Urban Ecosystems
https://doi.org/10.1007/s11252-022-01207-w

# Urban biodiversity: State of the science and future directions

Christine C. Rega-Brodsky[1] · Myla F. J. Aronson[2] · Max R. Piana[3] · Ela-Sita Carpenter[4] · Amy K. Hahs[5] · Adriana Herrera-Montes[6] · Sonja Knapp[7] · D. Johan Kotze[8] · Christopher A. Lepczyk[9] · Marco Moretti[10] · Allyson B. Salisbury[11] · Nicholas S. G. Williams[5] · Kirsten Jung[12] · Madhusudan Katti[13] · Ian MacGregor-Fors[8] · J. Scott MacIvor[14] · Frank A. La Sorte[15] · Vallari Sheel[16] · Caragh G. Threfall[17] · Charles H. Nilon[18]

Accepted: 24 January 2022


**Abstract**

Since the 1990s, recognition of urban biodiversity research has increased steadily. Knowledge of how ecological communities respond to urban pressures can assist in addressing global questions related to biodiversity. To assess the state of this research field in meeting this aim, we conducted a systematic review of the urban biodiversity literature published since 1990. We obtained data from 1209 studies that sampled ecological communities representing 12 taxonomic groups. While advances have been made in the field over the last 30 years, we found that urban biodiversity research has primarily been conducted in single cities within the Palearctic and Nearctic realms, within forest remnants and residential locations, and predominantly surveys plants and birds, with significant gaps in research within the Global South and little integration of multi-species and multi-trophic interactions. Sample sizes remain limited in spatial and temporal scope, but citizen science and remote sensing resources have broadened these efforts. Analytical approaches still rely on taxonomic diversity to describe urban plant and animal communities, with increasing numbers of integrated phylogenetic and trait-based analyses. Despite the implementation of nature-based solutions across the world's cities, only 5% of studies link biodiversity to ecosystem function and services, pointing to substantial gaps in our understanding of such solutions. We advocate for future research that encompasses a greater diversity of taxonomic groups and urban systems, focusing on biodiversity hotspots. Implementing such research would enable researchers to move forward in an equitable and multidisciplinary way to tackle the complex issues facing global urban biodiversity.

**Keywords** Biodiversity · Publication trends · Research bias · Sampling methodology · Systematic review · Urban gradient

## Introduction

Anthropogenic changes to ecosystems globally, including unprecedented climate change (IPCC 2021), have pushed biodiversity to the brink of a sixth mass extinction. Despite calls from scientists and international policy organizations for actions to stem the rapidly accelerating loss of biodiversity around the world (e.g., Convention on Biological Diversity; United Nations 2015), little progress has been made in achieving established targets. In particular, biodiversity loss continues nearly unabated due to increases in human population size and accompanying land use change, particularly in the world's biodiversity hotspots (Mazor et al. 2018; Seto et al. 2012). Cities have the potential to play a critical role in conservation (Soanes and Lentini 2019; Spotswood et al. 2021) with initiatives that preserve species and habitats, improve landscape connectivity by creating and maintaining habitat corridors, mainstreaming urban environmental planning, and enhancing residents' knowledge and stewardship of biodiversity (Knapp et al. 2021; Nilon et al. 2017; Oke et al. 2021).

The conservation and management of biodiversity in cities requires knowledge of the ecological patterns and processes that drive species' responses and adaptation. Over thirty years ago, McDonnell and Pickett (1990) argued that ecological research should include urban areas as an additional context for addressing core ecological questions as well as understanding the impacts of urbanization on

✉ Christine C. Rega-Brodsky
cbrodsky@pittstate.edu

Extended author information available on the last page of the article

ecological function. Similar arguments had been made by German ecologists earlier, but had not received wide exposure in what was then a less globalized world (Rebele 1994; Sukopp 2002; Sukopp and Weiler 1988). Urban ecologists have created a rapidly growing body of research on plant and animal communities in cities and towns. McKinney (2008) reviewed the effects of urbanization on plant and animal species richness, finding that species richness tended to decrease with high urbanization, while moderate levels of urbanization leads to diverging patterns in species diversity among taxonomic groups. Such patterns have been shown to occur on a global scale, where cities retain a subset of species from regional species pools (Aronson et al. 2014), but support non-native assemblages of varying diversity among different taxonomic groups. Interestingly, results of the few multi-taxonomic assessments in urban areas show that response to urbanization and to the management of green spaces vary among taxa (MacGregor-Fors et al. 2015; Sattler et al. 2014). Yet, the limited data available on taxa, besides plants and birds, have prevented the assessment of generalized patterns for other groups in urban areas.

Urban ecology has become an important focus across the ecological and environmental sciences (Cressey 2015), but there remain large gaps in our understanding of not only what species are found in cities, but also what enables them to persist or become established and adapt (Kowarik and von der Lippe 2018; Lepczyk et al. 2017; Rivkin et al. 2019). Therefore, urban biodiversity research is essential for understanding how intensive human activities affect the ecology and evolution of a region's species, which in turn can inform conservation initiatives designed to mitigate biodiversity loss (McKinney 2002).

One recommendation to emerge from a workshop hosted by the Urban Biodiversity Network (UrBioNet) in March 2017 at Rutgers University, New Brunswick, New Jersey, was the need to assess the current state of urban biodiversity research in order to reflect on the work conducted since McDonnell and Pickett (1990) and McKinney (2002, 2008) by identifying areas of saturation and gaps in the literature. In response to this recommendation, we performed a systematic review of the literature with the goal of addressing three objectives: (i) document patterns of geographic and taxonomic foci, and methodology used in urban biodiversity research since 1990, (ii) examine how ecosystem function, management, and restoration are addressed in urban biodiversity research, and (iii) identify critical knowledge gaps for future research. Our emphasis in this review is on understanding the nature of research on biodiversity in cities conducted primarily through the ecological lens. While the past decade has seen more publications on how social-ecological dynamics influence urban biodiversity, research on the mechanisms underlying these complex dynamics remains relatively scarce (Kuras et al. 2020; Morelli et al. 2020; Schell et al. 2020), and is therefore not a focus of this paper. Our broader objective through these efforts is to provide information that will guide science and policy towards enhancing the biodiversity, sustainability, and resilience of urban regions.

## Methods

Since 1990, many thousands of papers have been published that examine urban biodiversity from suborganismal to macroecological scales. Here we focus on biological communities (i.e., multiple interacting species in a shared space) as they capture the conservation needs of multiple species in a particular place and time. To address our objectives, we conducted a systematic literature search using PRISMA guidelines (PRISMA 2021) through the ISI Web of Science Core Collection for papers published between January 1990—May 2018. The search included terms related to species richness and biodiversity composition, organized by taxa (Supplementary Information, Search Terms). Focal taxa included amphibians, ants, bats, bees, birds, butterflies, carabid beetles, mammals (excluding bats), plants, reptiles, snails, and spiders, because initial literature screening indicated that these taxa were the subject of the vast majority of urban biodiversity research and would be representative of the literature.

The search returned 7300 unique articles. We reviewed the titles and abstracts of each for relevance regarding emphasis on biological communities, inclusion of multiple sites, and urban focus. We focused our review on community-level patterns, thus studies that analyzed only a single species within the focal taxonomic groups or lacked a multi-species focus were excluded from further consideration. Likewise, we excluded studies that examined one site with multiple plots within that site, such as sampling multiple plots or transects within a single park. Only studies from areas described as urban, suburban, or peri-urban (often located at the periphery of cities, which tend to differ in their nature across the globe) were considered for analysis. For any abstracts where these conditions were unclear, the abstract was reviewed by a second individual and if still unclear, the corresponding paper was included in the full-text review so that the article's suitably for inclusion could be assessed with more detail. We included all papers in English, Spanish, and Portuguese. We excluded review papers to avoid replicating any studies in our analyses; however, we kept meta-analyses as they presented new analyses regarding urban biodiversity trends over larger spatial or temporal dimensions compared to single studies.

The abstract review resulted in 1624 possible articles, some of which were duplicates if they covered more than one of the focal taxa (Table 1). We distributed the abstracts among our research group members for thematic analysis of the full-text. Additional articles were identified through relevant references

**Table 1** Literature search process by taxa for inclusion in systematic literature review of urban biodiversity studies. Numbers for articles included can exceed numbers of articles shortlisted because additional papers were identified through relevant references within shortlisted articles

| Taxa | Articles identified by Web of Science search → | Articles shortlisted based on abstract and review criteria | → | Articles included |
|---|---|---|---|---|
| Amphibians/Reptiles | 288 | 83 | | 92 |
| Ants | 392 | 77 | | 79 |
| Bats | 138 | 57 | | 81 |
| Bees | 398 | 167 | | 102 |
| Birds | 1338 | 284 | | 279 |
| Butterflies | 213 | 116 | | 104 |
| Carabids | 164 | 96 | | 70 |
| Mammals | 388 | 101 | | 63 |
| Plants | 3794 | 567 | | 564 |
| Snails | 52 | 20 | | 7 |
| Spiders | 135 | 56 | | 56 |

within these articles. From these articles, we collected a set of basic data in a shared Google Form (Supplementary Information, Table S1). All research group members followed guidelines provided by MFJA to ensure consistency for data entry. Once all articles were processed, quality control and assurance were performed by CCR-B and MFJA for errors or duplication, resulting in 1209 unique papers containing 1498 studies, as a single paper may have presented results from multiple taxa (Table 1). For papers that examined multiple taxa, we performed the thematic analysis individually by taxon. Studies were classified by publication year, journal, location(s) (city, country, biogeographic realm, or multiples of each), city of the lead author's institution, urban comparison type (urban only, gradient, urban vs. rural), how the urban area was defined (e.g., municipal boundary, land use, road density, population density), sampling effort (number of locations and duration) and methodology, land use and habitat types sampled, biodiversity metrics analyzed (e.g., species richness, taxonomic, functional, and/or phylogenetic diversity), data availability (e.g., species, traits, and/or coordinates identified), and linkages to restoration and management techniques and/or ecosystem service provision. Additional details for each study and the thematic analysis are included in the Supplementary Information.

## Results & Discussion

Urban biodiversity studies have increased steadily each year since 1990 and approximately doubled in the last five investigated years from 91 studies in 2012 to 176 in 2017 (Fig. 1). While the first journals to publish urban biodiversity studies included general ecology journals (e.g., *Economic Botany, Environmental Conservation, Oikos, Journal of Applied Ecology, Studies on Neotropical Fauna and Environment, Ecography*), urban biodiversity studies started to be published in urban-focused journals established in the late 1990s and early 2000s (Fig. 1), when, for example, *Urban Ecosystems* and *Urban Forestry & Urban Greening* published their first issues. The journals most frequently publishing urban biodiversity studies included *Urban Ecosystems* (13%), *Landscape and Urban Planning* (11%), *Urban Forestry & Urban Greening* (5%), and *Biological Conservation* (4%). Overall, 30% of urban biodiversity studies were published within

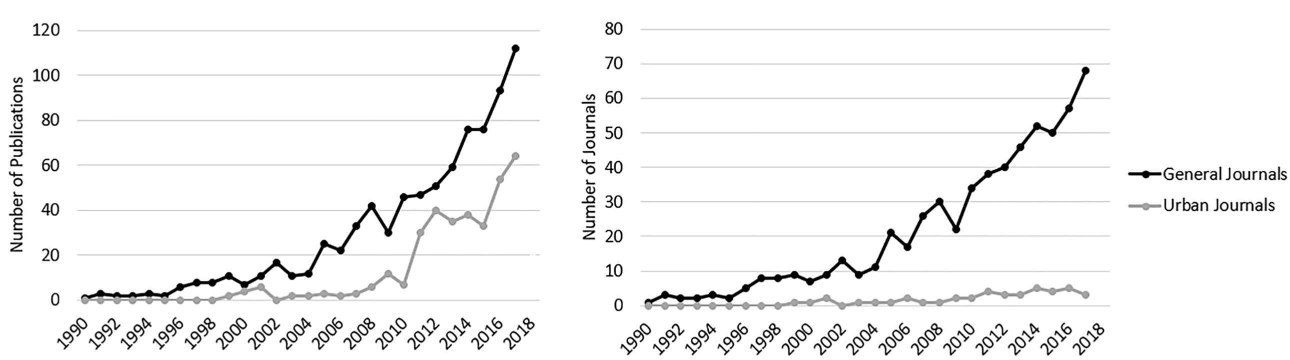


**Fig. 1** All publications ($n = 1209$) and number of unique journals publishing urban biodiversity studies by year and journal focus (urban topical journals and general ecological journals) from 1990–2017 and papers up to May 2018

urban-focused journals. Increases in publications after 2010 in both the urban and general ecological literature reflect increasing interest in and realization of the importance of urban ecological science as well as the recognition of cities as places for biodiversity conservation (Collins et al. 2021; Cressey 2015; Wu 2014). It is important to note that our search was primarily performed in the Web of Science Core Collection, which comprises a subset of papers published in journals indexed in that collection. Given that in the Global South there is an important wealth of information published in local and regional journals and theses/dissertations, often not in English, our results ought to be considered and interpreted from this lens, as information published in the "gray literature"—including high-quality science journals in a language other than English—is neglected (Haddaway et al. 2015). By including papers written in either English, Spanish, or Portuguese, we aimed to alleviate at least some of the linguistic, if not geographic, bias.

## Geographic focus

Overall, 1745 unique urban areas were studied around the world, but only 21% of studies compared biodiversity across multiple cities/urban regions and only 5% surveyed locations across multiple countries. Chicago (USA), Melbourne (Australia), Phoenix (USA), Sydney (Australia), Helsinki (Finland), New York City (USA), and Prague (Czech Republic) were the most studied cities (Fig. 2), illustrating the bias

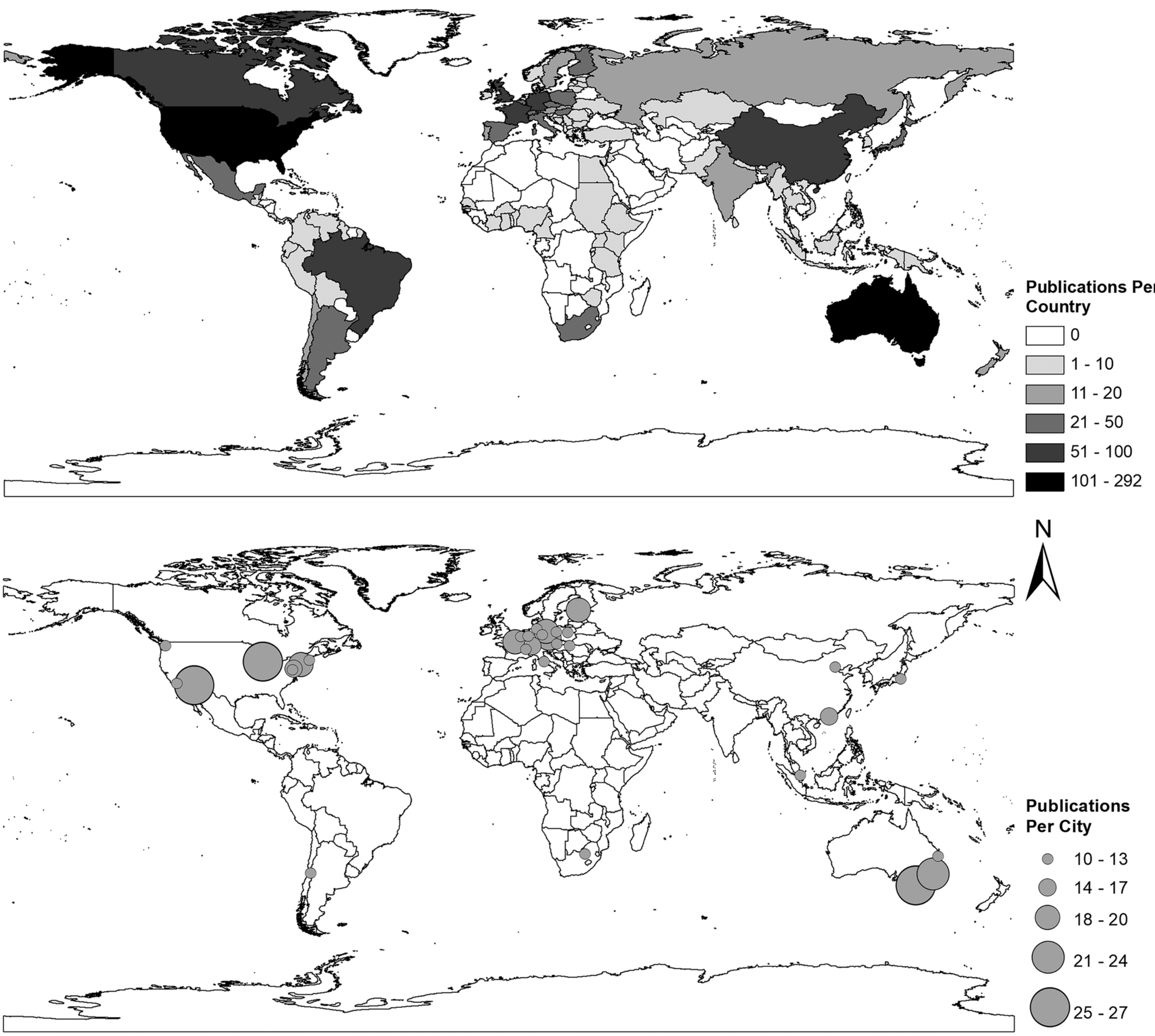


**Fig. 2** Urban biodiversity studies by country and city (cities with ≥ 10 studies displayed). This figure highlights the geographical bias of the current urban biodiversity literature towards the Palearctic and Nearctic regions, and the predominant focus on large cities

towards sampling larger cities (Kendal et al. 2020). Research in urban biodiversity was dominated by studies performed in the Palearctic (38%) and Nearctic (27%) realms, followed by the Neotropics (13%) and Australasia (10%), confirming published trends on the distribution of urban ecology studies (Collins et al. 2021; Magle et al. 2012). Most of these studies were performed in the USA (20%), Australia (7%), and China (5%). These trends confirm the challenges facing the study of biodiversity in the Global South, where the majority of people on earth reside, and where most of the world's natural resources, including biodiversity, are located (Nagendra et al. 2018). These challenges include (but are not limited to): lack of recognition of urban biodiversity as worthy of examination by researchers, limited national and international funding (Nagendra et al. 2018), reduced access to scholarly literature and data (Trisos et al. 2021), and overall less developed research infrastructure than in the Global North. While we do acknowledge that biodiversity assessments occur within these regions, our search criteria may have restricted some studies from inclusion in this review. Even so, a lack of information within the literature on urban biodiversity in these biodiverse regions potentially skew our understanding of patterns and processes in the urban milieu. For instance, there were few studies from Oceania (0.2%), Afrotropic (5%), or Indo-Malay realms (7%), with only 2.2% of papers surveying urban biodiversity across multiple realms. Recently, a number of important urban ecological studies have acknowledged this geographic bias as the field works towards closing this gap in the literature (see Nagendra et al. 2018; Shackelton et al. 2021).

Similar geographic patterns were found for each focal taxon (Supplementary Information, Fig. S1). Of the few urban reptile studies, research in the Nearctic region (44%) and Australasia (25%) dominated, which was unique among the focal taxonomic groups. Considering most of the world's biodiversity is found in the equatorial bands of the Neotropics, Indo-Malay, and Afrotropics, limited coverage of possibly the most diverse cities remains a significant gap (Aronson et al. 2016; Beninde et al. 2015). Only through additional studies and monitoring schemes that include those regions that are under-represented, will it be possible to maximize the potential of urban biodiversity while achieving conservation goals, and improving local and global urban governance (Secretariat of the Convention on Biological Diversity 2012).

Unlike biodiversity studies in natural areas, such as those in the tropics in which biodiversity is often assessed by scientists from foreign institutions (e.g., Reboredo Segovia et al. 2020), the science of urban biodiversity was primarily conducted in the city where the lead author's institution was located (58%). Very few lead authors were located outside of the country (7%) or region (4%) in which the study took place, potentially due to convenience or funding limitations. As a local or "backyard" science, the study of urban biodiversity allows for opportunities for education and engagement with communities surrounding universities and other research institutions, which likely enhance conservation interest by urban residents, even for biodiversity beyond the city and in natural areas (e.g., Narango 2020). Urban biodiversity studies conducted locally further enable direct contribution to city government conservation and monitoring programs. However, the trend towards sampling in the city in which an author lives or works has led to biases in the evidence base and limits our understanding of biodiversity responses in smaller cities and towns (Kendal et al. 2020).

## Taxonomic focus

Plants (38%) and birds (19%) remain the most studied taxa (Fig. 3), with a notable increase in publications around 1998. However, other taxonomic groups have increasingly been represented in the literature beginning around 2006–2007 (Supplementary Information, Fig. S2). While publications on the remaining focal taxa either steadily rose slowly over time (e.g., ants, bats, bees, butterflies) or occurred periodically during our sampled period (e.g., amphibians, carabid beetles, other mammals, reptiles, snakes, spiders), yearly publication rates did not surpass 20 publications in any year. Studies on urban snail communities were limited (n = 7). The underrepresentation of snails is a particular gap in the literature, as they are good indicators of local environmental and habitat determinants for urban green spaces (Barbato et al. 2017; Lososová et al. 2011), and of adaptation to a changing climate (Silvertown et al. 2011). Even so, the bulk of our surveyed species are becoming better studied over

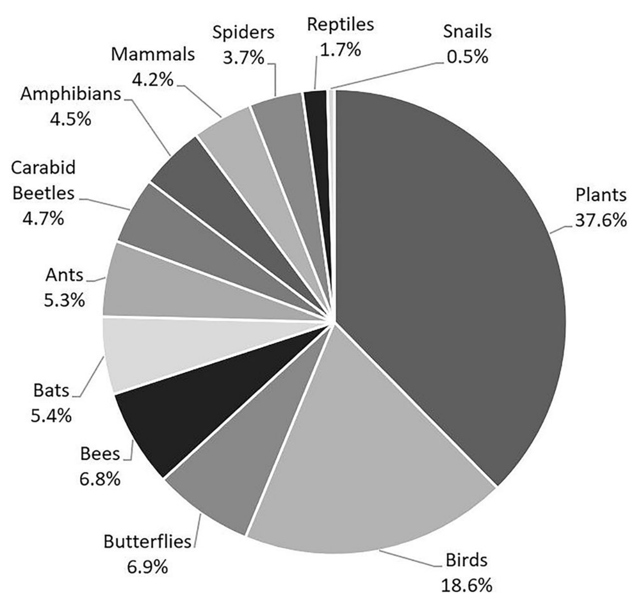


**Fig. 3** Proportion of studies by taxa group

time, albeit slowly, due to standardizations in global sampling protocols (e.g., carabids with GLOBENET; Niemelä et al. 2000), growing interest in the ecosystem services they provide (e.g., insect pollinators; Hall and Martins 2020; IPBES 2019), recognition of the critical gap in knowledge of these species within urban ecosystems (e.g., amphibians and reptiles; French et al. 2018; Hamer and McDonnell 2008), citizen science programs (Yang 2020), and access and availability of advanced technology to survey in complex environments. Publications that focus on echolocating bats, for example, increased from the mid-2000's due to technological advances in the acoustic equipment used to survey them; however, these studies are geographically biased towards countries and cities where researchers had access to such equipment. Other taxa beyond our focal subset had a minor presence within our database, such as mosquitoes, wasps, true bugs, lichens, molluscs, diatoms, earthworms, and odonates. However, these taxa should continue to be explored due to their diversity and important roles for urban ecosystem function, services, and disservices (e.g., Koch et al. 2019; Monteiro Júnior et al. 2015; Mutinova et al. 2020).

Most publications that assessed carabid beetles (94%), ants (89%), and snails (86%) surveyed the entire taxonomic group for inclusion within their analyses, compared to few mammal (29%) and plant (47%) studies that only sampled a subset of those respective taxa (e.g., sampling trees rather than the entire plant community). While we recognize the barriers preventing sampling of entire communities (i.e. taxonomic breadth and the requirement for multiple sampling techniques and time periods), trends obtained from such studies would be much more informative for an ecosystem-scale understanding of urbanization, in terms of both species assembly and ecosystem functioning (Aronson et al. 2016). Additionally, 19.8% of studies sampled more than one taxon (of the 12 focal taxa), with the most common pairings between plants and birds (29% of multi-taxonomic studies), plants and bees (15%), plants and butterflies (13%), and birds and mammals (9.2%). The lack of multi-species and multi-trophic surveys has been highlighted in the urban biodiversity literature (Beninde et al. 2015; Knapp et al. 2021; MacGregor-Fors et al. 2015; Melliger et al. 2017; Pinho et al. 2021). Addressing this knowledge gap would provide a more comprehensive view of the impacts of urbanization on biodiversity, especially by taking broad ecological networks into account (e.g., mutualistic and antagonistic interaction networks as well as entire food webs endangered by global change; Heleno et al. 2020).

## Urban biodiversity-ecosystem function and service relationships

Over the past two decades, there have been repeated calls for deeper mechanistic understandings of the social-ecological drivers of biodiversity (Knapp et al. 2021; McDonnell and Hahs 2013; Schell et al. 2020; Shochat et al. 2006), including elucidation of relationships and processes that link biodiversity with ecosystem function and ecosystem services (Pinho et al. 2021; Schwarz et al. 2017). While the study of biodiversity–ecosystem function relationships are common in the general ecological literature and ecosystem services (ESS) and nature-based solutions have taken center-stage in urban ecological practice, we found that only 9% of urban community studies implicitly linked biodiversity and ecosystem functions/services (EF/ESS) in the research question. Only 5% of studies compared biodiversity outcomes with explicitly measured EF/ESS (e.g., pollination, carbon storage, pollutant removal, food production/social services). Plant biodiversity was most commonly linked to measured EF/ESS (63%), with the remaining taxa represented with few papers in these efforts (i.e., birds, 8%; bees and ants, 7%; butterflies, 5%; spiders, mammals, and carabid beetles, 3%). In a next step forward for urban biodiversity research, studies that examine community patterns in multi-trophic interactions (e.g., pollination, predation, decomposition; Frey et al. 2018; Seibold et al. 2018; Tresch et al. 2019) and those that examine biodiversity of taxa closely associated with ecosystem function (e.g., soil microbial diversity), should be prioritized with biomonitoring surveys in taxa that are well studied (e.g., bees, birds). With the current emphasis on nature-based solutions to address environmental hazards and the effects of extreme weather events, understanding how biodiversity may drive the mechanisms behind ecosystem function in natural and artificial urban ecological systems should be emphasized in urban ecological research.

## Methodology of urban biodiversity studies

Early urban biodiversity research demonstrated that communities change between urban and non-urban areas or across urban–rural gradients in ways that result in novel species assemblages (Gaertner et al. 2017; Kowarik 2011; McKinney 2008). The urban gradient approach has been a prominent paradigm for studying urban ecology since 1990 (McDonnell and Pickett 1990) and has continued to spur on exciting ecological questions, experimentation, and collaboration with other disciplines. However, in the last five years, within-city studies have increased (e.g., those that do not have a non-urban component included in the study design), becoming the dominant type of study across taxa. Of the studies published between 1990–2018, 53% sampled exclusively within cities, while only 26% sampled an urban–rural gradient, and 21% contrasted biodiversity in sites within urban/suburban land uses to rural land uses. Over this 30-year period, the number of gradient and contrast studies leveled off, while studies within cities increased, especially since the early 2010s (Fig. 4). This new direction in urban

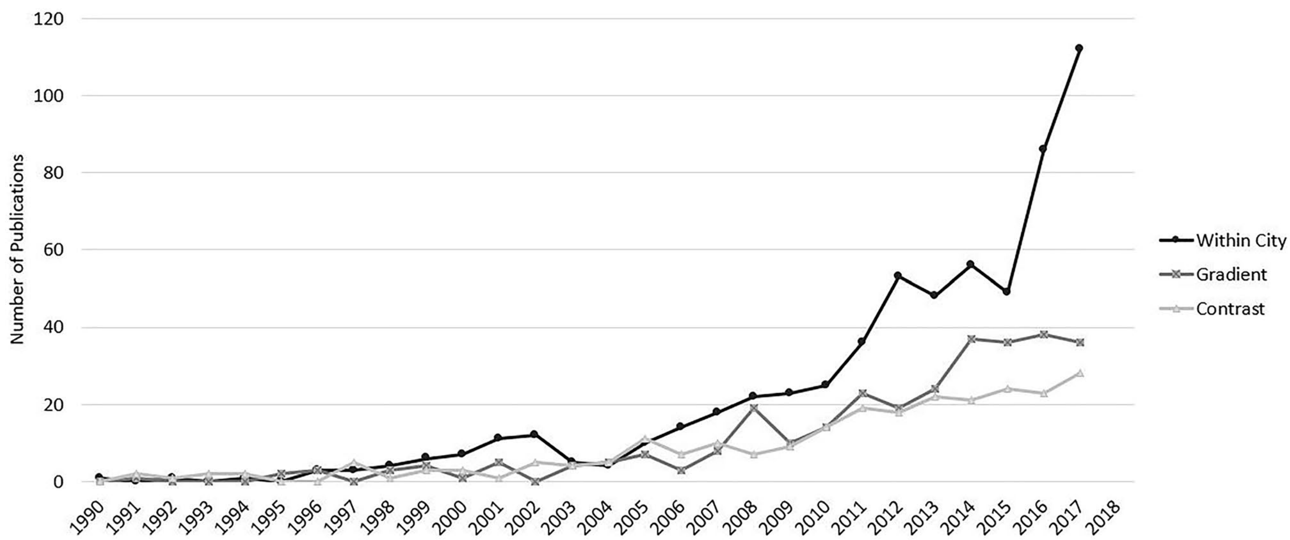


**Fig. 4** Annual changes in the number of publications that surveyed urban biodiversity as a contrast against non-urban regions, along a gradient, or within a city

biodiversity research, where studies are conducted entirely inside city boundaries, highlights the diversity and complexity of urban habitats and land uses within the city itself, and the necessity to look at urban areas from a regional perspective. Such a perspective is also crucial when thinking about the tight urban–rural linkages that connect humans, goods, services (Kroll et al. 2012), resources, species (Seebens et al. 2015), and more (Haase 2019) beyond municipal boundaries (McDonald et al. 2020).

Defining what constitutes "urban" has been a challenge in many disciplines (e.g., demography, sociology, geography) including ecology and the environmental sciences (Lepczyk et al. 2017; MacGregor-Fors 2011; McIntyre et al. 2000). The United Nations' (1955) view that ''*There is no point in the continuum from large agglomerations to small clusters of scattered dwellings where urbanity disappears and rurality begins; the division between urban and rural populations is necessarily arbitrary*'' remains as true today as it did 70 years ago. Thus, we see a variety of ways that researchers have defined urban in their work with the most common delineations of the urban landscape being the use of municipal boundaries (41%), land use (35%) or land cover (25%), and population density (13%), while 4% of studies did not define urban with any metric or description. Other quantitative variables, such as distance from the city center (9%), impervious cover (8%), building density (2%), road density (1%), and distance to roads (0.5%), were less frequently utilized as urbanization metrics. Non-urban was mostly characterized as "rural" (39%), by vegetation type (24%; e.g., forest, grassland, desert), or agricultural land use (17%; e.g., cropland, pasture, farm). Other terms used to characterize non-urban landscapes included peri-urban, natural/native/pristine, suburban, protected, and exurban (Supplementary Information, Table S2). Urban gradients were most often defined by land cover (41%), land use (30%), distance from the city center (20%), impervious cover (14%), building density (9%), and population density (9%) (Supplementary Information, Table S3). Such variation in the factors used to delineate 'urban' is unsurprising given the lack of a strict definition of what encompasses an urban area. Notably, there is no simple or elegant way to strictly denote what constitutes an urban setting, thus a good fraction of studies (20%) utilized multiple characteristics to quantify their urban sampling locations instead of using land use categories such as "urban" or "rural" (MacGregor-Fors 2011; MacGregor-Fors and Vázquez 2020). Nevertheless, the lack of simple, consistent, or agreed upon methods to define urban poses a challenge for comparative urban ecology.

Studying biodiversity within multiple land uses and vegetation habitat types within and across cities and towns allows for a more complete understanding of the effects that cities have on biodiversity, the value of cities for conservation, and applications in design and planning of cities for biodiversity (Filazzola et al. 2019). Increasing land use and habitat types sampled within one city can also broaden our understanding of the response of biodiversity in different socio-ecological contexts. Within cities, the most common land use types surveyed were remnant natural areas (56%), residential areas (44%), and parks (33%). Rare land use types/categories included brownfields (3%), roads (3%), and vacant lots (6%). Multiple land use types ($\geq 3$) were sampled in only 27% of studies, while 23% of the papers sampled multiple habitat types. Seven percent of studies did not specify the land use types sampled (e.g., city-wide surveys), and of those, a handful (0.4%) only specified the rural land uses and failed to specify the contrasting urban land use(s) (Supplementary Information, Table S4). Defining the specific land use surveyed in urban biodiversity studies is imperative to provide the socioeconomic and cultural contexts of a city (Kuras et al. 2020), and to compare trends across cities.

Close to half of all studies that specified the type of vegetation surveyed sampled forests (46%), followed by highly managed public landscapes (e.g., mowed/landscapes within parks, golf courses; 29%), or private yards and gardens (23%). The dominance of forest habitats may be a consequence of the geographic bias towards sampling temperate cities in North America and Europe (Fig. 2). Approximately 5% of studies sampled anthropogenic habitats unique from other categories, such as green roofs, bioswales, and stormwater ponds. The least common habitats studied included ruderal vegetation (1%), coastal dunes (1%), saline wetlands (2%), field margins (2%), and deserts (2%). Furthermore, we found that many studies confound land use and habitat type or define only one. For example, studies may have evaluated forest patches in commercial areas, but only "commercial" was used to describe the sample locations. Cities are mosaics of different land uses and habitat types (Niemelä 1999), which calls for additional studies that highlight land use and habitat diversity within urban areas and a typology of land use and habitat types that can be used across all cities for better comparative studies (i.e., similar to urban climate typology described in Stewart and Oke 2012). While focusing on one land use or habitat type is informative, especially for undersampled green space types, the lack of diversity in land use and habitat types reflects gaps in our understanding of how cities can act as refugia for biodiversity (Knapp et al. 2021), how multiple habitat types contribute to overall taxonomic and functional diversity (Casanelles-Abella et al. 2021; Fournier et al. 2020), which land use and habitat types act as ecological traps or population sinks, and how urban green spaces may be designed and managed to support biodiversity and in the long term (Kowarik and von der Lippe 2018; Lepczyk et al. 2017).

We also examined the methods utilized in urban biodiversity studies. Across all taxa, the median number of sites surveyed was 24 (mean = 790, mode = 3). The number of sites ranged from 2 to 880,310 (eBird; e.g., La Sorte et al. 2017). The largest sample sizes are from citizen science studies (e.g., Border et al. 2017; Fontaine et al. 2016; La Sorte et al. 2017). Excluding studies that utilized data from citizen science programs or museum specimens, the median number of sites surveyed across all taxa drops only slightly to 23 (mean = 104, mode = 3). Birds were sampled from the greatest number of sites, skewed again by eBird and other citizen science projects. Reptiles, spiders, carabid beetles, and ants were surveyed in the fewest number of locations (constrained in number and geography; Supplementary Information, Fig. S1), possibly due to the more time-intensive or handling-intensive survey methods needed for them and more limited taxonomic expertise in these groups.

Common sampling methods utilized in urban biodiversity research included point counts (birds, 54% of studies), transects (butterflies, 48%), physical traps or nets (amphibians, 43%; ants, 77%; bees, 72%; carabid beetles, 90%; mammals, 41%; reptiles, 46%; spiders, 86%), acoustic (amphibians, 43%; bats, 75%), and quadrats/relevés (plants, 65%). Other methods not commonly utilized across any taxon included physical evidence (e.g., tracks, scat), museum collections, atlas data, and citizen science (albeit increasing for birds and butterflies). For all taxa, most surveys occurred within one year. Except for butterflies (13%) and mammals (12%), < 5% of studies surveyed taxa over a period of five years or more. The longest duration studies utilized historical databases or museum specimens. For example, Knapp et al. (2017) utilized herbarium specimens, published historical and recent floras, and unpublished species lists and manuscripts, to examine 320 years (1687–2008) of vegetation change in the city of Halle, Germany. The limited number of long-term studies and low median survey sample size highlights the need to increase our understanding of spatiotemporal dynamics of urban biodiversity (Knapp et al. 2021). However, increasing rates of citizen science, broad-scale databases, and coordinated global research networks in the past decade could help to address this need (Amano et al. 2016; Poisson et al. 2020). Furthermore, we still lack any long-term, consistent urban biodiversity monitoring programs that can provide the information needed to evaluate many ecological relationships and assess temporal trends of populations.

Abundance was assessed for the sampled taxa in 72% of the studies, with 40% also utilizing traits to describe species' role in their community. The use of taxonomic diversity metrics, including species diversity and richness (85%) was overwhelmingly more common than functional (3%) or phylogenetic (1%) diversity metrics. Urban functional diversity studies became an important component of urban biodiversity science in the mid-2010s with over half of the studies focusing on the functional diversity of either plants or birds (62%) (Fig. 5). Phylogenetic diversity studies were rare until 2018 (1% of all studies), with plants serving as the dominant taxon analyzed (52%). Functional and phylogenetic diversity reflects evolved strategies for survival and use of available resources, differences among cities in how they support or filter out species from regional species pools, and allow for better comparisons across cities and taxa (Dolan et al. 2017; Hensley et al. 2019; La Sorte et al. 2018; Morelli et al. 2016; Vandewalle et al. 2010). These characteristics could be important for planning and design of biodiverse green spaces that support ecosystem functions and services (MacIvor et al. 2016).

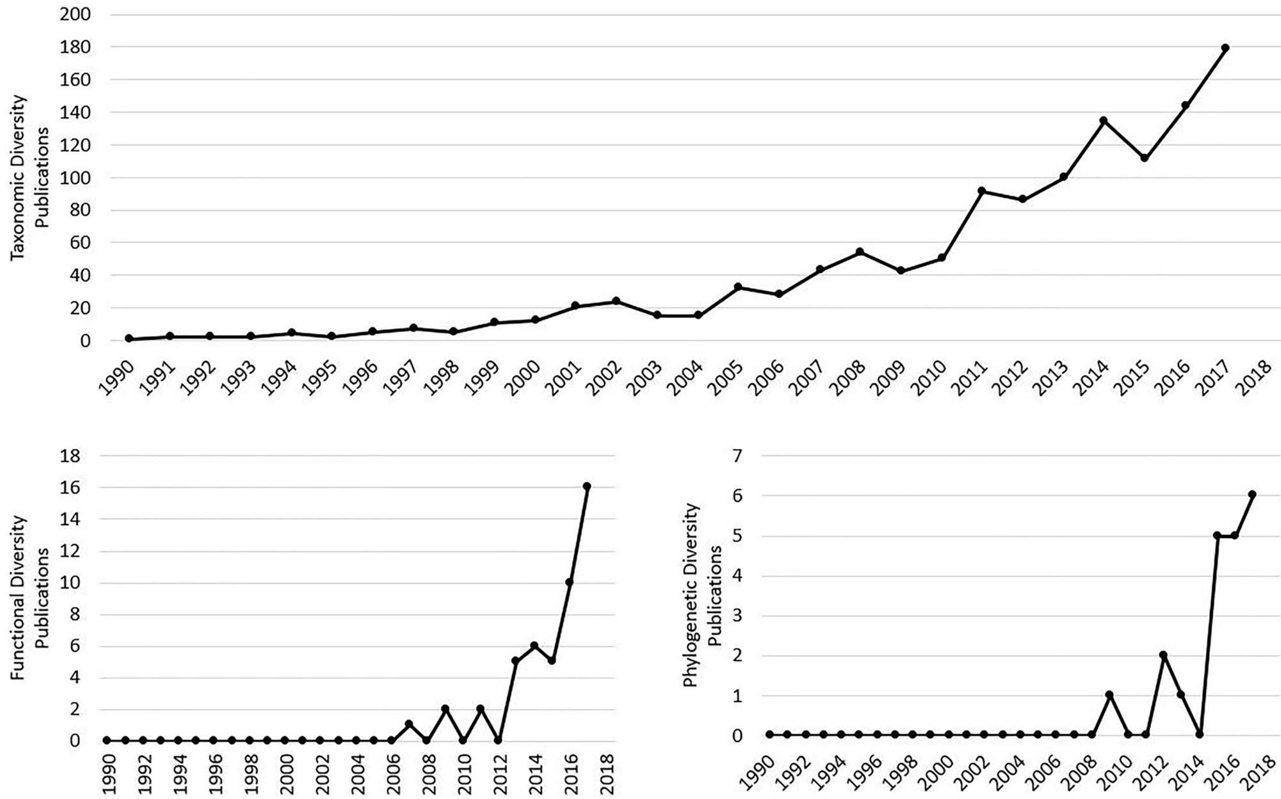


**Fig. 5** Numbers of publications evaluating taxonomic, functional, and phylogenetic diversity change time. A single paper may have multiple diversity measures. Patterns hold across all studied taxa

## Data transparency

Public data availability has become an increasingly important factor in scientific publication (Trisos et al. 2021) and collaborative urban biodiversity research. Species lists were reported in 65% of studies; however, we found that only 9.4% of studies published site coordinates and 6% reported species lists by site coordinates in either the paper, supplementary materials, or other online data repositories. Many urban ecological studies are conducted on residential property and sharing coordinates might infringe on privacy. Publishing localities of rare species may also drive collectors or other activities that cause harm. However, such data transparency would allow tackling research questions related to environmental change over time and space or relate biodiversity data to socio-ecological and socioeconomic context of different areas of cities; thus innovative approaches (e.g., beyond jittering coordinates) are needed. Additionally, of the papers that examined species traits, only 31% of those reported the traits of those species. Despite broad calls for data sharing across scientific communities (Costello et al. 2013; Reichman et al. 2011; Trisos et al. 2021), very few scientists share trait data, even for common, broadly distributed species. While some of these trait data are published in online repositories (e.g., PanTHERIA, Jones et al. 2009; TRY, Kattge et al. 2011), many taxa are not represented, and existing databases are not complete. Further, for some taxa, traits are tied closely to local conditions, and urban conditions are not well represented. Biodiversity science, particularly in urban areas, can only be enhanced with open data sharing and collaboration. This underlines the importance of research networks such as UrBioNet (Aronson et al. 2016; https://sites.rutgers.edu/urbionet) that are valuable, particularly to share data and findings with and link scientific and practitioner communities. This is particularly crucial if urban ecology is to become more inclusive and representative of cities in the Global South. However, funding is currently limited for long-term conglomerate research and networking that would properly support scholars and practitioners from the Global South as equal collaborators.

## Linking biodiversity to management and restoration

Although we did not specifically search for management and restoration case studies, we did evaluate how urban biodiversity studies addressed these. The effects of restoration or management strategies were tested in 8.5% (103) of urban biodiversity studies. An additional 4.6% of studies surveyed biodiversity of restored sites (but did not test any restoration or management strategies). The effects of restoration/management strategies were most often studied on plant (57%) and bird (12%) communities, and in forest (41%) and lawn/garden (29%) habitats within residential land uses (47%), remnant natural areas (41%), and parks (28%). Forests (48%) and freshwater wetlands (18%) were the most surveyed restored site habitats. The UN Decade on Ecosystem Restoration 2021–2030 highlights the need to prevent, halt and reverse the degradation of ecosystems across the globe, including in urban areas (United Nations Environment Programme 2021), but the paucity of studies that test restoration and management outcomes on ecological communities in urban areas needs to be addressed. Some countries (e.g., Germany) and cities (e.g., Toronto) even launched programs to enhance biodiversity friendly management within urban areas. Thus, individual municipalities are implementing biodiversity friendly management of green spaces, such as mowing parklands less frequently to benefit insect diversity or support the installation of artificial roosting sites for birds and bats by private owners. Yet, the effect of such management strategies within cities and towns is not systematically monitored. Furthermore, the urban bird ecology literature focusing on or providing management, planning or conservation suggestions based on their results indicates that their recommendations are often not implemented in meaningful ways (MacGregor-Fors et al. 2020). Early collaboration during the research process with practitioners, decision-makers, and community members and stakeholders can help co-produce and implement management and restoration strategies that are effective in urban areas (Apfelbeck et al. 2020). Transparent collaborative approaches that include more representative and diverse human communities living in cities in the co-production of urban biodiversity research are more likely to result in effective long-term management action (Trisos et al. 2021) to sustain biodiversity in cities.

## The way forward

Since McDonnell and Pickett's (1990) landmark publication outlining the possibilities of urban areas as locations for biodiversity and its conservation, urban ecology has become a significant component of the ecological literature. Even so, more work is required to advance the field, which is taking on greater urgency during an era of rapid urbanization, global biodiversity loss (Knapp et al. 2021), and climate change (IPCC 2021). We applaud the progression of urban biodiversity research in its geographic, taxonomic, and methodological scope. However, pushing these boundaries will continue to allow us to obtain a more comprehensive understanding of urban biodiversity, especially as cities, in some cases, are being identified as biodiversity refugia (Hall et al. 2017; Knapp et al. 2021; Soanes and Lentini 2019; Spotswood et al. 2021). Nonetheless, we echo calls of many authors to expand the geographic representation of research (e.g., Collins et al. 2021; La Sorte et al. 2014). The current geographic and study systems investigated (e.g., taxa, vegetation habitat, land use) bias our understanding of urban biodiversity towards birds and plants, forested ecosystems, the Global North, and areas of intense habitat management. We also recommend researchers and practitioners continue to broaden taxonomic representation in urban biodiversity research for understudied urban taxa (e.g., snails, spiders, reptiles, soil invertebrates, microbes) as these groups play important functional roles within urban ecosystems, as well as research that examines interactions of multiple taxa across trophic levels. We call for an expansion of sampling efforts beyond single year studies, examining differences among and within different urban habitat and land use types, and exploring new means of analyzing biodiversity. Finally, experimental studies, particularly those that test restoration and management outcomes in urban habitats, as well as those investigating biodiversity and ecosystem functions / services relationships, are needed to elucidate the mechanisms that lead to resilient communities, but these are rare and even fewer multi-city experimental studies have been performed.

While we did not explicitly examine social drivers of urban biodiversity in this study, we acknowledge that biodiversity is also shaped by peoples' social, cultural, political, and stewardship practices (Aronson et al. 2016; Kuras et al. 2020). Such drivers warrant further examination to better our understanding of the distribution of urban biodiversity, especially in the Global South. Additionally, Schell et al. (2020) highlighted the importance of going deeper into the social drivers of biodiversity, beyond socioeconomic gradient approaches (Leong et al. 2018), to considering the impacts of the racial and ethnic geography of cities on ecology and evolution of diverse taxa inhabiting cities. Funding agencies ought to support both fundamental and applied urban biodiversity projects, and with emphasis on the Global South, if we aim for the discipline to further develop and its applicability to materialize at faster rates.

Several of the journals included in our analysis have added new formats where paper submissions are encouraged from collaborative teams including researchers and practitioners involved in hands-on management (e.g., Practitioner's Perspective, *Journal of Applied Ecology*). Another recently developed tool by the British Ecological Society, *Applied Ecology Resources*, is a searchable database of grey literature where practitioners can host their materials now accessible to ecological researchers. We believe these represent an important opportunity to fill in some of the gaps identified in our review and by other recent calls for greater inclusivity and representation (Nagendra et al. 2018; Trisos et al. 2021). Action-oriented research projects designed with practitioners to ensure the results have impact may be a way forward in this area. In particular, the inclusion of local communities in decision making (e.g., Apfelbeck et al. 2020) will raise the acceptance for biodiversity-friendly urban planning that is equitable and considerate of different cultural and socioeconomic backgrounds. Recent research demonstrates that urban biodiversity conservation initiatives are most successful when practitioners actively engage communities to understand people's needs and embrace the diversity of values the public hold towards biodiversity (Taylor et al. 2021). Such information would be enormously valuable to advance the application of future urban biodiversity research towards more sustainable solutions tackling the global challenge to reconcile urbanization trends with conservation goals. We also encourage public data access, both the raw data and in secure open-access data repositories (e.g., Dryad; datadryad.org) or in supplementary materials and through the development and expansion of data sharing networks. Where possible, data and study results should be accessible to non-scientists, through web-based applications (e.g., R Shiny; Chang et al. 2021) to further enable transparency and engagement with all stakeholders. In doing so, we can commit to understanding biodiversity in cities and continuing to expand the scope, multidisciplinarity, equity, inclusivity, and rigor of urban ecological research within a rapidly urbanizing world, which could help pave the way to obtaining healthier, livable cities.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s11252-022-01207-w.

**Acknowledgements** This study resulted from a workshop held at Rutgers, the State University of New Jersey, New Brunswick, New Jersey, funded by the National Science Foundation's UrBioNet Research Coordination Network (grant no. DEB 1354676/1355151). We thank Carmela Buono, Eliana Geretz, Chris Hensley, Natalia Schneider, Hui-Anne Tan, and Christopher Trisos for their assistance with aspects of the data collection and two anonymous reviewers for comments on the draft manuscript.

**Authors' contributions** This study was developed during the UrBioNet workshop held at Rutgers, the State University of New Jersey, New Brunswick, New Jersey, 27–31 March 2017. All authors either designed the study, conducted the literature search, and/or reviewed studies resulting from the literature search. CCR-B, MFJA, MRP, AKH, and NSGW analyzed the data. CCR-B and MFJA wrote the first draft of the manuscript. All authors reviewed and edited the manuscript, and approved its final form.

**Funding** This study was funded by the National Science Foundation's UrBioNet Research Coordination Network (grant no. DEB 1354676/1355151).

**Availability of data and material** The dataset is available via the UrBioNet Database on the University of Missouri's MOspace at https://mospace.umsystem.edu/xmlui/handle/10355/46235.

**Code availability** Web of Science search terms are provided within the Supplementary Information.

## Declarations

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Conflicts of interest** We certify that we have no conflicts of interest regarding this work.

## References

Amano T et al (2016) Spatial gaps in global biodiversity information and the role of citizen science. Bioscience 66:393–400. https://doi.org/10.1093/biosci/biw022

Apfelbeck B et al (2020) Designing wildlife-inclusive cities that support human-animal co-existence. Landsc Urban Plan 200:103817. https://doi.org/10.1016/j.landurbplan.2020.103817

Aronson MFJ et al (2014) A global analysis of the impacts of urbanization on bird and plant diversity reveals key anthropogenic drivers. Proceedings of the Royal Society B: Biological Sciences 281:1–8. https://doi.org/10.1098/rspb.2013.3330

Aronson MFJ et al (2016) Hierarchical filters determine community assembly of urban species pools. Ecology 97:2952–2963. https://doi.org/10.1002/ecy.1535

Barbato D et al (2017) The role of dispersal and local environment in urban land snail assemblages: an example of three cities in Central Italy. Urban Ecosyst 20:919–931. https://doi.org/10.1007/s11252-017-0643-8

Beninde J et al (2015) Biodiversity in cities needs space: a meta-analysis of factors determining intra-urban biodiversity variation. Ecol Lett 18:581–592. https://doi.org/10.1111/ele.12427

Border JA et al (2017) Predicting the likely impact of urbanisation on bat populations using citizen science data, a case study for Norfolk, UK. Landsc Urban Plan 162:44–55. https://doi.org/10.1016/j.landurbplan.2017.02.005

Casanelles-Abella J et al (2021) Applying predictive models to study the ecological properties of urban ecosystems: A case study in Zürich. Switzerland Landsc Urban Plan 214:104137. https://doi.org/10.1016/j.landurbplan.2021.104137

Chang W et al (2021) shiny: Web Application Framework for R. RStudio, Boston, MA

Collins MK et al (2021) Global trends in urban wildlife ecology and conservation. Biol Conserv 261:109236. https://doi.org/10.1016/j.biocon.2021.109236

Costello MJ et al (2013) Biodiversity data should be published, cited, and peer reviewed. Trends Ecol Evol 28:454–461. https://doi.org/10.1016/j.tree.2013.05.002

Cressey D (2015) Ecologists embrace their urban side. Nature 524:399–400. https://doi.org/10.1038/524399a

Dolan RW et al (2017) Floristic response to urbanization: Filtering of the bioregional flora in Indianapolis, Indiana, USA. Am J Bot 104:1179–1187. https://doi.org/10.3732/ajb.1700136

Filazzola A et al (2019) The contribution of constructed green infrastructure to urban biodiversity: A synthesis and meta-analysis. J Appl Ecol 56:2131–2143. https://doi.org/10.1111/1365-2664.13475

Fontaine B et al (2016) Impact of urbanization and gardening practices on common butterfly communities in France. Ecol Evol 6:8174–8180. https://doi.org/10.1002/ece3.2526

Fournier B et al (2020) The origin of urban communities: From the regional species pool to community assemblages in city. J Biogeogr 47:615–629. https://doi.org/10.1111/jbi.13772
French SS et al (2018) Town and country reptiles: A review of reptilian responses to urbanization. Integr Comp Biol 58:948–966. https://doi.org/10.1093/icb/icy052
Frey D et al (2018) Predation risk shaped by habitat and landscape complexity in urban environments. J Appl Ecol 55:2343–2353. https://doi.org/10.1111/1365-2664.13189
Gaertner M et al (2017) Non-native species in urban environments: patterns, processes, impacts and challenges. Biol Invasions 19:3461–3469. https://doi.org/10.1007/s10530-017-1598-7
Haase D (2019) Urban telecouplings. In: Friis C, Nielsen JØ (eds) Telecoupling: Exploring land-use change in a globalised world. Springer International Publishing, Cham, pp 261–280
Haddaway NR et al (2015) The role of Google Scholar in evidence reviews and its applicability to grey literature searching. PLoS ONE 10:e0138237. https://doi.org/10.1371/journal.pone.0138237
Hall DM et al (2017) The city as a refuge for insect pollinators. Conserv Biol 31:24–29. https://doi.org/10.1111/cobi.12840
Hall DM, Martins DJ (2020) Human dimensions of insect pollinator conservation. Curr Opin Insect 38:107–114. https://doi.org/10.1016/j.cois.2020.04.001
Hamer AJ, McDonnell MJ (2008) Amphibian ecology and conservation in the urbanising world: A review. Biol Conserv 141:2432–2449. https://doi.org/10.1016/j.biocon.2008.07.020
Heleno RH et al (2020) Scientists' warning on endangered food webs. Web Ecol 20:1–10. https://doi.org/10.5194/we-20-1-2020
Hensley CB et al (2019) Effects of urbanization on native bird species in three Southwestern US cities. Frontiers in Ecology and Evolution 710.3389/fevo.2019.00071
IPBES (2019) Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. In: Díaz S, Settele J, Brondízio ES, Ngo HT, Guèze M, Agard J, Arneth A, Balvanera P, Brauman KA, Butchart SHM, Chan KMA, Garibaldi LA, Ichii K, Liu J, Subramanian SM, Midgley GF, Miloslavich P, Molnár Z, Obura D, Pfaff A, Polasky S, Purvis A, Razzaque J, Reyers B, Roy Chowdhury R, Shin YJ, Visseren-Hamakers IJ, Willis KJ, Zayas CN (eds), Bonn, Germany, p 56 pages. https://doi.org/10.5281/zenodo.3553579
IPCC (2021) Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds). Cambridge University Press, p 3949 pages
Jones KE et al (2009) PanTHERIA: A species-level database of life history, ecology, and geography of extant and recently extinct mammals. Ecology 90:2648–2648. https://doi.org/10.1890/08-1494.1
Kattge J et al (2011) TRY – a global database of plant traits. Glob Chang Biol 17:2905–2935. https://doi.org/10.1111/j.1365-2486.2011.02451.x
Kendal D et al (2020) City-size bias in knowledge on the effects of urban nature on people and biodiversity. Environ Res Lett 15:124035. https://doi.org/10.1088/1748-9326/abc5e4
Knapp S et al (2021) A research agenda for urban biodiversity in the global extinction crisis. Bioscience 71:268–279. https://doi.org/10.1093/biosci/biaa141
Knapp S et al (2017) Increasing species richness but decreasing phylogenetic richness and divergence over a 320-year period of urbanization. J Appl Ecol 54:1152–1160. https://doi.org/10.1111/1365-2664.12826
Koch NM et al (2019) Selecting lichen functional traits as ecological indicators of the effects of urban environment. Sci Total Environ 654:705–713. https://doi.org/10.1016/j.scitotenv.2018.11.107
Kowarik I (2011) Novel urban ecosystems, biodiversity, and conservation. Environ Pollut 159:1974–1983. https://doi.org/10.1016/j.envpol.2011.02.022
Kowarik I, von der Lippe M (2018) Plant population success across urban ecosystems: A framework to inform biodiversity conservation in cities. J Appl Ecol 55:2354–2361. https://doi.org/10.1111/1365-2664.13144
Kroll F et al (2012) Rural–urban gradient analysis of ecosystem services supply and demand dynamics. Land Use Policy 29:521–535. https://doi.org/10.1016/j.landusepol.2011.07.008
Kuras ER et al (2020) Urban socioeconomic inequality and biodiversity often converge, but not always: A global meta-analysis. Landsc Urban Plan 198:103799. https://doi.org/10.1016/j.landurbplan.2020.103799
La Sorte FA et al (2014) Beta diversity of urban floras among European and non-European cities. Glob Ecol Biogeogr 23:769–779. https://doi.org/10.1111/geb.12159
La Sorte FA et al (2017) Global change and the distributional dynamics of migratory bird populations wintering in Central America. Glob Chang Biol 23:5284–5296. https://doi.org/10.1111/gcb.13794
La Sorte FA et al (2018) The phylogenetic and functional diversity of regional breeding bird assemblages is reduced and constricted through urbanization. Divers Distrib 24:928–938. https://doi.org/10.1111/ddi.12738
Leong M et al (2018) Biodiversity and socioeconomics in the city: a review of the luxury effect. Biol Let 14:20180082. https://doi.org/10.1098/rsbl.2018.0082
Lepczyk CA et al (2017) Biodiversity in the city: Fundamental questions for understanding the ecology of urban green spaces for biodiversity conservation. Bioscience 67:799–807. https://doi.org/10.1093/biosci/bix079
Lososová Z et al (2011) Diversity of Central European urban biota: effects of human-made habitat types on plants and land snails. J Biogeogr 38:1152–1163. https://doi.org/10.1111/j.1365-2699.2011.02475.x
MacGregor-Fors I (2011) Misconceptions or misunderstandings? On the standardization of basic terms and definitions in urban ecology. Landsc Urban Plan 100:347–349. https://doi.org/10.1016/j.landurbplan.2011.01.013
MacGregor-Fors I et al (2015) Multi-taxonomic diversity patterns in a neotropical green city: a rapid biological assessment. Urban Ecosyst 18:633–647. https://doi.org/10.1007/s11252-014-0410-z
MacGregor-Fors I et al (2020) A dead letter? Urban conservation, management, and planning strategies from the Mexican urban bird literature. Urban Ecosyst 23:1107–1115. https://doi.org/10.1007/s11252-020-00970-y
MacGregor-Fors I, Vázquez L-B (2020) Revisiting 'rural.' Sci Total Environ 741:132789. https://doi.org/10.1016/j.scitotenv.2019.06.135
MacIvor JS et al (2016) Phylogenetic ecology and the greening of cities. J Appl Ecol 53:1470–1476. https://doi.org/10.1111/1365-2664.12667
Magle SB et al (2012) Urban wildlife research: Past, present, and future. Biol Conserv 155:23–32. https://doi.org/10.1016/j.biocon.2012.06.018
Mazor T et al (2018) Global mismatch of policy and research on drivers of biodiversity loss. Nat Ecol Evol 2:1071–1074. https://doi.org/10.1038/s41559-018-0563-x
McDonald RI et al (2020) Research gaps in knowledge of the impact of urban growth on biodiversity. Nat Sustain 3:16–24. https://doi.org/10.1038/s41893-019-0436-6

McDonnell MJ, Hahs AK (2013) The future of urban biodiversity research: Moving beyond the 'low-hanging fruit.' Urban Ecosyst 16:397–409. https://doi.org/10.1007/s11252-013-0315-2
McDonnell MJ, Pickett STA (1990) Ecosystem structure and function along urban-rural gradients: An unexploited opportunity for ecology. Ecology 71:1232–1237. https://doi.org/10.2307/1938259
McIntyre NE et al (2000) Urban ecology as an interdisciplinary field: differences in the use of "urban" between the social and natural sciences. Urban Ecosyst 4:5–24. https://doi.org/10.1023/A:1009540018553
McKinney ML (2002) Urbanization, biodiversity, and conservation: The impacts of urbanization on native species are poorly studied, but educating a highly urbanized human population about these impacts can greatly improve species conservation in all ecosystems. Bioscience 52:883–890. https://doi.org/10.1641/0006-3568(2002)052[0883:ubac]2.0.co;2
McKinney ML (2008) Effects of urbanization on species richness: A review of plants and animals. Urban Ecosyst 11:161–176. https://doi.org/10.1007/s11252-007-0045-4
Melliger RL et al (2017) Habitat- and matrix-related differences in species diversity and trait richness of vascular plants, Orthoptera and Lepidoptera in an urban landscape. Urban Ecosyst 20:1095–1107. https://doi.org/10.1007/s11252-017-0662-5
Monteiro Júnior CdS et al (2015) Analysis of urban impacts on aquatic habitats in the central Amazon basin: Adult odonates as bioindicators of environmental quality. Ecol Indic 48:303–311. https://doi.org/10.1016/j.ecolind.2014.08.021
Morelli F et al (2016) Evidence of evolutionary homogenization of bird communities in urban environments across Europe. Glob Ecol Biogeogr 25:1284–1293. https://doi.org/10.1111/geb.12486
Morelli F et al (2020) Editorial: Partitioning the effects of urbanization on biodiversity: Beyond wildlife behavioural responses to a multilevel assessment of community changes in taxonomic, functional and phylogenetic diversity. Frontiers in Ecology and Evolution 810.3389/fevo.2020.00023
Mutinova PT et al (2020) Benthic diatom communities in urban streams and the role of riparian buffers. Water 12:2799
Nagendra H et al (2018) The urban south and the predicament of global sustainability. Nat Sustain 1:341–349. https://doi.org/10.1038/s41893-018-0101-5
Narango DL (2020) Natural history in the city: Connecting people to the ecology of their plant and animal neighbors. Journal of Natural History Education & Experience 14:13–17
Niemelä J (1999) Is there a need for a theory of urban ecology? Urban Ecosyst 3:57–65. https://doi.org/10.1023/A:1009595932440
Niemelä J et al (2000) The search for common anthropogenic impacts on biodiversity: a global network. J Insect Conserv 4:3–9. https://doi.org/10.1023/A:1009655127440
Nilon CH et al (2017) Planning for the future of urban biodiversity: a global review of city-scale initiatives. Bioscience 67:332–342. https://doi.org/10.1093/biosci/bix012
Oke C et al (2021) Cities should respond to the biodiversity extinction crisis. npj Urban Sustainability 1: 11. https://doi.org/10.1038/s42949-020-00010-w
Pinho P et al (2021) Research agenda on biodiversity and ecosystem functions and services in European cities. Basic Appl Ecol 53:124–133. https://doi.org/10.1016/j.baae.2021.02.014
Poisson AC et al (2020) Quantifying the contribution of citizen science to broad-scale ecological databases. Front Ecol Environ 18:19–26. https://doi.org/10.1002/fee.2128
PRISMA (2021) Transparent reporting of systematic reviews and meta-analyses
Rebele F (1994) Urban ecology and special features of urban ecosystems. Glob Ecol Biogeogr Lett 4:173–187. https://doi.org/10.2307/2997649
Reboredo Segovia AL et al (2020) Who studies where? Boosting tropical conservation research where it is most needed. Front Ecol Environ 18:159–166. https://doi.org/10.1002/fee.2146
Reichman OJ et al (2011) Challenges and opportunities of open data in ecology. Science 331:703–705. https://doi.org/10.1126/science.1197962
Rivkin LR et al (2019) A roadmap for urban evolutionary ecology. Evol Appl 12:384–398. https://doi.org/10.1111/eva.12734
Sattler T et al (2014) Selection of multiple umbrella species for functional and taxonomic diversity to represent urban biodiversity. Conserv Biol 28:414–426. https://doi.org/10.1111/cobi.12213
Schell CJ et al (2020) The ecological and evolutionary consequences of systemic racism in urban environments. Science 369: eaay4497. https://doi.org/10.1126/science.aay4497
Schwarz N et al (2017) Understanding biodiversity-ecosystem service relationships in urban areas: A comprehensive literature review. Ecosyst Serv 27:161–171. https://doi.org/10.1016/j.ecoser.2017.08.014
Secretariat of the Convention on Biological Diversity (2012) Cities and biodiversity outlook. Montreal, 64 pages
Seebens H et al (2015) Global trade will accelerate plant invasions in emerging economies under climate change. Glob Chang Biol 21:4128–4140. https://doi.org/10.1111/gcb.13021
Seibold S et al (2018) The necessity of multitrophic approaches in community ecology. Trends Ecol Evol 33:754–764. https://doi.org/10.1016/j.tree.2018.07.001
Seto KC et al (2012) Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. PNAS 109:16083–16088. https://doi.org/10.1073/pnas.1211658109
Shackelton CM et al (eds) (2021) Urban ecoogy in the Global South. Springer, Cham, Switzerland, 461 pages
Shochat E et al (2006) From patterns to emerging processes in mechanistic urban ecology. Trends Ecol Evol 21:186–191. https://doi.org/10.1016/j.tree.2005.11.019
Silvertown J et al (2011) Citizen science reveals unexpected continental-scale evolutionary change in a model organism. PLoS ONE 6:e18927. https://doi.org/10.1371/journal.pone.0018927
Soanes K, Lentini PE (2019) When cities are the last chance for saving species. Front Ecol Environ 17:225–231. https://doi.org/10.1002/fee.2032
Spotswood EN et al (2021) The Biological Deserts Fallacy: Cities in their landscapes contribute more than we think to regional biodiversity. Bioscience 71:148–160. https://doi.org/10.1093/biosci/biaa155
Stewart ID, Oke TR (2012) Local climate zones for urban temperature studies. Bull Am Meteor Soc 93:1879–1900. https://doi.org/10.1175/BAMS-D-11-00019.1
Sukopp H (2002) On the early history of urban ecology in Europe. Preslia 74:373–393
Sukopp H, Weiler S (1988) Biotope mapping and nature conservation strategies in urban areas of the Federal Republic of Germany. Landsc Urban Plan 15:39–58. https://doi.org/10.1016/0169-2046(88)90015-1
Taylor L et al (2021) Enablers and challenges when engaging local communities for urban biodiversity conservation in Australian cities. Sustain Sci. https://doi.org/10.1007/s11625-021-01012-y
Tresch S et al (2019) Litter decomposition driven by soil fauna, plant diversity and soil management in urban gardens. Sci Total Environ 658:1614–1629. https://doi.org/10.1016/j.scitotenv.2018.12.235
Trisos CH et al (2021) Decoloniality and anti-oppressive practices for a more ethical ecology. Nat Ecol Evol. https://doi.org/10.1038/s41559-021-01460-w
United Nations (1955) United Nations demographic yearbook 1952. United Nations, New York

United Nations (2015) 2030 Agenda for sustainable development. https://sdgs.un.org/2030agenda

United Nations Environment Programme (2021) Becoming #GenerationRestoration: Ecosystem restoration for people, nature and climate. Nairobi

Vandewalle M et al (2010) Functional traits as indicators of biodiversity response to land use changes across ecosystems and organisms. Biodivers Conserv 19:2921–2947. https://doi.org/10.1007/s10531-010-9798-9

Wu J (2014) Urban ecology and sustainability: The state-of-the-science and future directions. Landsc Urban Plan 125:209–221. https://doi.org/10.1016/j.landurbplan.2014.01.018

Yang J (2020) Big data and the future of urban ecology: From the concept to results. Sci China Earth Sci 63:1443–1456. https://doi.org/10.1007/s11430-020-9666-3

## Authors and Affiliations

**Christine C. Rega-Brodsky[1] · Myla F. J. Aronson[2] · Max R. Piana[3] · Ela-Sita Carpenter[4] · Amy K. Hahs[5] · Adriana Herrera-Montes[6] · Sonja Knapp[7] · D. Johan Kotze[8] · Christopher A. Lepczyk[9] · Marco Moretti[10] · Allyson B. Salisbury[11] · Nicholas S. G. Williams[5] · Kirsten Jung[12] · Madhusudan Katti[13] · Ian MacGregor-Fors[8] · J. Scott MacIvor[14] · Frank A. La Sorte[15] · Vallari Sheel[16] · Caragh G. Threfall[17] · Charles H. Nilon[18]**

1 Department of Biology, Pittsburg State University, Pittsburg, KS 66762, USA

2 Department of Ecology, Evolution and Natural Resources, Rutgers, The State University of New Jersey, New Brunswick, NJ 08816, USA

3 USDA Forest Service, Northern Research Station, Amherst, MA 01003, USA

4 U.S. Fish and Wildlife Service, Chesapeake Bay Field Office, 177 Admiral Cochrane Dr, Annapolis, MD 21401, USA

5 School of Ecosystem and Forest Sciences, The University of Melbourne, Burnley Campus 500 Yarra Blvd, Richmond 3121 VIC, Australia

6 Department of Environmental Science, College of Natural Sciences, University of Puerto Rico, San Juan, Puerto Rico

7 Department of Community Ecology, Helmholtz Centre for Environmental Research - UFZ, Theodor-Lieser-Str. 4, 06120 Halle (Saale), Germany

8 Faculty of Biological and Environmental Sciences, Ecosystems and Environment Research Programme, University of Helsinki, Niemenkatu 73, 15140 Lahti, Finland

9 School of Forestry & Wildlife Sciences, Auburn University, Auburn, AL 36849, USA

10 Swiss Federal Research Institute WSL, Biodiversity and Conservation Biology, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland

11 The Morton Arboretum, 4100 Illinois Route 53, Lisle, IL 60532, USA

12 Evolutionary Ecology and Conservation Genomics, Ulm University, Albert-Einstein-Allee 11, 89077 Ulm, Germany

13 Department of Forestry and Environmental Resources, Faculty Excellence Program for Leadership in Public Science, North Carolina State University, Chancellor', Raleigh, NC 27695, USA

14 Department of Biological Sciences, University of Toronto Scarborough, 1265 Military Trail, Toronto M1C 1A4, Canada

15 Cornell Lab of Ornithology, Cornell University, Ithaca, NY 14850, USA

16 Department of Forestry and Environmental Resources, North Carolina State University, Campus, Box 8008, Raleigh, NC 27695, USA

17 School of Life and Environmental Sciences, The University of Sydney, Sydney, NSW 2006, Australia

18 School of Natural Resources, University of Missouri, Columbia, MO 65211, USA