). Clickstream data yields high-resolution maps of science. *PLoS One* **4**, e4803.

*Bonier, F. (2012). Hormones in the city: endocrine ecology of urban birds. *Hormones and Behavior* **61**, 763–772.

*Bonier, F., Martin, P. R. & Wingfield, J. C. (2007). Urban birds have broader environmental tolerance. *Biology Letters* **3**, 670–673.

*Bonnington, C., Gaston, K. J. & Evans, K. L. (2015). Ecological traps and behavioural adjustments of urban songbirds to fine-scale spatial variation in predator activity. *Animal Conservation* **18**, 529–538.

Borden, J. B. & Flory, S. L. (2021). Urban evolution of invasive species. *Frontiers in Ecology and the Environment* **19**, 184–191.

Börner, K. (2010). *Atlas of Science: Visualizing What we Know*. MIT Press, Cambridge.

Breuste, J. & Qureshi, S. (2011). Urban sustainability, urban ecology and the Society for Urban Ecology (SURE). *Urban Ecosystems* **14**, 313–317.

Brown, J. S., Laundré, J. W. & Gurung, M. (1999). The ecology of fear: optimal foraging, game theory, and trophic interactions. *Journal of Mammalogy* **80**, 385–399.

*Burghardt, K. T., Tallamy, D. W. & Gregory Shriver, W. (2009). Impact of native plants on bird and butterfly biodiversity in suburban landscapes. *Conservation Biology* **23**, 219–224.

Cadenasso, M. L. & Pickett, S. T. A. (2008). Urban principles for ecological landscape design and maintenance: scientific fundamentals. *Cities and the Environment (CATE)* **1**, 4.

Catterall, C. P., Cousin, J. A., Piper, S. & Johnson, G. (2010). Long-term dynamics of bird diversity in forest and suburb: decay, turnover or homogenization? *Diversity and Distributions* **16**, 559–570.

*Churcher, P. B. & Lawton, J. H. (1987). Predation by domestic cats in an English village. *Journal of Zoology* **212**, 439–455.

*Clauset, A. M. E. J. & Newman, C. M. (2004). Finding community structure in very large networks. *Physical Review* **70**, 066111.

Collins, J. P., Kinzig, A., Grimm, N. B., Fagan, W. F., Hope, D., Wu, J. & Borer, E. T. (2000). A new urban ecology: modeling human communities as integral parts of ecosystems poses special problems for the development and testing of ecological theory. *American Scientist* **88**, 416–425.

*Concepción, E. D., Moretti, M., Altermatt, F., Nobis, M. P. & Obrist, M. K. (2015). Impacts of urbanisation on biodiversity: the role of species mobility, degree of specialisation and spatial scale. *Oikos* **124**, 1571–1582.

Connell, J. H. (1978). Diversity in tropical rain forests and coral reefs: high diversity of trees and corals is maintained only in a nonequilibrium state. *Science* **199**, 1302–1310.

*Croci, S., Butet, A., Georges, A., Aguejdad, R. & Clergeau, P. (2008). Small urban woodlands as biodiversity conservation hot-spot: a multi-taxon approach. *Landscape Ecology* **23**, 1171–1186.

Crooks, K. R. & Soulé, M. E. (1999). Mesopredator release and avifaunal extinctions in a fragmented system. *Nature* **400**, 563–566.

Danneels, K. (2018). Historicizing ecological urbanism: Paul Duvigneaud, the Brussels agglomeration and the influence of ecology on urbanism (1970–2016). In *On Reproduction. Re-Imagining the Political Ecology of Urbanism. Urbanism & Urbanization Conference Proceedings* (eds M. Dehaene and D. Peleman), pp. 343–356. Ghent University, Gent.

*Davis, A. M. & Glick, T. F. (1978). Urban ecosystems and Island biogeography. *Environmental Conservation* **5**, 299–304.

*Debinski, D. M. & Holt, R. D. (2000). A survey and overview of habitat fragmentation experiments. *Conservation Biology* **14**, 342–355.

Des Roches, S., Brans, K. I., Lambert, M. R., Rivkin, L. R., Savage, A. M., Schell, C. J., Correa, C., De Meester, L., Diamond, S. E., Grimm, N. B., Harris, N. C., Govaert, L., Hendry, A. P., Johnson, M. T. J., Munshi-South, J., *et al.* (2021). Socio-eco-evolutionary dynamics in cities. *Evolutionary Applications* **14**, 248–267.

Diamond, S. E., Chick, L. D., Perez, A., Strickler, S. A. & Martin, R. A. (2018). Evolution of thermal tolerance and its fitness consequences: parallel and non-parallel responses to urban heat islands across three cities. *Proceedings of the Royal Society B: Biological Sciences* **285**, 20180036.

Diamond, S. E. & Martin, R. A. (2021). Evolution in cities. *Annual Review of Ecology, Evolution, and Systematics* **52**, 519–540.
*Donnelly, R. & Marzluff, J. M. (2004). Importance of reserve size and landscape context to urban bird conservation. *Conservation Biology* **18**, 733–745.
Dooling, S., Graybill, J. & Greve, A. (2007). Response to Young and Wolf: goal attainment in urban ecology research. *Urban Ecosystems* **10**, 339–347.
*Elek, Z. & Lövei, G. L. (2007). Patterns in ground beetle (Coleoptera: Carabidae) assemblages along an urbanisation gradient in Denmark. *Acta Oecologica* **32**, 104–111.
*Elton, C. S. (1933). *The Ecology of Animals*. Methuen, London.
*Elton, C. S. (1958). *The Ecology of Invasions by Animals and Plants*. Methuen, London.
Enders, M., Havemann, F., Ruland, F., Bernard-Verdier, M., Catford, J. A., Gómez-Aparicio, L., Haider, S., Heger, T., Kueffer, C., Kühn, I., Meyerson, L. A., Musseau, C., Novoa, A., Ricciardi, A., Sagouis, A., *et al*. (2020). A conceptual map of invasion biology: integrating hypotheses into a consensus network. *Global Ecology and Biogeography* **29**, 978–991.
Enders, M., Hütt, M.-T. & Jeschke, J. M. (2018). Drawing a map of invasion biology based on a network of hypotheses. *Ecosphere* **9**, e02146.
Eötvös, C. B., Magura, T. & Lövei, G. L. (2018). A meta-analysis indicates reduced predation pressure with increasing urbanization. *Landscape and Urban Planning* **180**, 54–59.
Erxleben, F., Günther, M., Krötzsch, M., Mendez, J. & Vrandecić, D. (2014). Introducing Wikidata to the linked data web. In *The Semantic Web – ISWC 2014*, pp. 50–65. Springer International Publishing, Cham.
Evans, K. L., Chamberlain, D. E., Hatchwell, B. J., Gregory, R. D. & Gaston, K. J. (2011). What makes an urban bird? *Global Change Biology* **17**, 32–44.
*Evans, T. S. & Lambiotte, R. (2009). Line graphs, link partitions, and overlapping communities. *Physical Review E* **80**, 016105.
*Faeth, S. H., Warren, P. S., Shochat, E. & Marussich, W. A. (2005). Trophic dynamics in urban communities. *BioScience* **55**, 399–407.
Fischer, J. D., Cleeton, S. H., Lyons, T. P. & Miller, J. R. (2012). Urbanization and the predation paradox: the role of trophic dynamics in structuring vertebrate communities. *BioScience* **62**, 809–818.
*Fischer, J. D., Schneider, S. C., Ahlers, A. A. & Miller, J. R. (2015). Categorizing wildlife responses to urbanization and conservation implications of terminology. *Conservation Biology* **29**, 1246–1248.
Forman, R. T. T. (2016). Urban ecology principles: are urban ecology and natural area ecology really different? *Landscape Ecology* **31**, 1653–1662.
*Fortunato, S. (2010). Community detection in graphs. *Physics Reports* **486**, 75–174.
*Gaublomme, E., Hendrickx, F., Dhuyvetter, H. & Desender, K. (2008). The effects of forest patch size and matrix type on changes in carabid beetle assemblages in an urbanized landscape. *Biological Conservation* **141**, 2585–2596.
Gering, J. C. & Blair, R. B. (1999). Predation on artificial bird nests along an urban gradient: predatory risk or relaxation in urban environments? *Ecography* **22**, 532–541.
Giere, R. N., Bickle, J. & Mauldin, R. (2005). *Understanding Scientific Reasoning*, Fifth Edition. Wadsworth Cengage Learning, Belmont.
*Gläser, J., Glänzel, W. & Scharnhorst, A. (2017). Same data – different results? Towards a comparative approach to the identification of thematic structures in science. *Scientometrics* **111**, 981–998.
Gloor, S., Bontadina, F., Hegglin, D., Deplazes, P. & Breitenmoser, U. (2001). The rise of urban fox populations in Switzerland. *Mammalian Biology* **66**, 155–164.
Grime, J. P. (1973). Competitive exclusion in herbaceous vegetation. *Nature* **242**, 344–347.
Grimm, N. B., Faeth, S. H., Golubiewski, N. E., Redman, C. L., Wu, J., Bai, X. & Briggs, J. M. (2008). Global change and the ecology of cities. *Science* **319**, 756–760.
Grimm, N. B., Grove, J. G., Pickett, S. T. & Redman, C. L. (2000). Integrated approaches to long-term studies of urban ecological systems: urban ecological systems present multiple challenges to ecologists – pervasive human impact and extreme heterogeneity of cities, and the need to integrate social and ecological approaches, concepts, and theory. *BioScience* **50**, 571–584.
Groffman, P. M., Cavender-Bares, J., Bettez, N. D., Grove, J. M., Hall, S. J., Heffernan, J. B., Hobbie, S. E., Larson, K. L., Morse, J. L. & Neill, C. (2014). Ecological homogenization of urban USA. *Frontiers in Ecology and the Environment* **12**, 74–81.
Grogan, P. (2005). The use of hypotheses in ecology. *Bulletin of the British Ecological Society* **36**, 43–47.
*Grossart, H. P., Van den Wyngaert, S., Kagami, M., Wurzbacher, C., Cunliffe, M. & Rojas-Jimenez, K. (2019). Fungi in aquatic ecosystems. *Nature Reviews Microbiology* **17**, 339–354.
Guetté, A., Gaüzère, P., Devictor, V., Jiguet, F. & Godet, L. (2017). Measuring the synanthropy of species and communities to monitor the effects of urbanization on biodiversity. *Ecological Indicators* **79**, 139–154.
*Haeupler, H. & Schönfelder, P. (1975). Arealkundliche Gesichtspunkte im Rahmen der Kartierung der Flora Mitteleuropas in der Bundesrepublik Deutschland. *Berichte der Deutschen Botanischen Gesellschaft* **88**, 451–468.
*Hahs, A. K., McDonnell, M. J., McCarthy, M. A., Vesk, P. A., Corlett, R. T., Norton, B. A., Clemants, S. E., Duncan, R. P., Thompson, K., Schwartz, M. W. & Williams, N. S. (2009). A global synthesis of plant extinction rates in urban areas. *Ecology Letters* **12**, 1165–1173.
*Hale, R., Coleman, R., Pettigrove, V. & Swearer, S. E. (2015). Identifying, preventing and mitigating ecological traps to improve the management of urban aquatic ecosystems. *Journal of Applied Ecology* **52**, 928–939.
Havemann, F. (2021). Topics as clusters of citation links to highly cited sources: the case of research on international relations. *Quantitative Science Studies* **2**, 204–223.
Havemann, F., Gläser, J. & Heinz, M. (2017). Memetic search for overlapping topics based on a local evaluation of link communities. *Scientometrics* **111**, 1089–1118.
Heger, T., Aguilar-Trigueros, C. A., Bartram, I., Braga, R. R., Dietl, G. P., Enders, M., Gibson, D. J., Gómez-Aparicio, L., Gras, P. & Jax, K. (2021). The hierarchy-of-hypotheses approach: a synthesis method for enhancing theory development in ecology and evolution. *BioScience* **71**, 337–349.
Heger, T., Jeschke, J. M., Febria, C., Kollmann, J., Murphy, S., Rochefort, L., Shackelford, N., Temperton, V. M. & Higgs, E. (2022). Mapping and assessing the knowledge base of ecological restoration. *Restoration Ecology* e13676.
Helden, A. J. & Leather, S. R. (2004). Biodiversity on urban roundabouts—Hemiptera, management and the species–area relationship. *Basic and Applied Ecology* **5**, 367–377.
*Hendry, A. P., Farrugia, T. J. & Kinnison, M. T. (2008). Human influences on rates of phenotypicchange in wild animal populations. *Molecular Ecology* **17**, 20–29.
*Hölker, F., Wolter, C., Perkin, E. K. & Tockner, K. (2010). Light pollution as a biodiversity threat. *Trends in Ecology & Evolution* **25**, 681–682.
*Hopkins, G. R., Gaston, K. J., Visser, M. E., Elgar, M. A. & Jones, T. M. (2018). Artificial light at night as a driver of evolution across urban–rural landscapes. *Frontiers in Ecology and the Environment* **16**, 472–479.
*Horváth, R., Magura, T. & Tóthmérész, B. (2012). Ignoring ecological demands masks the real effect of urbanization: a case study of ground-dwelling spiders along a rural–urban gradient in a lowland forest in Hungary. *Ecological Research* **27**, 1069–1077.
Inkpen, S. A. (2017). Demarcating nature, defining ecology: creating a rationale for the study of nature's "primitive conditions". *Perspectives on Science* **25**, 355–392.
Isaksson, C. (2015). Urbanization, oxidative stress and inflammation: a question of evolving, acclimatizing or coping with urban environmental stress. *Functional Ecology* **29**, 913–923.
Ives, C. D., Lentini, P. E., Threlfall, C. G., Ikin, K., Shanahan, D. F., Garrard, G. E., Bekessy, S. A., Fuller, R. A., Mumaw, L. & Rayner, L. (2016). Cities are hotspots for threatened species. *Global Ecology and Biogeography* **25**, 117–126.
*Jackson, M. T. (1966). Effects of microclimate on spring flowering phenology. *Ecology* **47**, 407–415.
James, A. R. & Stuart-Smith, A. K. (2000). Distribution of caribou and wolves in relation to linear corridors. *The Journal of Wildlife Management* **64**, 154–159.
Jeschke, J. M. & Heger, T. (eds) (2018). *Invasion Biology: Hypotheses and Evidence*. CABI, Wallingford.
Jeschke, J. M., Heger, T., Kraker, P., Schramm, M., Kittel, C. & Mietchen, D. (2021). Towards an open, zoomable atlas for invasion science and beyond. *NeoBiota* **68**, 5–19.
Jeschke, J. M., Keesing, F. & Ostfeld, R. S. (2013). Novel organisms: comparing invasive species, GMOs, and emerging pathogens. *Ambio* **42**, 541–548.
Jeschke, J. M., Lokatis, S., Bartram, I. & Tockner, K. (2019). Knowledge in the dark: scientific challenges and ways forward. *Facets* **4**(1), 423–441.
Jeschke, J. M. & Strayer, D. L. (2006). Determinants of vertebrate invasion success in Europe and North America. *Global Change Biology* **12**, 1608–1619.
*Johnson, L. J. & Tricker, P. J. (2010). Epigenomic plasticity within populations: its evolutionary significance and potential. *Heredity* **105**, 113–121.
Johnson, M. T. & Munshi-South, J. (2017). Evolution of life in urban environments. *Science* **358**, eaam8327.
Keane, R. M. & Crawley, M. J. (2002). Exotic plant invasions and the enemy release hypothesis. *Trends in Ecology & Evolution* **17**, 164–170.
Kinzig, A. P., Warren, P., Martin, C., Hope, D. & Katti, M. (2005). The effects of human socioeconomic status and cultural characteristics on urban patterns of biodiversity. *Ecology and Society* **10**, 23.
Klausnitzer, B. (1987). *Ökologie der Großstadtfauna*. G. Fischer, Jena.
Klavans, R. & Boyack, K. W. (2009). Toward a consensus map of science. *Journal of the American Society for Information Science and Technology* **60**, 455–476.
*Knapp, S. (2010). Urbanization causes shifts of Species' trait state frequencies – a large scale analysis. In *Plant Biodiversity in Urbanized Areas*, pp. 13–29. Vieweg Teubner, Wiesbaden.
Knight, R. L., Grout, D. J. & Temple, S. A. (1987). Nest-defense behavior of the American crow in urban and rural areas. *Condor* **89**, 175–177.
Kowarik, I. (1988). Zum menschlichen Einfluβ auf Flora und Vegetation. Theoretische Konzepte und ein Quantifizierungsansatz am Beispiel von Berlin (West). *Landschaftsentwicklung und Umweltforschung* **56**, 1–280.
*Kowarik, I. (1990). Some responses of flora and vegetation to urbanization in Central Europe. In *Urban Ecology* (eds H. Sukopp, S. Hejny and I. Kowarik), pp. 45–74. SPB Academic Publishing, The Hague.

Kowarik, I. (2008). On the role of alien species in urban flora and vegetation. In *Urban Ecology. An International Perspective on the Interaction between Humans and Nature* (eds J. M. Marzluff, E. Shulenberger, W. Endlicher, M. Alberti, G. Bradley, C. Ryan, U. Simon and C. ZumBrunnen), pp. 321–338. Springer, Boston.

Kowarik, I. (2020). Herbert Sukopp – an inspiring pioneer in the field of urban ecology. *Urban Ecosystems* **23**, 445–455.

Kühn, I., Brandl, R. & Klotz, S. (2004). The flora of German cities is naturally species rich. *Evolutionary Ecology Research* **6**, 749–764.

Kühn, I., Wolf, J. & Schneider, A. (2017). Is there an urban effect in alien plant invasions? *Biological Invasions* **19**, 3505–3513.

Kunick, W. (1974). *Veränderungen von Flora und Vegetation einer Grosstadt dargestellt am Beispiel von Berlin (West)*. Doctoral dissertation: Technische Universität Berlin.

Kurvers, R. H. & Hoelker, F. (2015). Bright nights and social interactions: a neglected issue. *Behavioral Ecology* **26**, 334–339.

*Kuussaari, M., Toivonen, M., Heliölä, J., Pöyry, J., Mellado, J., Ekroos, J., Hyyryläinen, V., Vähä-Piikkiö, I. & Tiainen, J. (2021). Butterfly species' responses to urbanization: differing effects of human population density and built-up area. *Urban Ecosystems* **24**, 515–527.

Lahr, E. C., Dunn, R. R. & Frank, S. D. (2018). Getting ahead of the curve: cities as surrogates for global change. *Proceedings of the Royal Society B: Biological Sciences* **285**, 20180643.

*Lampe, U., Reinhold, K. & Schmoll, T. (2014). How grasshoppers respond to road noise: developmental plasticity and population differentiation in acoustic signalling. *Functional Ecology* **28**, 660–668.

Laundré, J. W., Hernández, L. & Ripple, W. J. (2010). The landscape of fear: ecological implications of being afraid. *The Open Ecology Journal* **3**, 1–7.

*Leibold, M. A., Holyoak, M., Mouquet, N., Amarasekare, P., Chase, J. M., Hoopes, M. F., Holt, R. D., Shurin, J. B., Law, R., Tilman, D., Loreau, M. & Gonzalez, A. (2004). The metacommunity concept: a framework for multi-scale community ecology. *Ecology Letters* **7**, 601–613.

Leydesdorff, L., Carley, S. & Rafols, I. (2013). Global maps of science based on the new web-of-science categories. *Scientometrics* **94**, 589–593.

Linkola, K. (1916). Studien über den Einfluss der Kultur auf die Flora in den Gegenden nördlich vom Ladogasee. *Acta Societatis pro Fauna et Flora Fennica* **45**, 429–492.

*Lockwood, J. L., Cassey, P. & Blackburn, T. (2005). The role of propagule pressure in explaining species invasions. *Trends in Ecology & Evolution* **20**, 223–228.

Lokatis, S. & Jeschke, J. M. (2022). Urban biotic homogenization: approaches and knowledge gaps. *Ecological Applications* **32**, e2703.

*Lososová, Z., Chytrý, M., Kühn, I., Hájek, O., Horáková, V., Pysek, P. & Tichý, L. (2006). Patterns of plant traits in annual vegetation of man-made habitats in Central Europe. *Perspectives in Plant Ecology, Evolution and Systematics* **8**, 69–81.

*Lowry, H., Lill, A. & Wong, B. B. (2013). Behavioural responses of wildlife to urban environments. *Biological Reviews* **88**, 537–549.

Luck, G. W. (2007). A review of the relationships between human population density and biodiversity. *Biological Reviews* **82**, 607–645.

Lundholm, J. T. & Richardson, P. J. (2010). Habitat analogues for reconciliation ecology in urban and industrial environments. *Journal of Applied Ecology* **47**, 966–975.

*MacArthur, R. H. & MacArthur, J. W. (1961). On bird species diversity. *Ecology* **42**, 594–598.

MacArthur, R. H. & Wilson, E. O. (1967). *The Theory of Island Biogeography*. Princeton University Press, Princeton & Oxford.

MacGregor-Fors, I. (2011). Misconceptions or misunderstandings? On the standardization of basic terms and definitions in urban ecology. *Landscape and Urban Planning* **100**, 347–349.

Mader, H.-J. (1984). Animal habitat isolation by roads and agricultural fields. *Biological Conservation* **29**, 81–96.

Magle, S. B., Hunt, V. M., Vernon, M. & Crooks, K. R. (2012). Urban wildlife research: past, present, and future. *Biological Conservation* **155**, 23–32.

*Magura, T., Tóthmérész, B. & Lövei, G. L. (2006). Body size inequality of carabids along an urbanisation gradient. *Basic and Applied Ecology* **7**, 472–482.

*Magura, T., Tóthmérész, B. & Molnár, T. (2004). Changes in carabid beetle assemblages along an urbanisation gradient in the city of Debrecen, Hungary. *Landscape Ecology* **19**, 747–759.

Mannan, R. W. & Boal, C. W. (2000). Home range characteristics of male Cooper's hawks in an urban environment. *The Wilson Journal of Ornithology* **112**, 21–27.

*Maurer, R. (1974). The beetle and spider fauna of meadows affected by traffic pollution. *Oecologia* **14**, 327–351.

McClure, H. E. (1989). What characterizes an urban bird? *Journal of the Yamashina Institute for Ornithology* **21**, 178–192.

McDonnell, M. J. & Hahs, A. K. (2008). The use of gradient analysis studies in advancing our understanding of the ecology of urbanizing landscapes: current status and future directions. *Landscape Ecology* **23**, 1143–1155.

*McDonnell, M. J. & Hahs, A. K. (2015). Adaptation and adaptedness of organisms to urban environments. *Annual Review of Ecology, Evolution, and Systematics* **46**, 261–280.

McDonnell, M. J. & Niemelä, J. (2011). The history of urban ecology. In *Urban Ecology: Patterns, Processes, and Applications* (eds J. Niemelä, J. H. Breuste, G. Guntenspergen, N. E. McIntyre, T. Elmqvist and P. James), pp. 34–49. Oxford University Press, Oxford.

*McGlynn, T. P., Meineke, E. K., Bahlai, C. A., Li, E., Hartop, E. A., Adams, B. J. & Brown, B. V. (2019). Temperature accounts for the biodiversity of a hyperdiverse group of insects in urban Los Angeles. *Proceedings of the Royal Society B* **286**, 20191818.

*McIntyre, N. E. (2000). Ecology of urban arthropods: a review and a call to action. *Annals of the Entomological Society of America* **93**, 825–835.

McIntyre, N. E., Knowles-Yanez, K. & Hope, D. (2008). Urban ecology as an interdisciplinary field: differences in the use of "urban" between the social and natural sciences. In *Urban Ecology: An International Perspective on the Interaction Between Humans and Nature* (eds J. M. Marzluff, E. Shulenberger, W. Endlicher, M. Alberti, G. Bradley, C. Ryan, U. Simon and C. ZumBrunnen), pp. 49–65. Springer, Boston.

*McKinney, M. L. (2002). Urbanization, biodiversity, and conservation. *BioScience* **52**, 883–890.

McKinney, M. L. (2006). Urbanization as a major cause of biotic homogenization. *Biological Conservation* **127**, 247–260.

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

McPhearson, T., Haase, D., Kabisch, N. & Gren, Å. (2016*a*). Advancing understanding of the complex nature of urban systems. *Ecological Indicators* **70**, 566–573.

McPhearson, T., Pickett, S. T. A., Grimm, N. B., Niemelä, J., Alberti, M., Elmqvist, T., Weber, C., Haase, D., Breuste, J. & Qureshi, S. (2016*b*). Advancing urban ecology toward a science of cities. *BioScience* **66**, 198–212.

Miles, L. S., Rivkin, L. R., Johnson, M. T., Munshi-South, J. & Verrelli, B. C. (2019). Gene flow and genetic drift in urban environments. *Molecular Ecology* **28**, 4138–4151.

*Møller, A. P., Díaz, M., Flensted-Jensen, E., Grim, T., Ibáñez-Álamo, J. D., Jokimäki, J., Mänd, R., Markó, G. & Tryjanowski, P. (2015). Urbanized birds have superior establishment success in novel environments. *Oecologia* **178**, 943–950.

Morton, E. S. (1975). Ecological sources of selection on avian sounds. *The American Naturalist* **109**, 17–34.

Nakagawa, S., Dunn, A. G., Lagisz, M., Bannach-Brown, A., Grames, E. M., Sánchez-Tójar, A., O'Dea, R., Noble, D. W. A., Westgate, M. J., Arnold, P. A., Barrow, S., Bethel, A., Cooper, E., Foo, Y. Z., Geange, S. R., *et al.* (2020). A new ecosystem for evidence synthesis. *Nature Ecology & Evolution* **4**, 498–501.

*Neri, F., Cotta, C. & Moscato, P. (eds) (2012). *Handbook of Memetic Algorithms*. Springer, Berlin.

*Newman, M. (2006). Finding community structure using the eigenvectors of matrices. *Physical Review E* **74**, 36104.

Newman, M. E. & Girvan, M. (2004). Finding and evaluating community structure in networks. *Physical Review E* **69**, 26113.

Nielsen, F. Å., Mietchen, D. & Willighagen, E. (2017). Scholia, Scientometrics and Wikidata, The Semantic Web: ESWC 2017 Satellite Events. ESWC 2017. In *Lecture Notes in Computer Science 10577* (eds E. Blomqvist, K. Hose, H. Paulheim, A. Ławrynowicz, F. Ciravegna and O. Hartig), pp. 237–259. Springer, Cham.

Nielsen, F. Å., Mietchen, D. & Willighagen, E. (2018). Geospatial data and Scholia. In *Proceedings of the 3rd International Workshop on Geospatial Linked Data (GeoLD2018)*, pp. 34–40. CEUR Workshop Proceedings, Heraklion.

Niemelä, J. (1999). Is there a need for a theory of urban ecology? *Urban Ecosystems* **3**, 57–65.

Nilsen, E. B., Bowler, D. E. & Linnell, J. D. (2020). Exploratory and confirmatory research in the open science era. *Journal of Applied Ecology* **57**, 842–847.

*Numberger, D., Zoccarato, L., Woodhouse, J., Ganzert, L., Sauer, S., Márquez, J. R. G., Domisch, S., Grossart, H. P. & Greenwood, A. D. (2022). Urbanization promotes specific bacteria in freshwater microbiomes including potential pathogens. *Science of the Total Environment* **845**, 157321.

Nuorteva, P. (1963). Synanthropy of blowflies (Dipt., Calliphoridae) in Finland. *Annales Entomologici Fennici* **29**, 1–49.

Nuorteva, P. (1971). The synanthropy of birds as an expression of the ecological cycle disorder caused by urbanization. *Annales Zoologici Fennici* **8**, 547–553.

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R. R., Doshi, H., Dunnett, N., Gaffin, S., Köhler, M., Liu, K. K. & Rowe, B. (2007). Green roofs as urban ecosystems: ecological structures, functions, and services. *BioScience* **57**, 823–833.

Palacio, F. X. (2020). Urban exploiters have broader dietary niches than urban avoiders. *Ibis* **162**, 42–49.

Parajuli, A., Grönroos, M., Siter, N., Puhakka, R., Vari, H. K., Roslund, M. I., Jumpponen, A., Nurminen, N., Laitinen, O. H., Hyöty, H., Rajaniemi, J. & Sinkkonen, A. (2018). Urbanization reduces transfer of diverse environmental microbiota indoors. *Frontiers in Microbiology* **9**, 1–13.

Parris, K. M. (2018). Existing ecological theory applies to urban environments. *Landscape and Ecological Engineering* **14**, 201–208.
Perring, M. P., Manning, P., Hobbs, R. J., Lugo, A. E., Ramalho, C. E. & Standish, R. J. (2013*a*). Novel urban ecosystems and ecosystem services. In *Novel Ecosystems: Intervening in the New Ecological World Order* (eds R. J. Hobbs, E. S. Higgs and C. Hall), pp. 310–325. John Wiley & Sons, Chichester.
*Perring, M. P., Standish, R. J. & Hobbs, R. J. (2013*b*). Incorporating novelty and novel ecosystems into restoration planning and practice in the 21st century. *Ecological Processes* **2**, 1–8.
*Petchey, O. L., Evans, K. L., Fishburn, I. S. & Gaston, K. J. (2007). Low functional diversity and no redundancy in British avian assemblages. *Journal of Animal Ecology* **76**, 977–985.
Peter, C. & Swilling, M. (2012). *Sustainable, Resource Efficient Cities – Making it Happen!* United Nations Environmental Program (UNEP), Nairobi.
Pickett, S. T., Burch, W. R., Dalton, S. E., Foresman, T. W., Grove, J. M. & Rowntree, R. (1997). A conceptual framework for the study of human ecosystems in urban areas. *Urban Ecosystems* **1**, 185–199.
Pickett, S. T. & Cadenasso, M. L. (2017). How many principles of urban ecology are there? *Landscape Ecology* **32**, 699–705.
Pickett, S. T., Kolasa, J. & Jones, C. G. (2010). *Ecological Understanding: The Nature of Theory and the Theory of Nature*. Elsevier, San Diego & London.
Pickett, S. T. A. & Cadenasso, M. L. (2012). Urban ecology. In *Ecological Systems: Selected Entries from the Encyclopedia of Sustainability Science and Technology* (ed. R. Leemans), pp. 273–301. Springer, New York.
Planillo, A., Kramer-Schadt, S., Buchholz, S., Gras, P., von der Lippe, M. & Radchuk, V. (2021). Arthropod abundance modulates bird community responses to urbanization. *Diversity and Distributions* **27**, 34–49.
*Pons, P. & Latapy, M. (2006). Computing communities in large networks using random walks. *Journal of Graph Algorithms and Applications* **10**, 191–218.
Popkin, G. (2022). Urban oasis. *Science* **378**, 466–469.
Potapov, P., Hansen, M. C., Laestadius, L., Turubanova, S., Yaroshenko, A., Thies, C., Smith, W., Zhuravleva, I., Komarova, A. & Minnemeyer, S. (2017). The last frontiers of wilderness: tracking loss of intact forest landscapes from 2000 to 2013. *Science Advances* **3**, e1600821.
Potgieter, L. J. & Cadotte, M. W. (2020). The application of selected invasion frameworks to urban ecosystems. *NeoBiota* **62**, 365–386.
Pouyat, R. V., Russell-Anelli, J., Yesilonis, I. D. & Groffman, P. M. (2002). Soil carbon in urban forest ecosystems. In *The Potential of US Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect* (eds J. M. Kimble, R. Lal, R. Birdsey and L. S. Heath), pp. 347–362. CRC Press, Boca Raton, London, New York & Washington, DC.
Povolný, D. (1962). Versuch einer Klärung des Begriffes der Synanthropie von Tieren. *Folia Zoologica* **25**, 105–112.
*Prange, S., Gehrt, S. D. & Wiggers, E. P. (2004). Influences of anthropogenic resources on raccoon (*Procyon lotor*) movements and spatial distribution. *Journal of Mammalogy* **85**, 483–490.
*Prugh, L. R., Stoner, C. J., Epps, C. W., Bean, W. T., Ripple, W. J., Laliberte, A. S. & Brashares, J. S. (2009). The rise of the mesopredator. *BioScience* **59**, 779–791.
Pysek, P. (1989). On the richness of Central European urban flora. *Preslia* **61**, 329–334.
Pysek, P., Jarosík, V., Hulme, P. E., Kühn, I., Wild, J., Arianoutsou, M., Bacher, S., Chiron, F., Didziulis, V. & Essl, F. (2010). Disentangling the role of environmental and human pressures on biological invasions across Europe. *Proceedings of the National Academy of Sciences USA* **107**, 12157–12162.
Ramadier, T. (2004). Transdisciplinarity and its challenges: the case of urban studies. *Futures* **36**, 423–439.
*Rapport, D. J., Regier, H. A. & Hutchinson, T. C. (1985). Ecosystem behavior under stress. *The American Naturalist* **125**, 617–640.
Raupp, M. J., Shrewsbury, P. M. & Herms, D. A. (2010). Ecology of herbivorous arthropods in urban landscapes. *Annual Review of Entomology* **55**, 19–38.
*Rikli, M. (1903). Die Anthropochoren und der Formenkreis des Nasturtium palustre (Leyss.) DC. *Berichte der Zürcherischen Botanischen Gesellschaft* **13**, 71–82.
Riley, S. P., Brown, J. L., Sikich, J. A., Schoonmaker, C. M. & Boydston, E. E. (2014). Wildlife friendly roads: the impacts of roads on wildlife in urban areas and potential remedies. In *Urban Wildlife Conservation: Theory and Practice* (eds R. A. McCleery, C. E. Moorman and M. N. Peterson), pp. 323–360. Springer, New York, Heidelberg, Dordrecht & London.
*Rodriguez, L. (2006). Can invasive species facilitate native species? Evidence of how, when, and why these impacts occur. *Biological Invasions* **8**, 927–939.
Roetzer, T., Wittenzeller, M., Haeckel, H. & Nekovar, J. (2000). Phenology in Central Europe–differences and trends of spring phenophases in urban and rural areas. *International Journal of Biometeorology* **44**, 60–66.
Rondinini, C. & Doncaster, C. (2002). Roads as barriers to movement for hedgehogs. *Functional Ecology* **16**, 504–509.
Rosenzweig, C., Solecki, W., Hammer, S. A. & Mehrotra, S. (2010). Cities lead the way in climate-change action. *Nature* **467**, 909–911.
Ruiz-Calderon, J. F., Cavallin, H., Song, S. J., Novoselac, A., Pericchi, L. R., Hernandez, J. N., Rios, R., Branch, O. H., Pereira, H. & Paulino, L. C. (2016). Walls talk: microbial biogeography of homes spanning urbanization. *Science Advances* **2**, e1501061.
Saari, S., Richter, S., Higgins, M., Oberhofer, M., Jennings, A. & Faeth, S. H. (2016). Urbanization is not associated with increased abundance or decreased richness of terrestrial animals-dissecting the literature through meta-analysis. *Urban Ecosystems* **19**, 1251–1264.
*Saarisalo-Taubert, A. (1963). *Die Flora in ihrer Beziehung zur Siedlung und Siedlungsgeschichte in den südfinnischen Städten Porvoo*, pp. 19–24. Loviisa und Hamina. Springer, Dordrecht.
Sachs, J. D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N. & Rockström, J. (2019). Six transformations to achieve the sustainable development goals. *Nature Sustainability* **2**, 805–814.
Santini, L., González-Suárez, M., Russo, D., Gonzalez-Voyer, A., von Hardenberg, A. & Ancillotto, L. (2019). One strategy does not fit all: determinants of urban adaptation in mammals. *Ecology Letters* **22**, 365–376.
Sattler, T., Duelli, P., Obrist, M., Arlettaz, R. & Moretti, M. (2010). Response of arthropod species richness and functional groups to urban habitat structure and management. *Landscape Ecology* **25**, 941–954.
Schlaepfer, M. A., Runge, M. C. & Sherman, P. W. (2002). Ecological and evolutionary traps. *Trends in Ecology & Evolution* **17**, 474–480.
Scholz, C., Firozpoor, J., Kramer-Schadt, S., Gras, P., Schulze, C., Kimmig, S. E. & Ortmann, S. (2020). Individual dietary specialization in a generalist predator: a stable isotope analysis of urban and rural red foxes. *Ecology and Evolution* **10**, 8855–8870.
Schwarz, A. & Jax, K. (2011). Etymology and original sources of the term "ecology". In *Ecology Revisited: Reflecting on Concepts, Advancing Science* (eds A. Schwarz and K. Jax), pp. 145–147. Springer Science & Business Media, Dordrecht.
Seabrook, W. A. & Dettmann, E. B. (1996). Roads as activity corridors for cane toads in Australia. *The Journal of Wildlife Management* **60**, 363–368.
*Senar, J. C., Conroy, M. J., Quesada, J. & Mateos-Gonzalez, F. (2014). Selection based on the size of the black tie of the great tit may be reversed in urban habitats. *Ecology and Evolution* **4**, 2625–2632.
Sepp, T., McGraw, K. J. & Giraudeau, M. (2020). Urban sexual selection. In *Urban Evolutionary Biology* (eds M. Szulkin, J. Munshi-South and A. Charmantier), pp. 234–252. Oxford University Press, USA.
Shackleton, C. M., Cilliers, S. S., du Toit, M. J. & Davoren, E. (2021). The need for an urban ecology of the global South. In *Urban Ecology in the Global South* (eds C. M. Shackleton, S. S. Cilliers, E. Davoren and M. J. du Toit), pp. 1–26. Springer, Cham.
Shapiro, A. M. (2002). The Californian urban butterfly fauna is dependent on alien plants. *Diversity and Distributions* **8**, 31–40.
Shochat, E. (2004). Credit or debit? Resource input changes population dynamics of city-slicker birds. *Oikos* **106**, 622–626.
Shochat, E., Lerman, S. B., Anderies, J. M., Warren, P. S., Faeth, S. H. & Nilon, C. H. (2010). Invasion, competition, and biodiversity loss in urban ecosystems. *BioScience* **60**, 199–208.
Shochat, E., Warren, P. S., Faeth, S. H., McIntyre, N. E. & Hope, D. (2006). From patterns to emerging processes in mechanistic urban ecology. *Trends in Ecology & Evolution* **21**(4), 186–191.
*Shwartz, A., Strubbe, D., Butler, C. J., Matthysen, E. & Kark, S. (2009). The effect of enemy-release and climate conditions on invasive birds: a regional test using the rose-ringed parakeet (*Psittacula krameri*) as a case study. *Diversity and Distributions* **15**, 310–318.
*Slabbekoorn, H. & Peet, M. (2003). Birds sing at a higher pitch in urban noise. *Nature* **424**, 267.
*Soga, M. & Koike, S. (2013). Mapping the potential extinction debt of butterflies in a modern city: implications for conservation priorities in urban landscapes. *Animal Conservation* **16**, 1–11.
*Sol, D., Bartomeus, I. & Griffin, A. S. (2012). The paradox of invasion in birds: competitive superiority or ecological opportunism? *Oecologia* **169**, 553–564.
Sol, D., Gonzalez-Lagos, C., Moreira, D., Maspons, J. & Lapiedra, O. (2014). Urbanisation tolerance and the loss of avian diversity. *Ecology Letters* **17**, 942–950.
Sol, D., Lapiedra, O. & Ducatez, S. (2020). Cognition and adaptation to urban. In *Urban Evolutionary Biology* (eds M. Szulkin, J. Munshi-South and A. Charmantier), pp. 253–266. Oxford University Press, USA.
Sorace, A. (2002). High density of bird and pest species in urban habitats and the role of predator abundance. *Ornis Fennica* **79**, 60–71.
Sorace, A. & Gustin, M. (2009). Distribution of generalist and specialist predators along urban gradients. *Landscape and Urban Planning* **90**, 111–118.
Spiliotopoulou, M. & Roseland, M. (2020). Urban sustainability: from theory influences to practical agendas. *Sustainability* **12**, 7245.
Start, D., Barbour, M. A. & Bonner, C. (2020). Urbanization reshapes a food web. *Journal of Animal Ecology* **89**, 808–816.

Stearns, F. & Montag, T. (eds) (1975). *The Urban Ecosystem: A Holistic Approach. Community Development Series 14.* Halsted Press, Stroudsburg.
*Stillfried, M., Gras, P., Börner, K., Göritz, F., Painer, J., Röllig, K., Wenzler, M., Hofer, H., Ortmann, S. & Kramer-Schadt, S. (2017). Secrets of success in a landscape of fear: urban wild boar adjust risk perception and tolerate disturbance. *Frontiers in Ecology and Evolution* **5**, 1–12.
Sukopp, H. (1969). Der Einfluss des Menschen auf die Vegetation. *Vegetatio* **17**, 360–371.
Sukopp, H. (1998). Urban ecology—scientific and practical aspects. In *Urban Ecology* (eds J. Breuste, H. Feldmann and O. Uhlmann), pp. 3–16. Springer, Springer, Berlin, Heidelberg.
Sukopp, H. (2008). On the early history of urban ecology in Europe. In *Urban Ecology: An International Perspective on the Interaction Between Humans and Nature* (eds J. M. Marzluff, E. Shulenberger, W. Endlicher, M. Alberti, G. Bradley, C. Ryan, U. Simon and C. ZumBrunnen), pp. 79–97. Springer, Boston.
Sukopp, H., Numata, M. & Huber, A. (eds) (1995). *Urban Ecology as the Basis of Urban Planning.* Balogh Scientific Books, Amsterdam.
*Sumasgutner, P., Nemeth, E., Tebb, G., Krenn, H. W. & Gamauf, A. (2014). Hard times in the city–attractive nest sites but insufficient food supply lead to low reproduction rates in a bird of prey. *Frontiers in Zoology* **11**, 1–13.
*Tallamy, D. W. (2004). Do alien plants reduce insect biomass? *Conservation Biology* **18**, 1689–1692.
Tanner, C. J., Adler, F. R., Grimm, N. B., Groffman, P. M., Levin, S. A., Munshi-South, J., Pataki, D. E., Pavao-Zuckerman, M. & Wilson, W. G. (2014). Urban ecology: advancing science and society. *Frontiers in Ecology and the Environment* **12**, 574–581.
Thellung, A. (1919). Zur Terminologie der Adventiv-und Ruderalfloristik. *Allgemeine Botanische Zeitschrift* **24**, 36–42.
Tomialojc, L. (1982). Synurbanization of birds and the prey-predator relations. In *Animals in Urban Environment: Proceedings of the Symposium on the Occasion of the 60th Anniversary of the Institute of Zoology of the Polish Academy of Sciences* (eds M. Luniak, B. Pisarski and Z. Wydawnictwo), pp. 131–137. Warszawa-Jabłonna 22–24 October 1979.
Tóthmérész, B., Máthé, I., Balázs, E. & Magura, T. (2011). Responses of carabid beetles to urbanization in Transylvania (Romania). *Landscape and Urban Planning* **101**, 330–337.
Uchida, K., Suzuki, K. K., Shimamoto, T., Yanagawa, H. & Koizumi, I. (2019). Decreased vigilance or habituation to humans? Mechanisms on increased boldness in urban animals. *Behavioral Ecology* **30**, 1583–1590.
UN-Habitat (2017). *New Urban Agenda*. United Nations.
UN-Habitat (2020). World cities report 2020: the value of sustainable urbanization. In *United Nations Human Settlements Programme (UN-Habitat)*. United Nations.
*Vilisics, F. & Hornung, E. (2009). Urban areas as hot-spots for introduced and shelters for native isopod species. *Urban Ecosystems* **12**, 333–345.
*von der Lippe, M., Bullock, J. M., Kowarik, I., Knopp, T. & Wichmann, M. (2013). Human-mediated dispersal of seeds by the airflow of vehicles. *PLoS One* **8**, e52733.
von der Lippe, M. & Kowarik, I. (2007). Long-distance dispersal of plants by vehicles as a driver of plant invasions. *Conservation Biology* **21**, 986–996.
von der Lippe, M. & Kowarik, I. (2008). Do cities export biodiversity? Traffic as dispersal vector across urban-rural gradients. *Diversity and Distributions* **14**, 18–25.
Vrandecić, D. & Krötzsch, M. (2014). Wikidata: a free collaborative knowledgebase. *Communications of the ACM* **57**, 78–85.
Waagmeester, A., Stupp, G., Burgstaller-Muehlbacher, S., Good, B. M., Griffith, M., Griffith, O. L., Hanspers, K., Hermjakob, H., Hudson, T. S., Hybiske, K., Keating, S. M., Manske, M., Mayers, M., Mietchen, D., Mitraka, E., *et al.* (2020). Science forum: Wikidata as a knowledge graph for the life sciences. *eLife* **9**, e52614.
Walters, S. M. (1970). The next twenty years. In *The Flora of a Changing Britain* (ed. F. Perring), pp. 136–141. Classey, Hampton.
*Wandeler, P., Funk, S. M., Largiader, C. R., Gloor, S. & Breitenmoser, U. (2003). The city-fox phenomenon: genetic consequences of a recent colonization of urban habitat. *Molecular Ecology* **12**, 647–656.
Watson, J. E. M., Shanahan, D. F., Di Marco, M., Allan, J., Laurance, W. F., Sanderson, E. W., Mackey, B. & Venter, O. (2016). Catastrophic declines in wilderness areas undermine global environment targets. *Current Biology* **26**, 2929–2934.
*Way, J. M. (1977). Roadside verges and conservation in Britain: a review. *Biological Conservation* **12**, 65–74.
Weiland, U. & Richter, M. (2011). Urban ecology – brief history and present challenges. In *Applied Urban Ecology: A Global Framework* (eds M. Richter and U. Weiland), pp. 1–11. John Wiley & Sons, Chichester.
Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., *et al.* (2016). The FAIR guiding principles for scientific data management and stewardship. *Scientific Data* **3**, 1–9.
Williams, N. S., Lundholm, J. & Scott MacIvor, J. (2014). Do green roofs help urban biodiversity conservation? *Journal of Applied Ecology* **51**, 1643–1649.
Winchell, K. M., Battles, A. C. & Moore, T. Y. (2020). Terrestrial locomotor evolution in urban environments. In *Urban Evolutionary Biology*, pp. 197–216. Oxford University Press, Oxford.
*Wittig, R. & Durwen, K. J. (1981). Das ökologische Zeigerwertspektrum der spontanen Flora von Großstädten im Vergleich zum Spektrum ihres Umlandes. *Natur und Landschaft* **56**, 12–16.
Wolf, J. M., Jeschke, J. M., Voigt, C. C. & Itescu, Y. (2022). Urban affinity and its associated traits: a global analysis of bats. *Global Change Biology* **28**, 5667–5682.
Wolfram, M., Frantzeskaki, N. & Maschmeyer, S. (2016). Cities, systems and sustainability: status and perspectives of research on urban transformations. *Current Opinion in Environmental Sustainability* **22**, 18–25.
Wright, J. D., Burt, M. S. & Jackson, V. L. (2012). Influences of an urban environment on home range and body mass of Virginia opossums (*Didelphis virginiana*). *Northeastern Naturalist* **19**, 77–86.
Wu, J. (2014). Urban ecology and sustainability: the state-of-the-science and future directions. *Landscape and Urban Planning* **125**, 209–221.
Young, R. F. & Wolf, S. A. (2006). Goal attainment in urban ecology research: a bibliometric review 1975–2004. *Urban Ecosystems* **9**, 179–193.
*Zacharias, F. (1972). Blühphaseneintritt an Straßenbäumen (insbesondere Tilia × euchlora Koch) und Temperaturverteilung in Westberlin. Doctoral dissertation: Freie Universität Berlin.

VIII. SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Data S1. Excel-file containing four sheets: (1) a glossary, (2) the full list of 62 hypotheses included in the network, their attributes and relevant literature, (3) a list of additional sub-hypotheses and (4) cited literature over all sheets.
Appendix S1. Detailed description of the network analysis.
Fig. S1. Dendrogram of clusters calculated by igraph's Walktrap algorithm.
Table S1. Details of seven link communities (resolution $r = 1/3$) ordered by Ψ; size is given as number of links and as sum of membership grades of nodes (μ_{total}).
Fig. S2. Paths through the Ψ landscape for six seed sub-graphs obtained from Walktrap.
Fig. S3. Approximative hierarchy of the main clusters we identified.

(*Received 21 June 2022; revised 31 March 2023; accepted 4 April 2023; published online 18 April 2023*)