JNCC Report 754

Review of opportunities for urban biodiversity monitoring

(*Guidance report*)

Marion, S.[1] and Hoskins, H.[1]

January 2024

© JNCC, Peterborough 2024

ISSN 0963 8091

JNCC's report series serves as a record of the work undertaken or commissioned by JNCC. The series also helps us to share, and promote the use of, our work and to develop future collaborations.

For further information on JNCC's report series please contact:
Joint Nature Conservation Committee, Quay House, 2 East Station Road, Fletton Quays, Peterborough PE2 8YY
https://jncc.gov.uk/
Communications@jncc.gov.uk

This report was produced by JNCC for Defra through the Natural Capital and Ecosystem Assessment (NCEA) programme.

This report should be cited as:
Marion, S.[1] & Hoskins, H.[1] 2024. Review of opportunities for urban biodiversity monitoring (Guidance report). *JNCC Report 754*, JNCC, Peterborough, ISSN 0963-8091. https://hub.jncc.gov.uk/assets/476b6b62-cea8-48e6-931e-b597d8b3d8b9.

Author affiliation:
[1] JNCC, Quay House, Peterborough.

Acknowledgments:
This project was funded by the Department for Environment, Food and Rural Affairs (Defra) as part of the Natural Capital and Ecosystem Assessment (NCEA) programme. The NCEA programme is leading the way in supporting Government ambition to integrate natural capital approaches into decision making. Find out more at https://www.gov.uk/government/publications/natural-capital-and-ecosystem-assessment-programme.

We thank British Trust for Ornithology, Royal Society for the Protection of Birds, Butterfly Conservation, and the Bat Conservation Trust for their contributions to reviewing the report. Additionally, we extend our thanks to Natural England, UK Centre for Ecology & Hydrology and the Natural History Museum for their input throughout the development of the report. We also thank Niki Newton, Paul Woodcock, Kirsi Peck, Caroline Coogan and Chris Cheffings for their valuable contributions.

Evidence Quality Assurance:
This report is compliant with JNCC's Evidence Quality Assurance Policy https://jncc.gov.uk/about-jncc/corporate-information/evidence-quality-assurance/

This report and any accompanying material is published by JNCC under the Open Government Licence (OGLv3.0 for public sector information), unless otherwise stated. Note that some images and tables may not be copyright JNCC; please check sources for conditions of re-use.'

The views and recommendations presented in this report do not necessarily reflect the views and policies of JNCC.

Summary

Aim: This report aims to provide insight into urban biodiversity monitoring using citizen science (CS) and indicators in the UK. We first explore how urbanisation impacts biodiversity and how biodiversity is monitored in urban areas. We then use case studies of indicators that can be used to assess biodiversity status in urban areas. This report highlights the importance of CS in monitoring urban biodiversity, identifies gaps in current monitoring practices, and provides recommendations for future research and monitoring efforts.

Context: Urban areas, while contributing to the decline in biodiversity, also have the potential to support biodiversity conservation. Therefore, it is crucial to monitor and understand population trends and the ecological mechanisms underlying species-specific responses in these areas. This can be achieved using CS monitoring and the use of indicators.

Biodiversity in urban areas:

- Plant biodiversity is influenced by human activities, leading to a decline in native species but an overall increase in plant richness.
- Bird populations are influenced by factors such as temperature, habitat patch size, and resource availability, resulting in lower species richness in urban regions compared to non-urban areas. However, this is highly species-specific.
- Urbanisation affects mammals and invertebrates, altering their behaviour, habitat selection, and species compositions.
- Soil biodiversity is also influenced by urbanisation, impacting plant composition and ecosystem functions.

In the UK, urban green spaces encompass various types, including natural and semi-natural green spaces, street trees, public parks, formal gardens, green corridors, outdoor sports facilities, allotments, community gardens, urban farms, cemeteries, and churchyards.

Monitoring urban biodiversity:

- Urban biodiversity can be monitored at different spatial scales: broad-scale, comparative, rural-urban or native-urban gradient, and urban-centric.
- Various sources of data for monitoring urban biodiversity and urban components are available, including geospatial data, satellite/aerial imaging, geo-located social media, citizen science (national schemes and recording, and urban-specific programmes).

In this report, CS is highlighted as a common approach to monitor biodiversity in the UK, and several examples of citizen science projects related to urban monitoring are provided. We show that all different parts of the urban ecosystem (e.g. soil, air and water quality, species) can be monitored using existing CS schemes. In practice monitoring of some species groups is more often undertaken than for others. We also show that CS can be used at the local scale (i.e. individual cities) or at a large spatial scale (cities worldwide). However, we also show that some challenges remain in monitoring urban areas using CS, such as bias in areas recorded, difficulties in recruiting volunteers, and difficulties in adapting some protocols to urban situations.

Indicators and frameworks to assess urban biodiversity: We discuss five case studies focusing on different indicators and frameworks used to assess urban biodiversity. We discuss Biodiversity Net Gain (BNG), Green and Blue Infrastructures (GI), Natural Capital

Indicators (NCIs), Singapore Index (SI), and IUCN's Urban Nature Indices (UNI). We show the interconnectedness of these indicators and frameworks and the importance of habitat monitoring in assessing urban biodiversity. Habitat size and quality are key components of most indicators, and CS can contribute to monitoring and data collection efforts.

Take-home message: In the last section of this report, we highlight different gaps in the current monitoring of urban biodiversity. Note that these points also apply to monitoring in various habitats:

- Current urban monitoring using CS is skewed toward species and the recording of their presence/absence and/or abundance. We suggest focusing on a broader range of urbanisation impacts, such as behavioural shifts, and focusing on other diversities, such as genetic and functional diversity.
- We found that monitoring (not only inclusively using CS) is skewed toward some species and some areas. We suggest that different CS schemes help with the effort of monitoring under-recorded species in urban areas while focusing on under-recorded areas across taxa.
- We highlight the importance of habitat quality and quantity monitoring and suggest that CS schemes incorporate habitat monitoring into their current protocols (if not already included). However, this might be limited by volunteers' willingness to take part in habitat monitoring.
- Finally, we highlight that one of the main specificities of the urban environment is the different socio-economic contexts. Future work needs to consider how these factors can be incorporated into different monitoring protocols and what the different engagement options available are to remove socio-economic barriers to participation.

Take home messages and next steps: we highlight the importance of addressing various aspects of urban biodiversity monitoring using CS and indicators, such as stakeholder objectives, spatial scales, taxonomic groups, data quality, accessibility, and the development of an inclusive framework, to achieve effective biodiversity conservation in urban areas. Local pilot projects are recommended to refine and implement the identified framework successfully.

Contents

1. Context

We are currently experiencing the sixth mass extinction and collapse of biodiversity (Kolbert 2014). This decline is evident across taxa, ranging from plants to invertebrates, to large mammals (Cowie *et al.* 2022). The causes of this decline are anthropogenic: deforestation (Giam 2017), climate change (Tangcharoensathien *et al.* 2022), and habitat modification (Krauss *et al.* 2010). Habitat loss due to urbanisation is a major concern, as the urban population is expected to increase by 2.5 billion people in the next 30 years (United Nations 2018). Cities and towns need to accommodate their growing populations, often at the expense of biodiversity and natural habitats (McDonald *et al.* 2018).

Biodiversity in urban areas is complex and high variation in species responses can be observed. For example, in their literature review, Faeth *et al.* (2011) found that the overall diversity, abundance, and species richness of terrestrial fauna decreased in urban areas but with a high level of variation among taxonomic groups. For instance, bird abundances often increase in cities relative to rural or natural habitats, while their richness and diversity decline (Faeth *et al.* 2011). Although variations in species' responses exist, urban areas have the potential to contribute to biodiversity conservation (e.g. Ives *et al.* 2016). They can support endemic native species and other species on both regional and global scales (Aronson *et al.* 2016; Lepczyk *et al.* 2017). For example, research on wild bees has shown that diverse populations live in urban landscapes (Hall *et al.* 2017). Cities have high levels of landscape heterogeneity, which may favour a variety of threatened species (Ives *et al.* 2016). However, landscapes with a high level of heterogeneity create small patch sizes, which can be hotspots of biodiversity with high conservation values. (Yan *et al.* 2021). Actively managing and monitoring biodiversity in urban areas can help nature recovery, whilst increasing the quality of life of urban inhabitants (McDonnell & Hahs 2013).

Currently, in urban areas, we have a limited understanding of population trends, ecological drivers, and ecological mechanisms underlying species-specific responses (McDonnell & Hahs 2013); for example, what are the drivers that lead some species population abundances to increase while some other populations are decreasing? Pollution, habitat fragmentation and inter-species competition are amongst other stressors that urban species are facing, but their impact on species populations is highly variable. For example, McKinney (2008) found that the majority of plant increased in species richness with moderate urbanization while only a minority of invertebrate studied, and a very small minority of non-avian vertebrate studied demonstrate an increase in species richness. Similarly, not all taxa have been monitored to the same extent, leading to a gap in the overall understanding of urban biodiversity's current state (Rega-Brodsky *et al.* 2022). These factors highlight the need to monitor biodiversity in urban areas, across taxa, and at different spatiotemporal scales as well as their local habitat and environmental condition.

Due to urban areas being highly fragmented, combined with land access difficulties, monitoring urban biodiversity across space and time is challenging (Farinha-Marques *et al.* 2011). For example, access to private gardens for monitoring purposes is not always straightforward or realistic. Additionally, various components of the urban environment need to be considered, such as socioeconomic factors (education, access to nature, etc.). Thus, organisations such as the International Union for Conservation of Nature (IUCN) or Convention on Biological Diversity (CBD) have developed indicators and frameworks to provide information about the state of biodiversity and trends in urban areas. We define an indicator as a measure based on verifiable data that conveys information about more than just itself. This means that indicators are purpose dependent - the interpretation or meaning given to the data depends on the purpose or issue of concern. Measurable indicators with accompanying targets and/or verifiable outputs are important for understanding biodiversity in urban areas as well as determining whether interventions for biodiversity enhancement are successful (Pierce *et al.* 2020). A framework of indicators refers to a structured set of measurable variables or metrics that are used to assess and monitor the state of the environment as well as track and evaluate conservation actions. The selection of indicators is crucial as they should be relevant, reliable, and sensitive to changes in the ecosystem being monitored. A well-designed framework of indicators ensures that the essential aspects of conservation are captured and measured consistently over time. The use of these frameworks relies on data collected in the field and these data can be obtained but not exclusively, from local records, research outputs, or citizen science.

It is widely recognised that life depends on healthy ecosystems as they offer a variety of goods and services, collectively known as ecosystem services. Defra's Natural Capital and Ecosystem Assessment (NCEA) programme covers various environments, across water and land, including urban areas. The NCEA programme aims to comprehend the condition and trends of terrestrial, freshwater, and marine environments to guide environmental policy and management. The programme encompasses aspects such as air quality, biodiversity, carbon storage, habitats, natural flood defences, and resilience. The objective is to gather data on England's ecosystems and natural capital, assessing their extent, condition, and changes over time, as well as the benefits they provide to society. In the UK, the collection of environmental data and the monitoring of biodiversity heavily rely on the efforts of (volunteer) citizen scientists.

Citizen science (hereafter CS) – the mass involvement of non-professionals in scientific research – brings opportunities to gather biodiversity information quickly and efficiently at large and local spatial scales (Amano *et al.* 2016). CS projects have increased over the last 20 years and have focused on different taxa, such as plants, pollinators, and birds (Feldman *et al.* 2021). It is a cost-effective, reliable way to collect data and technological advances (e.g. smartphone apps) have made data collection more straightforward (Pocock *et al.* 2014). In urban areas, CS projects have involved broad types of monitoring such as that of urban trees (Roman *et al.* 2017), gardens (Beumer & Martens 2015; Williams *et al*. 2015), and bird populations (McCaffrey 2005). CS in urban areas allows monitoring in private and hard-to-access areas while being cost-effective (Callaghan *et al.* 2020, 2019).

The UK has a long history of successful CS schemes (e.g. vascular plant monitoring, Pescott *et al.* 2019) and alongside JNCC, organisations such as the British Trust for Ornithology (BTO) lead multiple monitoring schemes every year to increase our understanding of UK biodiversity. For instance, volunteers can get involved in monitoring schemes such as the Breeding Bird Survey, the UK Butterfly Monitoring Scheme and the National Plant Monitoring Scheme, which JNCC runs in partnership with a range of other environmental organisations. These different schemes and citizen science programmes in the UK are valued tools to support environmental monitoring.

In this report, we investigate how we can monitor urban natural capital over time and across space using citizen science, with a particular focus on biodiversity. Here we focus on the definition of urban areas, how biodiversity is currently monitored in urban areas, which indicators require data from biodiversity monitoring across space and time, and how citizen science can help with the monitoring of biodiversity in urban areas in the UK.

2. Biodiversity in urban areas

Biodiversity can be characterised into three distinct types: genetic diversity, species diversity, and ecosystem diversity (ecological). Genetic (or genomic) diversity refers to the variety within and between organisms, capturing the diversity at the genetic level. Species diversity represents the "richness" or the number of native or non-native species present in a specific area. Ecosystem (or ecological) diversity encompasses the variation in species assemblages at different scales (Gaston & Spicer 2013).

In the UK, the Office of National Statistics classifies "urban" as contiguous areas with a population of 10,000 or more, referred to as "physical settlement areas". Urban areas are predominantly characterised by anthropogenic features such as buildings, roads, and other infrastructure. Within these urban settings, there are urban green spaces that include heavily maintained and modified patches, such as ornamental flower beds in city cores, green roofs, bioswales, and community gardens. Additionally, urban green spaces encompass areas with managed and unmanaged vegetation, such as city parks, home gardens, unmanaged vacant lots, brownfield sites, and remnant natural areas (Lepczyk *et al.* 2017).

2.1 Species' diversity

Species exhibit varying responses to urbanisation and the specific forms it takes (Davies *et al.* 2011). Species that tend to be impacted by urbanisation include habitat specialists, species that require large patches, and species typically associated with more complex vegetation structures, such as forests (Davies *et al.* 2011). Overall, urbanisation has a negative impact on species. However, the extent of the impact varies across species groups.

2.1.1 Plants

Plant biodiversity in urban areas is primarily influenced and controlled by human activities (Faeth *et al.* 2011). While efforts can be made to preserve native plant diversity, human activities often involve complete deconstruction and subsequent reconstruction of plant communities using predominantly non-native species, including grasses, herbs, forbs, trees, and shrubs. This occurs in the creation of lawns, recreational areas, urban forests, gardens, and landscapes (Faeth *et al.* 2011). Thus, while native species decline, the overall richness of plants can increase (Walker *et al.* 2009, p. 20). This phenomenon is driven by socioeconomic factors, such as the “luxury effect”, which associates human resource abundance (wealth) with plant diversity (Hope *et al.* 2003). For example, trees planted in urban areas are often chosen for their ornamental value and these species provide a large range of services including mitigation of urban heat or air quality. However, the provision of these services relies on the morphological and physiological adaptations of urban trees to cope with urban pressures, such as space constraints, soil compaction, restricted access to water, and air pollution (Roman *et al.* 2017). While they can support biodiversity (e.g. bird nesting), non-native plants and trees can impact other parts of the ecosystem, such as soil/stream acidification, hybridization and reduction of native diversity through competition and habitat alteration (Manchester & Bullock 2000).

Urban areas consist of highly heterogeneous patches, ranging from patches lacking any plants (e.g. car parks) to those with high levels of diversity (e.g. remnants of native habitats) (Faeth *et al.* 2011). The combination of these patches can result in an overall high plant diversity in urban areas, but the spatial distribution of this diversity among the patches is not uniform (Walker *et al.* 2009, p. 20). This spatial heterogeneity can produce very high levels of beta diversity (i.e. species composition or community structure between different habitat or spatial units) and greater species richness than surrounding rural areas especially in groups that require relatively small areas to support viable populations (e.g. plants and insects) (McKinney 2008). Finally, urban habitats often have much greater primary productivity than surrounding areas, due to the importation of water, fertilizers and other limiting factors (McKinney 2008).

2.1.2 Birds

Bird populations can be impacted differently by urbanisation depending on local characteristics and their own traits. For instance, the temperature increase in urban areas can extend the vegetation period, enabling a longer breeding season (Seress & Liker 2015). Evans *et al.* (2009) reviewed 72 studies on the influences of habitat on urban bird populations and concluded that larger habitat patches support larger and more stable bird populations. Birds generally exhibit lower species richness and evenness in urban regions compared to more natural areas, with the lowest levels of diversity typically observed in urban core areas (McKinney 2008). However, bird richness often reaches its peak in the suburbs, at intermediate levels of urbanisation (see section 2.3.3). Importantly, urbanisation also influences the species composition of the avifauna (Seress & Liker 2015). Depending on their tolerance to disturbance and their ability to utilise and rely on human-provided resources, bird species in urban areas can be categorized as urban avoiders, urban adapters, or urban exploiters (McKinney 2002). The species composition will vary, with one type of bird prevailing over others depending on the degree of urbanisation.

2.1.3 Mammals

Mammals in urban areas are often studied less extensively than birds or plants. However, Ritzel *et al.* (2020) examined the behavioural responses of mammals to urban environments and found that the urban environment drives adaptive behavioural changes, including changes in home range and diet preference, shifts in activity patterns and vigilance, decreased flight initiation distance, and increased nocturnal activity. Similarly, Villaseñor *et al.* (2017) studied the impact of low and high-density housing developments on the occupancy and abundance of six mammal species using modelling techniques. They found that high-density housing can reduce the area of occupancy and/or abundance of five out of the six mammal species examined by up to 6%, while low-density housing resulted in an overall increase in mammal abundance, although results varied between species. Likewise, Baker *et al.* (2007) found that housing developments in Britain can impact patterns of habitat selection. They found that all species appeared to be negatively affected by increased fragmentation and reduced proximity of natural and semi-natural habitats, as well as decreased garden size and garden structure.

2.1.4 Invertebrates

McIntyre (2000) summarised the importance of studying invertebrates in urban areas in five points:

(1) As a diverse group they provide a good indication of the overall biodiversity of an area.
(2) Their rapid generation times enable them to respond quickly to anthropogenic changes in soil and vegetation.
(3) They are easily sampled, and sampling does not generate controversy in the public eye.
(4) They are present at many trophic levels.
(5) They hold sociological, agronomic, and economic significance within habitats undergoing anthropogenic changes.

Much research shows that urbanisation has detrimental effects on invertebrate diversity and abundance (Fenoglio *et al*. 2020; Jones & Leather 2012). The magnitude of the changes in diversity and abundance along the urban gradient depended on the arthropod taxonomic group and the age of the cities (Fenoglio *et al.* 2020). Additionally, urban areas exhibit different species compositions compared to non-urban areas, with an increasing dominance of predominantly generalist and opportunist species. Urban areas have lower insect species richness, especially of Diptera and Lepidoptera, compared to neighbouring rural sites (Theodorou *et al.* 2020). In contrast, Hymenoptera, especially bees, show higher species richness and flower visitation rates in cities (Theodorou *et al.* 2020). The impact of urbanisation on pollinator biodiversity is likely to depend on the intensity of land use, the spatial scale of investigation, and the taxonomic group studied (McKinney 2008).

2.1.5 Soil diversity

Soil biodiversity and the decomposition of organic matter are essential for ecosystem functions, and urban soils provide a range of functions and services, including supporting soil formation, nutrient cycling, provisioning food and fresh water, regulating climate and temperature, flood or greenhouse gas regulation, carrying electrical earthing, and cultural aesthetics (Rawlins *et al.* 2015). However, urbanisation also influences soil functioning. For example, Nikula *et al.* (2010) found that urbanisation increases the decomposition of certain litter. However, in the subtropics, Enloe *et al.* (2015), found no difference between urban and rural forests in litter decay rates, litter quality indices and nutrient release patterns in decomposing litter despite differences in soil temperature (urban forest being warmer). They also found that urban forest land patches had higher aboveground net primary productivity and foliar productivity compared to rural forest land patches. Soil biodiversity, pollution and compaction ultimately influence plant composition with cascading effects on the ecosystem (Robinson & Strauss 2018).

Table 1: Adapted from Marcotullio *et al.* (2008), shows the general differences between urban and non-urban soils.

Characteristics of urban soils versus natural soils	Causes	Problems
Boundaries between soil layers	Artificial origins of soil lead to layers of different materials	No continuity for rooting plants and burrowing soil animals
Compaction	Trampling and pressure	Water infiltration, air spaces, plants development
Low water drainage	Change in natural water flow through soil, diversion of runoff to drains	Low water availability for plants
Crust and water repellence	Compaction, chemical dispersion, and waxy surface	Limited gas and water exchange between soil and surface
High pH	Use of salts for de-icing and water running from concrete buildings	Can immobilise some nutrients
High temperatures and moisture regimes	Higher air temperature and no protection due to lack vegetation	Low moisture in upper layers for plant growth

Gardens play a crucial role in urban green spaces and soil composition. The management practices employed by gardeners and the composition of the surrounding urban matrix can significantly impact litter decomposition (Tresch *et al.* 2019). For example, the use of compost has been reported as a moderately effective and relatively economical management practice to address urban soil problems such as compaction, lack of organic matter, or heavy metal pollution. Monitoring soil biodiversity in urban areas can be challenged by access to private lands, especially gardens. Traditional methods, such as urban-rural gradient analysis (as discussed in section 4), clarify the impact of urbanisation on soil. However, newer techniques utilising GIS and satellite imagery hold promise in advancing our understanding of urban growth and soil quality, particularly when examining larger scales (Marcotullio *et al.* 2008).

2.2 Genetic diversity

Urbanisation and the resulting habitat fragmentation can reduce connectivity between populations, leading to decreased gene flow and genetic diversity (Miles *et al.* 2019). Genetic studies offer insights into functional landscape connectivity by examining gene flow, effective population sizes, and monitoring genetic diversity over large geographical areas (Trumbo *et al.* 2019). Previous studies on genetic diversity have focused on various species, including feral honeybees (Patenković *et al.* 2022), trees (e.g. Andrianjara *et al.* 2021; Rimlinger *et al.* 2021; Vanden Broeck *et al.* 2018), deer (Blanchong *et al.* 2013), fox (Wandeler *et al.* 2003) and puma (Trumbo *et al.* 2019). Among these, tree diversity is probably the most studied due to the ease of monitoring.

Collecting data for genetic analysis can present challenges. For instance, in the case of feral bee colonies, collaboration with beekeepers' societies may be necessary to locate colonies (Patenković *et al.* 2022). In the case of mammals and birds, capturing the animals is required to obtain tissue samples (Blanchong *et al.* 2013; Trumbo *et al.* 2019). Similarly, reptiles and small mammals also need to be captured for sampling purposes (Fusco *et al.* 2021). However, the field of eDNA and DNA monitoring is constantly evolving, and new monitoring techniques would help with these challenges. Comparing urban and non-urban populations is often the next step in understanding the influence of urban areas on genetic diversity (e.g. Wandeler *et al.* 2003). Combining multiple methods is also crucial. For example, Wood *et al.* (2020) combined morphological and genetic monitoring to inform conservation efforts regarding urban snakes.

2.3 Drivers of biodiversity

2.3.1 Factors that influence species distributions

Different factors influence species distribution in urban areas. Aronson *et al.* (2016) hypothesised that various filters shape species distribution in urban environments, including:

(1) regional climatic and biogeographical factors,
(2) human facilitation,
(3) urban form and development history,
(4) socioeconomic and cultural factors, and
(5) species' interactions. Additionally, life history and functional traits also influence community assembly (see Figure 1).

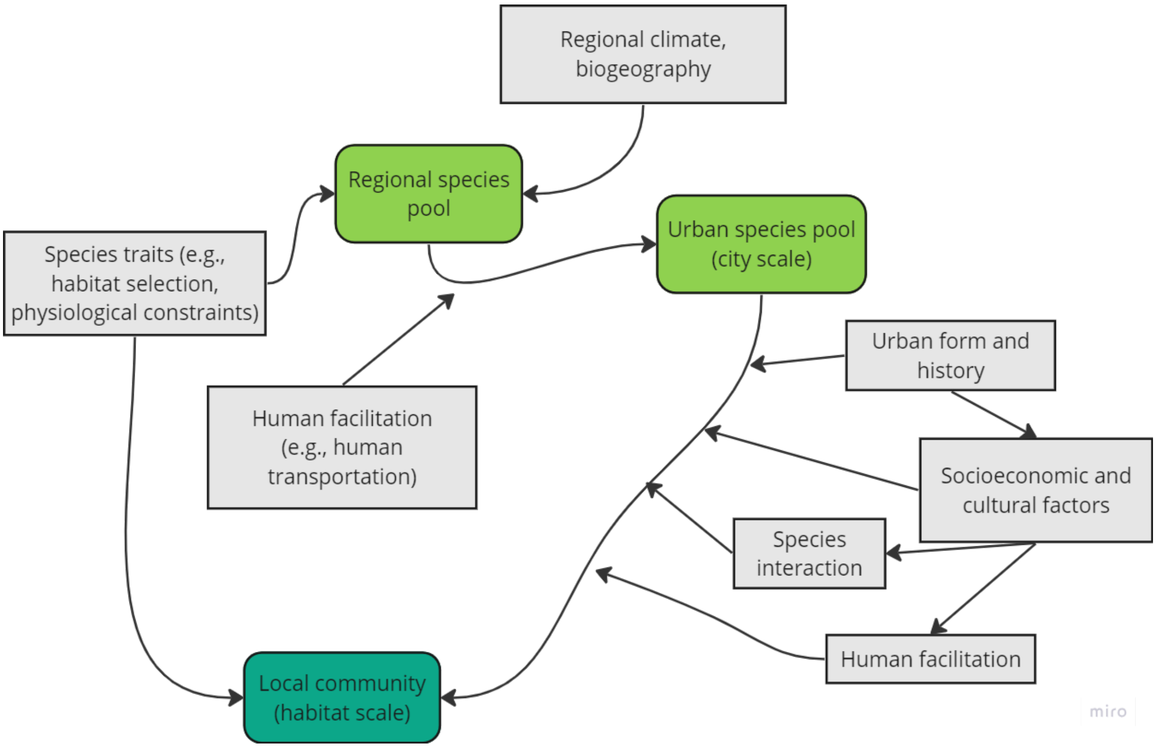

Figure 1: Adapted from Aronson *et al.* (2016). The community assembly of urban species pools is determined by a series of hierarchical filters.

2.3.2 Fragmentation

Urban areas are fragmented habitats composed of patches of various sizes with different land-use types. Fragmentation alters the quantity, quality, and pattern of habitats, and is associated with changes in species richness for vertebrates, invertebrates, and microorganisms (Faeth *et al.* 2011). Fragmentation can alter species composition with the presence of non-native species resulting in a "reshuffling" of urban communities (McKinney 2006). While many species may be lost during the urbanisation process, a newly constructed habitat can facilitate the recruitment of other species (Shochat *et al.* 2010). Some species are able to adapt to urban environments, leading to biotic homogenization (McKinney 2006).

Fragmentation and altered habitats induce changes in behavioural and ecological interactions and processes that determine the presence, absence, and relative abundance of species. In the longer term, these ecological processes and interactions can drive evolution, including genetic shifts in isolated urban populations and adaptation of certain species to urban environments (Faeth *et al.* 2011). For example, Wandeler *et al.* (2003) observed genetic drift and genetic differentiation between rural and urban fox populations in Switzerland. Fragmentation can also affect landscape connectivity, which plays a crucial role in enhancing biodiversity. Genetic techniques have confirmed that connectivity can increase gene flow between urban green spaces, while fragmentation reduces genetic connectivity between isolated urban habitat patches (Lepczyk *et al.* 2017). In section 4.3, we discuss how landscape connectivity can be monitored and improved.

2.3.3 Gradient of urbanisation and biodiversity

Biodiversity in urban areas does not exhibit a uniform distribution; instead, it follows a gradient known as the urban-rural gradient. This gradient indicates that species richness generally declines from the urban core towards the outskirts. However, researchers have identified certain cases where species richness peaks at intermediate levels of disturbance or urbanisation. Examples of such patterns have been observed in plants (e.g. Zerbe *et al.* 2003), butterflies (e.g. Blair *et al.* 1997), lizards (Germaine & Wakeling 2001), and birds (e.g. Marzluff 2005). At this intermediate level of disturbance, there is greater variation in the number of land-use types, often due to multiple private owners of land and varying management practices.

Island biogeography theory and Connell's intermediate disturbance hypothesis might explain these patterns (Faeth *et al.* 2011). The intermediate disturbance hypothesis suggests that species richness peaks at intermediate disturbance levels because such disturbances promote coexistence by preventing dominant species from excluding others. Faeth *et al.* (2011) also noted that the specific impacts of urbanisation-related disturbances on diversity may vary depending on factors such as the taxonomic group studied, the geographic location of the city, historical and economic factors, and the spatial scale of analysis. The differing responses of taxa to urbanisation may be related to their dispersal abilities, habitat preferences, and the distribution of suitable habitat along the rural-urban gradient (Luck & Smallbone 2010).

3. UK urban green habitat and interventions

3.1 Urban green habitat in the UK

In the UK, the proportion of green space within urban areas ranges from 23% (Liverpool) to 58% (Newcastle), with London midway at 38% (Ravetz 2015). Davies *et al.* (2011) summarised the types of urban green spaces in the UK:

- Natural and semi-natural greenspace: woodlands, Sites of Special Scientific Interest (SSSIs), urban forestry, scrub.
- Street trees: single trees and small areas with scattered trees, often surrounded by paved ground.
- Public parks and formal gardens, domestic gardens, green corridors: verges and hedges, river and canal banks, cycleways, and rights of way.
- Outdoor sports facilities, recreational areas, and amenity greenspace: sports facilities such as golf courses, football pitches, athletics tracks, school and other institutional playing fields, and other outdoor sports facilities informal recreation spaces, greenspaces in and around housing.
- Allotments, community gardens and urban farms: arable farmland and orchards.
- Cemeteries, churchyards and burial grounds, previously developed land (brownfield) but not including domestic gardens.

Ravetz's (2015) report summarised the state, trends and outlook and threats and risks for each habitat. They classified these ecosystems features as physical types (Table 2a), outdoor functions (Table 2b), and environment qualities (Table 2c). This latter encompassed urban air and water quality as well as urban biodiversity.

Table 2a: From Ravetz 2015: Ecosystems features: physical types.

Habitat	State	Trends	Opportunities	Threats and risks
Natural / Semi-natural greenspace	Total area 11% of urban land in UK	Urban forests are increasing total wooded area	Increase in Green/Blue infrastructure strategies	Pest and pathogens, climate change
Street trees	66% in gardens and grounds. 20% in parks and 12% street trees	Mixed trends	New eco-urban design concepts	Climate change, pest and pathogens, water flow changes
Public parks and formal gardens	13% of parks are in poor condition	Mixed trends	Public Engagement	Lack of maintenance, privatisation and deregulation
Domestic gardens	Total area 13% of urban land in UK	47% of front gardens have been paved	Raise in awareness of ecological planting and paving	Invasive species, paving and housing infill

Habitat	State	Trends	Opportunities	Threats and risks
Green corridors	Part of the UK BAP	Increase in Green/Blue infrastructure strategies	Increase in walking and cycling routes	Privatisation of access

Table 2b: From Ravetz 2015: Ecosystems features: outdoor functions.

Habitat	State	Trends	Opportunities	Threats and risks
Outdoor sports facilities, recreational areas, and amenity greenspace	Up to 33% of design. Green space is outdoor sport	Rapid selling off has been halted and development pressure	New community partnerships for management and stewardship	No funding, housing development
Allotments, community gardens and urban farms	Reduction of food production since 1940	No trends	Interest in local food, health, and education	Housing development
Cemeteries, churchyards, and burial grounds	Around 18,000 Church of England burial grounds in England	No trends	Could provide rich habitat	Change of use of church grounds
Brownfield	More than 60,000 ha in England	Declined	Could provide rich habitat	Housing development
Green Belt	More than 15% total area. 60% of UK population live in areas surrounded by green belt	80,000 dwellings and 1,000 ha of business parks have permission on GB sites (England)	New concepts for multi-functional “ecological belt”. New local economies	Housing development

Table 2c: From Ravetz 2015: Ecosystems features: environmental qualities.

Habitat	State	Trends	Opportunities	Threats and risks
Urban Water and water quality	34% of urban water bodies below good/ moderate key parameters	Improvement since 1960s	Waterfront development, heritage, lifestyles	Climate change, saline incursion
Urban air quality	Most cities have traffic related air issues with health consequences	Improvement of air quality	Green/Blue Infrastructures can help air quality improvement	Urban heat island, tropospheric ozone, etc.

Habitat	State	Trends	Opportunities	Threats and risks
Urban biodiversity	Urbanisation can cause decline or increase in richness and/or abundance of some species	Increase in non-native species can cause rapid change in habitat	Ecological awareness in gardening, local food, etc.	Climate change, non-native species, pests and disease. Pesticide

3.2 Nature-based solutions

To promote biodiversity in urban areas, various nature-based solutions can be utilised. We can classify nature-based solutions into four groups (NatureScot 2023):

(i) Ecological innovations, which involve the creation of new green or blue natural spaces, improved management of existing green and blue spaces, and the restoration of functional ecosystems to provide a wider range of ecosystem services and benefits.

(ii) Social innovations, which encompass changes in public policy and governance, cultural and economic frameworks, or methods for generating and sharing knowledge about nature in urban areas (e.g. the UK Ward Canopy Cover Map).

(iii) Technological innovations, which include product, process, and infrastructure advancements.

(iv) System innovations, which facilitate the effective interaction and integration of all the innovations to achieve resilient, nature-rich environments.

Similarly, the World Bank has compiled a catalogue of nature-based solutions and classified them into 14 families: urban forests, terraces and slopes, river, and stream renaturation, building solutions, open green spaces, green corridors, urban farming, bioretention areas, natural inland wetlands, constructed inland wetlands, river floodplains, mangrove forests, salt marshes and sandy shores.

Nature-based solutions can be utilised to address various societal challenges, such as improving human well-being, urban regeneration, enhancing coastal resilience, managing watersheds in a multi-functional manner, restoring ecosystems, promoting sustainable use of resources and energy, developing the insurance value of ecosystems, and increasing carbon sequestration (Faivre *et al.* 2017). Additionally, green, and blue infrastructure can help reduce energy and resource demands and costs. Trees, for example, provide cooling, insulation, and mitigate the urban heat island effect, while green roofs and green walls can decrease the need for heating and air conditioning (Bolund & Hunhammar 1999). Furthermore, nature-based solutions offer benefits like reduced air pollution, flood control, and recreational opportunities.

4. Monitoring biodiversity

4.1 The importance of spatial scales

The methods used to monitor biodiversity in urban areas depend on the spatial scale being studied. Luck *et al.* (2010) identified four categories to describe the spatiotemporal patterns in species diversity: ‘broad-scale’, ‘comparative’, ‘gradient’, and ‘urban-centric’. These categories reflect an increasing size of spatial scale, ranging from national/continental scale to narrower scales. However, the authors also recommended adopting a multi-scaled approach for urban ecology studies. Below, we summarise the four scales described by Luck *et al.* (2010).

4.1.1 Broad scales

In most cases, this uses the correlations between Human Population Density (HPD) and species richness. This straightforward correlation approach is easily applicable to large spatial scales and enables comparisons across cities or countries. Surprisingly, Luck *et al.* (2010) discovered that many studies observed a positive correlation between HPD and species richness, particularly for plants, birds, and mammals. This approach promotes a hierarchical method for examining the relationships between species and human populations. However, this broad-scale measure can obscure more intricate patterns between species richness and urbanisation that occur at local levels, including the factors driving species richness. We recommend using this approach when the focus is on the relationship between population density and species richness, as well as the understanding of overall patterns.

4.1.2 Comparative

This uses a comparison of species richness between urban areas and those dominated by agriculture and/or native vegetation. Some researchers confine their sampling entirely to patches of native vegetation (e.g. surrounded by agriculture or urbanised areas), while others sample the full range of available habitats. Amongst species, different results can be found depending on species groups. For example, richness patterns for plants often differ from faunal species; plant richness (native and non-native) is greater in urban areas than surrounding non-urban areas while fauna species might not increase in urban areas. Comparison of species richness inside and outside urban areas can also help understanding if urban areas act as a sink or a source of biodiversity.

4.1.3 Rural-urban or native-urban gradient

Rural-urban sampling is a specific form of comparative sampling, building upon the urban/rural gradient discussed in section 3. Sampling along this gradient can provide valuable insights into the impact of urbanisation on biodiversity. The sampling can be conducted at non-contiguous points within different land-use/urbanisation categories or randomly distributed throughout the entire study area. Various indicators of urbanisation can be employed, such as building density, land-use types, vegetation cover, road density, distance to the central business district, population density, demographic indices, patch fragmentation, patch size, edge effects, and land-use heterogeneity Luck *et al.* (2010). This method should be preferred when studying phenomena that are hypothesised to occur along the rural-urban gradient.

4.1.4 Urban-centric

The urban-centric approach involves comparing biodiversity across different neighbourhoods, examining the relationship between household or neighbourhood socioeconomic characteristics with vegetation cover and species diversity. This approach helps to identify the drivers of neighbourhood variation in urban areas and sheds light on social disparities in access to nature and green spaces. Urban-centric studies also focus on species richness in gardens and how household behaviours, such as gardening practices, influence species richness. This method should be prioritised when focusing on comparing specific areas of the urban area.

4.2 Monitoring in time

While there are numerous studies examining spatial patterns of diversity across urban areas, there have been limited investigations into urban biodiversity over time Luck *et al.* (2010). Examples of temporal studies include assessing changes in vegetation cover in urban areas using earth observation and satellite imagery (e.g. Morawitz *et al.* 2006). As land cover changes are one of the most pervasive human impacts on the natural environment, tracking changes can reveal deep shifts in urban biodiversity. Another study focused on the distinction between the evolutionary trajectories of native and non-native species in urban areas (Tait *et al.* 2005). Studying this can reveal more profound changes in urban populations that can impact biodiversity across generations. Due to the scarcity of data regarding changes in species diversity or population size over time, there is a need to investigate the impact of urbanisation on biodiversity across different time periods by conducting repeated sampling efforts.

4.3 Connectivity

Landscape connectivity can be defined as the effect that the landscape has on movement along resource patches (Taylor *et al.* 1993). Optimising habitat patch connectivity is important to reduce the negative impact of habitat loss and fragmentation. To estimate connectivity, two parameters can be estimated: the structural connectivity, which is the Euclidian distance between patches, and the functional connectivity, which considers movement behaviour between two patches (Hyseni *et al.* 2021). The latter estimates the route between patches which are suitable for dispersal. Functional connectivity is organism-oriented and can be quantified using two different (non-exclusive) methods: the first by assessing the movement of gametes or individuals through the landscape, using genetic or tracking techniques, which require information on both the spatial characteristics of a landscape (e.g. the structural connectivity of habitat patches) and the behaviour of the organism(s). The second approach uses modelling techniques (e.g. least-cost path analysis, circuit theory and other graph theoretic models) to model functional connectivity via estimates of landscape 'resistance' (LaPoint *et al.* 2015).

Connectivity is well studied in the literature; Lapoint *et al.* (2015) reviewed 174 papers that discussed aspects of ecological connectivity. They found that studies that focus on connectivity are often associated with large-bodied animals such as red foxes (*Vulpes vulpes*), probably due to the high interest in understanding potential disease transmission to humans. They also found that telemetric methods such as GPS tracking and genetic sampling could be increasingly used to gain a full understanding of connectivity. Finally, they suggested some actions to improve monitoring of connectivity in urban areas, such as:

(i) capturing greater geographic and taxonomic variety,
(ii) explicitly stating and objectively measuring the urban context,

(iii) clearly defining the aspects of connectivity of interest,
(iv) formulating precise predictions and hypotheses for evaluation, and
(v) increasing the use of emerging technological and analytical tools for quantifying actual movements and gene flow.

4.4 Sources of data

4.4.1 Overview

Davies *et al.* (2011) identified various sources of urban data that can be utilised in biodiversity studies:

- Geo-spatial data, which offers layering, analytical, and interactive functions, including remote sensing with Wi-Fi functionality, wearable monitoring, and similar technologies.
- Satellite/aerial imaging, which provides valuable imagery for processing and analytics.
- Geo-located social media, which can be a valuable source of data through feeds from platforms like X (previously known as Twitter) or Tumblr.
- Citizen science, participatory mapping, and environmental monitoring, involving the active involvement of citizens in data collection.

In the same report, the authors also highlighted various methods used in urban biodiversity studies that help explain variations in documented patterns (Table 3). They mentioned: the range of and position on the rural-urban gradient, the sampling design along the gradient, the quality of the rural (i.e. less urbanised) landscape with which to compare the urban areas, the extent to which sample areas contain heterogeneous land cover or focus on a particular land cover, the spatial resolution (as different groups of species operate and are managed across different spatial scales and by different stakeholders), study plot area and the history of urbanisation (long-term temporal dynamics of the response of species richness, abundance and composition to urbanisation).

4.4.2 Citizen science

Monitoring using CS is common in the UK, and various tools, techniques, and protocols have been developed or adapted specifically for urban areas (for example see Appendix 1). CS biodiversity monitoring schemes provide powerful data that can be used to assess biodiversity state. The wide spatial coverage and large sample size and density of CS biodiversity monitoring are especially valuable in increasing biodiversity evidence. Recently, new technologies or targeted sampling such as eDNA or audio capture technologies have increased CS capacities. The local knowledge of CS volunteers mean surveying is locally informed, and findings are of relevance and use to local communities. CS is proving to be a powerful and reliable tool in providing evidence for environmental policy making and implementation.

Pocock *et al.* (2022) and Pocock *et al.* (unpublished) looked at the patterns of biodiversity citizen science recording in urban areas in England. They found that large amounts of CS data were available in urban areas. They found that recordings were strongly related to human population density and affluence at large and fine spatial resolutions. They also found that different types of urban habitats were not recorded with the same intensity. Interestingly they found that amenity and natural habitats were under-represented in recording. Recordings were influenced by the greenness of the surrounding area, and proximity to water. These types of biases are commonly found in CS data; for example, more records are collected during weekends (Courter *et al.* 2013) and with taxonomic preferences for some species.

In the urban context, a wide range of CS projects can be used to monitor biodiversity. In Appendix 1 ('Schemes_in_urban' worksheet), we have recorded past and current projects of CS in urban areas in the UK (not exclusively NCEA-related). This list is not exhaustive, and some of these projects were not carried out on a longer-term basis. However, this shows they cover a broad range of taxa: from glow worm (the UK Glow Worm Survey), to mammals such as hedgehogs (https://www.hedgehogstreet.org/), to birds such as swifts (Swiftmapper, Tayside swift survey). They can cover large spatial scales with a nationwide survey such as Mammals Mapper, to the county level (https://www.wiltshirewildlife.org/hedgehog), to the city/town level such as the urban plant survey that focuses on London (https://morethanweeds.co.uk/urban-plants/). Finally, some schemes are run across cities and internationally; for example, the City Nature Challenge is a large bioblitz event to encourage people to get involved with biological recording, and is run as a competition between cities, involving 419 cities in 44 countries (14 in the UK).

Surveillance programmes supported by JNCC contribute to monitoring biodiversity within the UK. A key set of monitoring schemes are brought together into a partnership managed by JNCC, known as the UK Terrestrial Evidence Partnership of Partnerships (UKTEPoP). The aim is to facilitate best practice and communication to enhance joint working under an agreed Declaration of Intent. These schemes are widespread and systematic which allow for assessment of trends in distribution and/or population. Schemes are taxonomically based and the data they help collect provide information relevant to a wide range of policies. Table 3 summarises the work currently ongoing with national schemes and how their protocols can be applied to urban areas.

Some monitoring schemes due to their specificity have a high number of recordings in urban areas. For instance, BTO's Garden BirdWatch focuses on garden monitoring and consequently increase urban bird recording. BTO have a long history of promoting bird monitoring in urban areas. BTO is aiming to raise engagement levels in urban communities with a view to increasing data collection for their schemes in these areas. It is worth noticing that they also conduct research in urban areas that covers three different topics:

(i) understanding how wildlife responds to the features of our towns and cities;
(ii) interpreting the value of urban wildlife for human well-being, and
(iii) using applied research to inform wildlife-friendly urban planning (https://www.bto.org/our-science/focal-areas/urban-birds-and-urban-planning).

Table 3: Examples of work currently ongoing with UK Terrestrial Evidence Partnership of Partnerships (UKTEPoP) partners with some additional schemes and how their protocols can be applied to urban areas.

National schemes – surveys	Current urban monitoring	Applicability of current methods in urban areas	Urban-specific limitation and challenges
Breeding Bird Survey (BBS)	BBS sampling is not targeted or weighted against urban areas and includes some urban in their monitored areas. Around 500 squares (sampling areas) were classed as urban in one study (Plummer *et al.* 2020). This number varies annually.	Citizen Science (CS) involves walking along a line transect which might be challenging in urban areas, but not impossible. BBS aims to produce national or regional summary data from random locations. The method is not appropriate for targeting at specific locations.	Plummer *et al.* (2020) notes that bird detection might be reduced in highly urban centres due to greater building densities and increased background noise, but that these effects might be minimal (Chace & Walsh 2006). Engagement with volunteers in urban areas was noted as a challenge by BTO.
Wetland Bird Survey (WeBS)	Some WeBS sites are in urban areas (generally smaller sites), given that sites are selected based on presence of wetland habitat. An unpublished analysis for England and Wales in 2021 suggested that just under 7% of all WeBS count locations were in built-up areas.	Yes, same methods are used in urban areas.	The ability to count smaller water bodies within urban areas is limited by volunteers' availability. An unpublished analysis in 2021 found that 58% of available urban WeBS sites in England and Wales are surveyed, like the overall proportion of 59%. However, as effort is concentrated on sites with higher importance (larger numbers of birds), most small urban sites have not been digitised onto the WeBS database, resulting in them currently not being available for the counters to select.

National schemes – surveys	Current urban monitoring	Applicability of current methods in urban areas	Urban-specific limitation and challenges
Goose and Swan Monitoring Programme (GSMP)	None taking place. GSMP aims for as complete population count as possible of native migratory goose and swan populations, which do concentrate on a small number of sites, mainly large ones, generally away from human population centres.	If significant populations were to occupy urban sites, the same methodology would apply.	This survey is probably not applicable to urban areas.
Garden Constant Effort Sites (CES)	Pilot testing of a ringing survey that uses similar methods to Constant Effort Sites (CES) but in gardens.	Designed to be applied in gardens.	No particularly urban-specific limitations but current Garden CES coverage is biased towards England. Anecdotally there are concerns about mist netting birds when domestic cats are nearby.
Winter Constant Effort Sites (WCES)	Pilot testing of a ringing survey that uses similar methods to spring/summer Constant Effort Sites (CES) but in winter.	40–50% of sites are in gardens.	
Nesting Neighbours	Pilot of an urban version of the Nest Record Scheme, Methods are similar, but intended to be more accessible/suitable for entry-level involvement (see BTO website).	Designed to be applied in urban areas.	No urban-specific limitations.
Retrapping Adults for Survival (RAS)	RAS aims to provide information on adult survival for a range of species in a variety of habitats.	No urban-specific RAS methods. Surveys individual species, so it depends whether the relevant species can be caught in urban areas.	

National schemes – surveys	Current urban monitoring	Applicability of current methods in urban areas	Urban-specific limitation and challenges
NBMP (National Bat Monitoring Programme) – Sunset survey	Methods can be undertaken anywhere including in urban environments.	Methods can be undertaken anywhere including in urban environments.	No urban-specific limitations but it is entry-level survey to encourage new participants in bat surveying. The survey is effectively an ad-hoc survey (as opposed to random stratified), and thus it does not directly feed into population trends.
NBMP – Field Survey	Some sampling squares overlap with urban areas (e.g. London).	Walking a line transect according to scheme protocols is at least theoretically possible in urban areas, though there may be more/different limitations as to the route that can be selected. However, some urban areas will not have any sample 1km squares within/overlapping them so creating one for specific urban areas would deviate from national scheme sampling protocol.	Buildings can make surveying of an urban square a challenge. However, those barriers also apply to rural areas. Other challenges involve monitoring trouble spots which need to be avoided at night for safety reasons.
NBMP – Roost Count	Occurs wherever there are bat roosts.	Occurs wherever there are bat roosts.	

National schemes – surveys	Current urban monitoring	Applicability of current methods in urban areas	Urban-specific limitation and challenges
NBMP – Hibernation survey	Occurs wherever there are hibernating bats, although currently less such survey activity in urban areas.	Occurs wherever there are hibernating bats. Same methodology everywhere. As hibernating bats can be found in many buildings (e.g. old churches) and other structures (e.g. under bridges) in urban areas, there is potential for more urban surveying.	No urban-specific limitations but any surveyor entering a bat hibernation area to carry out a count must have a minimum Level 2 bat survey class licence
NBMP – Nightwatch	Designed to be undertaken in urban areas using AudioMoth.	Designed to be undertaken in urban areas using AudioMoth.	Most participants put the device up in their own gardens.
NBMP – British Bat Survey (BBatS)	Designed to be undertaken across a random stratified sample of sites using AudioMoth. This will include urban areas.	Designed to be undertaken across a random stratified sample of sites using AudioMoth. This will include urban areas.	
NBMP – Waterway Survey	The survey primarily targets Daubenton bats as they forage along water courses	Same methods would apply regardless of where the waterway is.	

National schemes – surveys	Current urban monitoring	Applicability of current methods in urban areas	Urban-specific limitation and challenges
NPMS (National Plant Monitoring Scheme)	1 km sample squares are weighted against sampling urban areas so less likely to be sampling these in scheme compared to other habitats, but there are some squares in/overlapping urban areas.	Quadrat monitoring using Domin scale according to scheme protocols is possible in urban areas, though may be more/ different limitations as to the quadrat locations that can be selected. However, some urban areas will not have any sample 1 km squares within/overlapping them so creating one for an urban area would deviate from national scheme sampling protocol.	For Wildflower and Indicator recording levels, would need to provide species lists that cover the different possible habitats that might be found in heterogeneous urban landscapes. Higher proportion of non-native/horticultural plant species, would need to advise on whether to record or not.
United Kingdom Butterfly Monitoring Scheme (UKBMS)	Standard transects at sites selected by recorders/volunteers. Fixed routes are designed to best monitor the butterflies at the site.	Same line transect methodology specified in scheme protocols applies in any habitat.	Self-selection means most standard transects are on semi-natural sites with high butterfly value. Transects set up in 'urban' areas will typically be in Local Natural Reserves, town parks and old cemeteries.
Wider Countryside Butterfly Survey (WCBS)	WCBS is an integral part of the UKBMS. It is conducted on a set of random squares which includes, but is not restricted, to BBS squares. BBS volunteers have the option to carry out WCBS on their square. Coverage is usually higher in the BC squares.	The method was incorporated into the UKBMS to improve coverage of habitats which were generally under-represented through the self-selection of standard transect sites – including urban areas.	Same as for UKBMS.

National schemes – surveys	Current urban monitoring	Applicability of current methods in urban areas	Urban-specific limitation and challenges
PoMS (Pollinator Monitoring Scheme) – 1 km^2	None of the PoMS 1 km squares are in urban areas as the monitoring is in agricultural and semi-natural habitat.	Pan traps used for the monitoring could be used gardens or allotments. However, expert identification is needed which is challenging for most species (but this challenge is not specific to urban habitat).	Risks of leaving pan traps unattended in urban areas (contamination/disturbance). Negative perceptions/complaints about insect trapping. Cost of equipment and sample analysis.
PoMS – FIT counts	Undertaken wherever there is a target plant species, so samples are collected from urban areas.	Undertaken wherever there is a target plant species, so data can be collected from urban areas.	No urban-specific limitations.

5. Defining data priorities for urban

To assess urban biodiversity across space and time, various indicators and frameworks have been developed. Indicators are key to understanding changes in biodiversity at different scales (Lusardi *et al.* 2018). In the context of urban ecosystems, indicators are diverse and tailored to local needs for assessing biodiversity in urban areas. Currently, there are over 22 frameworks, which are combinations of indicators, specifically designed for assessing urban biodiversity on an international level (McDonald *et al.* 2018).

Here, as case studies, we focus on five indicators and frameworks that are widely recognised, broadly applicable, and relevant to urban areas in the UK: Biodiversity Net Gain (BNG), Green and Blue Infrastructures (BI), SONC indicators Natural Capital Indicator (NCI), Singapore Index (SI), and IUCN Urban Nature Indices (UNI). We specifically focus on this set of indicators, which comprises a mix of international and national indicators. Some are recent, while others have been implemented for a long time, and all are specific to urban habitats.

We first present each indicator, how it works, and which data are needed to use it. We also identify any missing data for the indicators and explore the potential of filling the data gaps or facilitating data collection through citizen science. Through this analysis, we demonstrate how citizen science can contribute to these indicators.

5.1 Case study 1: Biodiversity Net Gain

BNG is an approach to development, land, and marine management that aims to leave biodiversity in a better state than before the development took place (CIEEM 2016). BNG is quantified using the Biodiversity Metric, which assesses changes in the extent and quality of habitats (CIEEM, 2016). It compares the habitat present on a site before and after development, considering different types of habitats and their respective qualities. The BNG score is adjusted based on the size, condition, and location of each habitat. However, a limitation of this indicator is its complexity, as its application typically requires expert ecologists who can accurately assess habitat quality.

The Biodiversity Metric requires the following data:

(i) Habitat types, including artificial and sealed surfaces with no biodiversity value.
(ii) Area of each habitat parcel in hectares.
(iii) Condition of each habitat parcel, categorized as good, moderate, or poor.
(iv) Strategic significance of each habitat parcel, classified as high, medium, or low.

Typically, ecologists collect these data through field assessments. While BNG primarily focuses on habitat assessment, citizen science initiatives recording habitat components could be utilised to apply BNG. However, certain aspects of the biodiversity metric, such as habitat quality or strategic significance, may be complex and require extensive volunteer training. This challenge can be overcome but requires extensive funding and can be time-intensive for trainers and trainees.

BNG enables the assessment of biodiversity at different time periods, either at the same location or across multiple locations. Periodic assessments are crucial in the context of reversing biodiversity loss. However, due to its complexity, the full BNG approach may not be suitable for CS assessments. Nevertheless, a simplified version of BNG could be applied by integrating metrics like size and basic information on habitat quality into existing CS schemes that already survey habitat types with repeated observations at the same location. Similarly, CS could be used to help with the long-term monitoring of sites used in the BNG framework. For example, sampling sites of current schemes could target locations where habitats have been enhanced to compensate for other development.

5.2 Case study 2: Blue-Green Infrastructures

GI is a “strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services such as water purification, air quality, space for recreation and climate mitigation and adaptation. This network of green (land) and blue (water) spaces can improve environmental conditions and therefore citizens' health and quality of life. It also supports a green economy, creates job opportunities, and enhances biodiversity”. The blue-green infrastructure indicator is included in various international frameworks, including England’s Environmental Improvement Plan 2023 (EIP23), and it aims to demonstrate changes in the quantity, quality, accessibility, and overall multiple functions of green and blue infrastructure.

Different approaches can be used to quantify this indicator, and Natural England is developing their indicator related to Green Infrastructure, called the GI Framework. In collaboration with Defra, they have created an England-wide Green Infrastructure mapping database that consolidates data from approximately 50 sources of environmental and socio-economic information. The initial analysis focused on access to green spaces within different distances and is based on the Accessible Natural Green Space Standard (ANGSt) (Moss 2021). The ANGSt considered the quantity and proximity of greenspaces at different scales. The GI indicator utilises the number of people who have access to green spaces based on the area's size and the walking or cycling distance to reach it.

The ANGSt assessment method requires a limited amount of information from the ground. Polygons representing green features can be obtained from various datasets (OS Greenspace, Local Nature Reserve, National Nature Reserve, Country Parks, etc). Subsequently, GIS data processing can create information about distance and population density using information from the census.

GI indicators require knowledge of the type of habitat and its extent. There is an opportunity for citizen science to record habitats less than 10 ha which will be left over from the official list of Green Infrastructure. Earth Observation (EO) data can also be improved by its validation on the ground. Citizen science volunteers could be used to validate the size of areas and habitat types obtained from the various dataset used. Similarly, there is a value in taking a multi method approach and one next step will be to integrate the GI with other data obtained from CS schemes such as species presence/absence, as this framework focuses only on habitat it will allow linking of habitat to species preferences.

5.3 Case study 3: Natural Capital Indicators

NCIs can be used to measure changes in natural capital for different habitat types (Lusardi *et al.* 2018). In urban habitats, 15 indicators have been identified and categorised as SONC (State of Natural Capital) indicators. Each indicator is associated with a metric that can be used to assess whether it is improving or not over time. The aim of NCIs is to encompass multiple facets of urban ecology, including habitat quality, cultural aspects, and soil health.

In this framework, data sources are provided for each indicator. Additionally, we categorised the type of data required by the NCIs. Four different types of data were identified: "Land cover and habitat surveys," "soil health," "cultural information," and "GI" (Green Infrastructure). Land cover and habitat surveys involve measuring the size of habitats in hectares and the percentage cover of specific habitats and SSSIs. Soil health is characterized by metrics such as bulk density, earthworm counts, and/or microbial activity, although further development of the metric is needed. The cultural aspect is relevant to four indicators and emphasises the connection between people and nature. Lastly, GI refers to the Accessible Natural Green Space Standard (ANGSt) metric discussed in the previous section.

Similar to BNG and GI, NCIs rely in part on habitat surveys, making any citizen science survey that collects habitat information potentially useful. Additional data, such as habitat size, would need to be collected. Citizen science can also play a role in confirming EO data. Soil health also needs to be assessed and surveys like the OPAL soil and earthworm survey could be used for this.

5.4 Case study 4: Singapore Index (City Biodiversity Index)

Chan *et al.* (2021) in the “Handbook on the Singapore Index on Cities’ Biodiversity” defines the Singapore Index: “The Singapore Index on Cities’ Biodiversity serves as a self-assessment tool for cities to benchmark and monitor the progress of their biodiversity conservation efforts against their own individual baselines. It comprises two parts: first, the “Profile of the City” provides background information on the city; and second, 28 indicators (see Figure 2 below) that measure native biodiversity, ecosystem services and governance and management of biodiversity in the city. Each indicator is assigned a scoring range between zero and four points, with a maximum score of 112 points. Cities will have to conduct a baseline scoring in the first application of the SI and conduct subsequent application every 3–5 years to allow sufficient time between applications for the results of biodiversity conservation efforts to materialise”.

The SI was developed by the CBD and has evolved over the years. The index begins by profiling the city, utilizing information about its location, physical features, demographics, economic parameters, biodiversity features, and administration and links related to biodiversity. The second part of the index focuses on indicators, which are categorized into three core components: "Native Biodiversity in the City", "Ecosystem Services provided by Biodiversity", and "Governance and Management of Biodiversity." Each indicator is accompanied by a clear summary explaining the rationale for its selection, the calculation method, data sources, and scoring guidelines for the overall biodiversity index of the city. Notably, citizen science datasets are mentioned as data sources for several indicators, including "Native biodiversity in built-up areas (Bird species)", "Change in number of native vascular plant species", "Change in number of native arthropod species", "Proportion of invasive alien species", "Participation and partnership,", "Number of biodiversity projects implemented by the city annually", "Awareness" and, "Community science." We have provided links between these indicators and potential CS schemes in Table 4 below.

As mentioned, the SI is a robust framework with biodiversity fiches for each indicator and a clear metric for assessing biodiversity. The list of indicators is comprehensive, and the reasoning behind each indicator is well-defined. Pierce *et al.* (2020) conducted a mixed methods content analysis of biodiversity plans from 39 cities using the SI. They found that the native biodiversity component of the SI was the most included indicator in cities' biodiversity plans. However, they also identified 20 additional urban biodiversity topics not covered by the Singapore Index framework, including socioeconomic considerations, data collection, genetic diversity, urban agriculture and forestry, green infrastructure, human-wildlife conflicts, indigenous concerns, and citizen science. The utilisation of the Singapore Index with citizen science data is highly feasible, especially within the "native biodiversity in the city" group. Citizen science data could also be valuable for indicators in the "Ecosystem Services provided by biodiversity" group.

SINGAPORE INDEX ON CITIES' BIODIVERSITY			
	Core Components	Indicators	Maximum Score
PART II – INDICATORS	Native Biodiversity in the City	1. Proportion of Natural Areas in the City	4 POINTS
		2. Connectivity Measures or Ecological Networks to Counter Fragmentation	4 POINTS
		3. Native Biodiversity in Built Up Areas (Bird Species)	4 POINTS
		4. Change in Number of Vascular Plant Species	4 POINTS
		5. Change in Number of Native Bird Species	4 POINTS
		6. Change in Number of Native Arthropod Species	4 POINTS
		7. Habitat Restoration	4 POINTS
		8. Proportion of Protected Natural Areas	4 POINTS
		9. Proportion of Invasive Alien Species	4 POINTS
	Ecosystem Services provided by Biodiversity	10. Regulation of Quantity of Water	4 POINTS
		11. Climate Regulation – Benefits of Trees and Greenery	4 POINTS
		12. Recreational Services	4 POINTS
		13. Health and Wellbeing – Proximity/Accessibility to Parks	4 POINTS
		14. Food Security Resilience – Urban Agriculture	4 POINTS
	Governance and Management of Biodiversity	15. Institutional Capacity	4 POINTS
		16. Budget Allocated to Biodiversity	4 POINTS
		17. Policies, Rules and Regulations – Existence of Local Biodiversity Strategy and Action Plan	4 POINTS
		18. Status of Natural Capital Assessment in the City	4 POINTS
		19. State of Green and Blue Space Management Plans in the City	4 POINTS
		20. Biodiversity Related Responses to Climate Change	4 POINTS
		21. Policy and/or Incentives for Green Infrastructure as Nature-based Solutions	4 POINTS
		22. Cross-sectoral and Inter-agency Collaborations	4 POINTS
		23. Participation and Partnership: Existence of Formal or Informal Public Consultation Process Pertaining to Biodiversity Related Matters	4 POINTS
		24. Participation and Partnership: Number of Agencies/Private Companies/ NGOs/Academic Institutions/International Organisations with which the City is Partnering in Biodiversity Activities, Projects and Programmes	4 POINTS
		25. Number of Biodiversity Projects Implemented by the City Annually	4 POINTS
		26. Education	4 POINTS
		27. Awareness	4 POINTS
		28. Community Science	4 POINTS
		Native Biodiversity in the City (Sub-total for indicators 1-9)	**36 points**
		Ecosystem Services provided by Biodiversity (Sub-total for indicators 10-14)	**20 points**
		Governance and Management of Biodiversity (Sub-total for indicators 15-28)	**56 points**
		Maximum Total:	**112 points**

Figure 2: The Singapore Index on Cities' Biodiversity,with each row displaying an indicator (from Chan *et al*. 2021).

Table 4: Singapore indicators and potential citizen science scheme.

Singapore Indicators	Example citizen science scheme
Native biodiversity in built-up areas (Bird species)	BTO schemes (Garden BirdWatch, BirdTrack), iRecord, iNaturalist
Change in number of native vascular plant species	NPMS, iRecord, iNaturalist, Challenge, Garden Wildflower Hunt, Urban plant survey
Change in number of native arthropod species	UKBMS, garden butterfly survey, iRecord, iNaturalist, Big Butterfly Count, British Dragonfly Society schemes, Buglife, UK beetle recording
Proportion of invasive alien species	Plant tracker, any schemes used above for vascular plants
Participation and partnership	?
Number of biodiversity projects implemented by the city annually	Can we count the number of citizen science projects in a city?
Awareness	?
Community science	?

5.5 Case study 5: The IUCN's Urban Nature Indices

The UNI framework consists of 30 indicator topics organised under six themes (Figure 3). Its purpose is to assist cities in understanding their impacts on nature, setting science-based improvement targets, and monitoring progress accordingly. The framework initially assesses the level of capacity and recommends the number of indicators to implement based on the assessment. Each city will have a specific number of indicators to select, depending on its scale. The framework is adaptive in nature. Users are then required to choose at least one indicator per theme.

In the first step, users need to assess data availability and their capabilities in using the different indicators. They then select different indicators from the list of 30 indicators. Each indicator is accompanied by its purpose, calculation instructions, suggested resources, and a tentative scoring system. The indicator themes cover consumption drivers, human pressures, habitat status, species status, nature's contributions to people, and governance responses. CS data has the potential to be applied to several indicators, including water pollution, noise pollution, light pollution, invasive species, animal species, plant species, functional diversity, microbiota, and endemic species.

This framework aims to combine multiple lists of indicators and to select the most appropriate set for each city. It appears that all aspects of urban areas have been considered in the creation of the indicator list. It is interesting to note that a pre-analysis of the local context is recommended to determine the number of indicators to be considered for each area. However, some indicators in the framework seem less developed compared to those in the SI. For example, data sources are not always provided, and the rationale behind the varying levels of assessment based on city levels is not explained. Additionally, the reason behind cities having different numbers of indicators is not clarified. Nevertheless, it is an ongoing work in progress that holds promise for the future, especially for urban-focused policymakers. This framework sets a complementary approach to the SI.

Theme	ID	Indicator Topics	Equity	Local	Hinterland	Global	SDG
1 Consumption Drivers	**1.1**	Material Consumption			x	x	12, 11.6
	1.2	Harmful Harvest & Trade			x	x	12
	1.3	GHG Emissions from Energy				x	7, 13
	1.4	Unsustainable Diets	x			x	2
	1.5	Water Withdrawal		x	x		6
2 Human Pressures	**2.1**	Sprawl			x		15
	2.2	Water Pollution		x	x	x	6, 12.4
	2.3	Noise Pollution		x			14, 15
	2.4	Light Pollution		x	x		15
	2.5	Invasive Species		x	x		14, 15
3 Habitat Status	**3.1**	Land Use/Protection		x	x		15
	3.2	Ecosystem Restoration		x	x		15
	3.3	Shorelines & River Banks		x	x	x	14
	3.4	Vegetation		x			13, 11.6
	3.5	Connectivity		x	x		14, 15
4 Species Status	**4.1**	Animal Species		x	x	x	14, 15
	4.2	Plant Species		x	x	x	14, 15
	4.3	Functional Diversity		x			14, 15
	4.4	Microbiota		x	x		14, 15
	4.5	Endemic Species		x	x	x	14, 15
5 Nature's Contributions to People	**5.1**	Exposure to Nature		x			11.7
	5.2	Access to Nature	x	x			10, 11.7
	5.3	Human Health	x	x		x	3
	5.4	Livelihoods	x	x	x		1, 8, 9
	5.5	Sacred Natural Sites	x	x	x	x	11.4
6 Governance Responses	**6.1**	Planning		x	x	x	11
	6.2	Law & Policy		x	x	x	16
	6.3	Education		x	x	x	4, 12.8
	6.4	Management	x	x			11
	6.5	Incentives & Participation		x	x	x	17

Figure 3: The IUCN's Urban Nature Indices list (SDG = Sustainable Development Goal, GHG= Green House Gas), © IUCN: https://www.iucnurbannatureindexes.org/en.

5.6 Summary of data need

Our subset of indicators/frameworks to which CS could contribute is not exhaustive, as there are over 22 frameworks specific to urban biodiversity used worldwide (McDonald *et al.* 2018). However, the indicators and frameworks discussed here are closely interconnected. BNG and GI are indicators that mostly focus on habitat size and quality. The calculation of GI using the ANGSt is like BNG, as it assesses habitat areas and can be applied at different time periods. Similarly, the NCI framework includes GI as one of its indicators. The NCI, SI and UNI, being comprehensive frameworks, encompass various components of urban biodiversity, including habitats, species, soil, and socio-economic factors. The Singapore Index holds high political value as it was developed by the CBD during Conference of Parties (COP) events. Both the Singapore Index and UNI represent more developed lists of indicators, with each indicator accompanied by a biodiversity form and associated metric. They offer transparency and can be applied to the specific needs of cities, enabling monitoring of urban areas across different locations and over time.

We have found that habitat plays a crucial role in assessing biodiversity in urban areas. Habitat monitoring was utilised, either directly or indirectly, in each of the indicators/frameworks examined in this study, and it served as a fundamental aspect of monitoring using BNG and GI indicators. Pierce *et al.* (2020) found that natural areas were frequently included in cities' biodiversity plans using SI, as they might have already been part of the original city plans. Additionally, incorporating them into new biodiversity plans requires only minor adjustments while remaining easy to monitor. We distinguish between two aspects of habitat that can be monitored: its quantity (habitat size) and its quality. The former is typically obtained through EO, and the accuracy of EO data can be validated or enhanced through direct field observations (Farinha-Marques *et al.* 2011).

Assessing the quality of habitat is more challenging. For instance, in the BNG framework, expert ecologists are required to evaluate the condition of the habitat. However, these assessments are specific to each surveyor and volunteers often display more interest in species rather than habitat surveys, and extensive questioning about habitat can potentially diminish their enthusiasm for the scheme (Hassall *et al.* 2019). It is worth noticing that in the broader context of this report, i.e., different work under the tNCEA is currently investigating how to incorporate habitat quality assessment into different citizen science programs. Incorporating assessments of habitat quality is necessary, as large areas can have poor biodiversity while small areas can exhibit high biodiversity. There are also opportunities to monitor small areas using citizen science initiatives. For example, in the case of GI, areas smaller than 10 ha were not recorded using EO, likely due to a lack of accuracy (Moss 2021).

Urban areas present specific challenges due to the dense population and variations in people's perception of biodiversity, which can be influenced by their socio-economic background and access to green spaces. Quantifying these factors is challenging. In the context of GI, the number of people with access to green spaces was simply quantified (Moss 2021). However, this simplistic approach fails to account for multiple factors such as education or mobility. In the SI, multiple indicators focused on these aspects, including awareness, community science, and the number of biodiversity projects. For instance, the awareness indicator suggests calculating the number of outreach events per million persons.

The review by Pierce *et al.* (2020) showed that native biodiversity received primary focus when using the Singapore Index, as mentioned earlier, particularly in relation to "natural areas" due to the ease of monitoring. In contrast, monitoring connectivity or species counts can pose greater challenges. Bird and plant monitoring are extensively studied in urban areas (Pierce *et al.* 2020; Rega-Brodsky *et al.* 2022). Together, plants and birds represent more than 50% of the total recording in published papers (not exclusive to CS projects)

(Rega-Brodsky *et al.* 2022). For example, among others (e.g. reptiles, spiders, mammals, amphibians), snails are underrepresented in the literature, despite being good indicators of local environmental and habitat determinants for urban green spaces (Barbato *et al.* 2017). In their review, Barbato *et al.* (2017), also suggest the need to: increase monitoring of taxa that are currently underrepresented, extend monitoring beyond single-year studies, explore differences among and within various urban habitats and land use types, as well as investigate the outcomes of experimental studies (restoration and management) on biodiversity and ecosystem function.

6. Moving forward

This report aims to investigate how biodiversity can be monitored over time and space using CS. We defined biodiversity in urban areas, identified the different drivers of biodiversity, and explored the types of interventions used to enhance biodiversity, particularly in the UK. We also examined how biodiversity can be monitored, including the use of indicators and frameworks. Finally, we presented how CS can support these indicators/frameworks.

In this section, and in Appendix 1, we aim to summarise these different concepts by:

(i) identifying gaps in biodiversity monitoring in urban areas,
(ii) identifying the role future monitoring can have within indicators, and
(iii) identifying the role of citizen science in collecting data in urban areas.

Finally, we conclude by highlighting specific points to move forward in this area.

6.1 Gaps in the current assessment of biodiversity in urban areas

Different impacts of urbanisation on biodiversity: The impact of urban areas is often studied by quantifying changes in species presence/absence/abundance, especially in CS projects (e.g. Westgate *et al.* 2015). However, few CS studies have focused on other impacts of urbanisation, such as changes in reproductive behaviours, inter-species interactions, diel activities, or other behavioural shifts. Studying these behaviours is highly relevant to understanding patterns of species presence/absence and abundance (Faeth *et al.* 2011). For example, local extinctions in Seattle birds are likely caused by behavioural changes, increased brood parasitism, and nest predation in highly urbanised patches (Oliveira Hagen *et al.* 2017). Behavioural shifts can be monitored using traditional methods (e.g. field observations or new technologies such as camera traps and GPS tracking). The use of new technology should be encouraged to help monitor the various impacts of urbanisation on species. Current CS surveys that use this type of technology include Nightwatch (led by the Bat Conservation Trust) passive acoustic monitoring (in use by tNCEA-supported projects for bat monitoring), and MammalWeb which uses camera traps.

Focus on species' diversity: Similarly, genetic, and functional diversity are less commonly studied in the context of urban biodiversity, despite being highly relevant for understanding patterns of species' presence/absence. We noticed that genetic diversity was not addressed in any of the frameworks we investigated in this work, while functional diversity was mentioned in the IUCN framework. We previously stated that monitoring genetic diversity can be challenging, depending on the taxa studied and the local context. In the case of CS, particularly in the UK, only a few projects have focused on genetic biodiversity. For example, GenePools is one NCEA project that uses eDNA to identify species. Such research within the context of CS is rare but could help in the future with the understanding of genetic diversity.

Likewise, there is a lack of understanding of functional biodiversity in urban areas (Oliveira Hagen *et al.* 2017), although this is not an issue specific to urban areas. Functional diversity metrics provide a useful approach for quantifying ecological function and complement the current focus on more traditional measures of biodiversity, such as species richness (Oliveira Hagen *et al.* 2017). Open access data and big data present different opportunities to study functional diversity post-hoc and across multiple scales (e.g. Borowy *et al.* 2020). Several software and related packages now enable the study of traits and functional diversity based on species lists (e.g. BRYOATT (Hill *et al.* 2007), R packages "traits" *(Chamberlain et al.* 2020) and "TR8" (Gionata 2015)). The use of functional diversity can complement other metrics, and, for example, help evaluate the impact of interventions on biodiversity. For instance, Pinho *et al.* (2021) employed a multi-taxa and functional diversity approach to assess the value of green infrastructure in urban environments. The approach of functional diversity is highly relevant in the context of urban work, as different biological groups respond to disturbance divergently at different spatial and temporal scales. Thus, the use of traits and functional diversity provides a holistic view of ecosystem functioning. While this work does not specifically focus on functional diversity, given its potential to address multiple questions across taxonomic groups, we suggest that work could be conducted to assess the current use of functional biodiversity in urban areas, with a specific focus on how data collected by CS volunteers could contribute to this. Currently, CS scheme data obtained from bird (e.g. BTO), plant (e.g. NPMS) or arthropods (e.g. PoMS) could be used. Similarly, more generalist recording such as iRecord data could be used to obtain functional diversity information across taxa after the different recording. For example, volunteers could assist in the process of classifying data used in functional diversity assessment as part of their data collection.

Soil biodiversity: We found that, overall, not all components of the urban ecosystem were equally monitored. For instance, soil biodiversity in urban areas is poorly understood. However, soil health is of high importance for multiple socio-economic factors worldwide. In citizen science, particularly in the UK, Bone *et al.* (2012) demonstrated how surveys like the Open Air Laboratories (OPAL) “soil and earthworm survey” can generate data and contribute to soil protection policies. Although this survey was not specific to urban areas, it could be adapted to address urban challenges, such as to access private land, this will require further consultation. Learning from other citizen science schemes, such as the “MyBackyard” monitoring, will be an important step. Soil health in urban habitats has been used as an indicator in the SONC and IUCN frameworks. Therefore, we highly recommend investigating how CS monitoring can support soil monitoring and enhance understanding in urban areas.

Under recorded taxa: In the previous section, we highlighted that in the literature birds and plants are often the primary focus in urban areas. However, limited information is available for other taxonomic groups. This could be attributed to existing schemes taking up much of the recording space (e.g. that the availability of interested contributors has been maxed), and/or the ease of monitoring these groups. Future monitoring efforts in urban areas should prioritise under-recorded taxa, such as reptiles and snails in order to have an holistic view of urbanisation impact of biodiversity. However, it is also important to continue monitoring birds and plants, which are crucial for understanding trends. In Appendix 1, we suggest different CS schemes that could increase the number of records of some specific taxa in urban areas. Discussion with these different schemes will be of prime importance to understand their current sampling in urban areas.

Under recorded areas: Research has shown that some locations are not recorded with the same intensity in urban areas. In the UK, Pocock *et al.* (2022) assessed urban CS according to land use based on 80,000 insect iRecord records at 50,000 sites. They found records were more likely made in public parks, religious grounds and cemeteries, allotments and in private gardens, while amenity and natural land uses were slightly under recorded. The development of decision tools such as DECIDE (i.e. DECIDE Tool shows you where records of butterflies and moths are most needed) will allow recorders to identify potential recording locations of particular value (including under recorded areas) and drive the choice of sampling location. Similarly, it will be interesting to understand what the current strategies of the various schemes are to increase monitoring in under-recorded areas. Current works under tNCEA and TSDA are currently looking at how to improve these different under-recorded areas. However, this raises a question of the necessity of monitoring everything everywhere. While it is necessary to have a good understanding of species habitat preferences and thus have a sampling effort comparable across habitats, monitoring needs to answer specific questions (e.g. understanding trends) and data mobilisation needs to be effective to inform habitat and species that need more monitoring.

Native versus non-native species: In our review of different frameworks, we found that the distinction between native and non-native species was frequently utilised. This differentiation holds significant relevance in urban areas, where non-native species thrive due to human concentrations and activities. Moreover, the conventional focus on presence/absence, abundance, and biodiversity indices may not effectively distinguish between native and non-native species or account for shifts in community structure, particularly among plant populations. In this context, the role of CS is to monitor species of all types, and post-hoc analysis can be employed to assess and compare community assemblages. In Appendix 1, we suggest some CS schemes that can be used to collect data and obtain information about the proportion of native and non-native species. Comparing this type of information is crucial for understanding the individual evolution of native species (i.e. rather than focusing exclusively on beta diversity) and the impact of urbanisation on the overall assemblage of species.

Post-hoc data analysis: The use of post-hoc methods of data analysis emerged as a recurring theme throughout this report. Post-hoc data analysis is highly relevant for various areas of interest such as functional biodiversity, comparisons between native and alien species, community assemblage, and analysing different drivers (like the relationship between a biodiversity index and population density/gradient). For instance, enhancing connectivity is crucial for promoting biodiversity in urban areas. Analysing connectivity can be achieved through post-hoc analysis and the utilization of GIS software, requiring minimal information from the ground. CS data prove valuable in feeding the model and understanding species connectivity across habitat patches. For example, collaborative efforts between CS and remote sensing (EO) can be employed to map key features that facilitate connectivity between patches, contributing to a better understanding of urban connectivity. Such activities could be carried out through CS with ground-truthing as a foundation. Similarly, CS monitoring data are essential as different taxa have different home ranges and thus connectivity across taxa might vary a lot.

Habitat quality and quantity: Habitat recording surveys that include the classification of habitat types are a common component of ecological monitoring. However, the assessment of habitat quality and quantity is less frequently conducted. Firstly, assessing the quality of a habitat can be challenging and heavily relies on the judgment of the surveyor, making comparisons across sites and surveyors difficult. As a result, frameworks that incorporate habitat quality, such as BNG, have traditionally been accessible only to trained ecologists and not realistically accessible to CS. However, since habitat classification is already part of different surveillance schemes (e.g. NPMS), it could be worthwhile to consider adding a simplified version of the BNG methods or providing simplified training on assessing habitat quality. Similarly, it is worth considering a species monitoring system which allows habitat quality to be inferred. For example, UKCEH have developed the E-Surveyor app which helps infer habitat quality using species identification. To minimise bias in assessing quality, it will be important to identify specific indicators that represent habitat quality in urban habitats. These indicators may include factors such as vegetation composition, species diversity, water quality, soil health, and/or habitat structure. Currently, the E-Surveyor app supports farmers and land managers to conduct habitat monitoring. We suggest investigating how such surveys could be adapted or used in urban areas.

Different monitoring techniques: In this report, we also attempt to study how urban biodiversity is monitored and what different tools there are specific to this type of area. We found that obtaining this information was difficult, most of the research focused on differences in scale and used their own definitions of urban habitat. It was challenging to find specific tools used for urban monitoring, other than those presented by Davies *et al.* in 2011.

Future work should emphasise the differences between monitoring in an urban context and other habitats. Highlighting these differences will help understanding of urban pressures and ensure accurate monitoring of biodiversity in these areas. However, we also encourage the development of methods and protocols that can be used across habitats. The choice of specific monitoring methods and protocols should be focused on addressing specific questions.

Drivers of urban biodiversity: We have identified potential drivers of urban biodiversity that should be monitored in the future. Habitat fragmentation (including related connectivity), socio-economic factors, water and air quality, and noise and light pollution are understudied drivers of biodiversity patterns, (this is not an exhaustive list). We emphasised the importance of studying socio-economic factors, which are listed as indicators in the SONC, IUCN, and SI frameworks. The other drivers (water, air, noise, and light) are all included in the IUCN framework. Collecting information on these drivers can potentially be done post-hoc. For example, in the context of socio-economic factors, local surveys can be used to complement studies that collect biodiversity information. CS can also be utilised to gather this type of information. For instance, volunteers can contribute their perceptions about specific locations in their surveys. However, this introduces complexity and may deter some volunteers. Their judgments may be highly biased and influenced by individual backgrounds/personal experiences. If other data are available through local authority research, it may be more appropriate to use those data rather than employing a CS approach. Similarly, in England, water and air quality are already monitored as part of multiple surveys by the Environment Agency or though services such as the Air Pollution Information System. Therefore, the immediate need is to link these different data sources together rather than involving more citizen scientists in collecting additional data, which could discourage their participation in surveys. Some of the frameworks presented above are highly valuable as they integrate different data sources while addressing various biodiversity drivers in urban areas.

6.2 Data mobilisation

In this report, we presented five indicators/frameworks developed by different organisations as case studies to understand the state of urban biodiversity. We demonstrated how these indicators can be applied using CS data and we highlighted their advantages and disadvantages. Ultimately, each indicator serves a distinct purpose with different objectives. To apply these indicators/frameworks in their entirety, data mobilisation (i.e. sharing data) across schemes to cover their large data requirement is needed. Applying them to the data requirements of these indicators as a trial will help gauge their feasibility in UK urban areas. We propose an initial framework that incorporates objectives, CS data collection, and data flow. Figure 4 provides an example of the connections between different survey components and how each part of the potential framework incorporating indicators could operate.

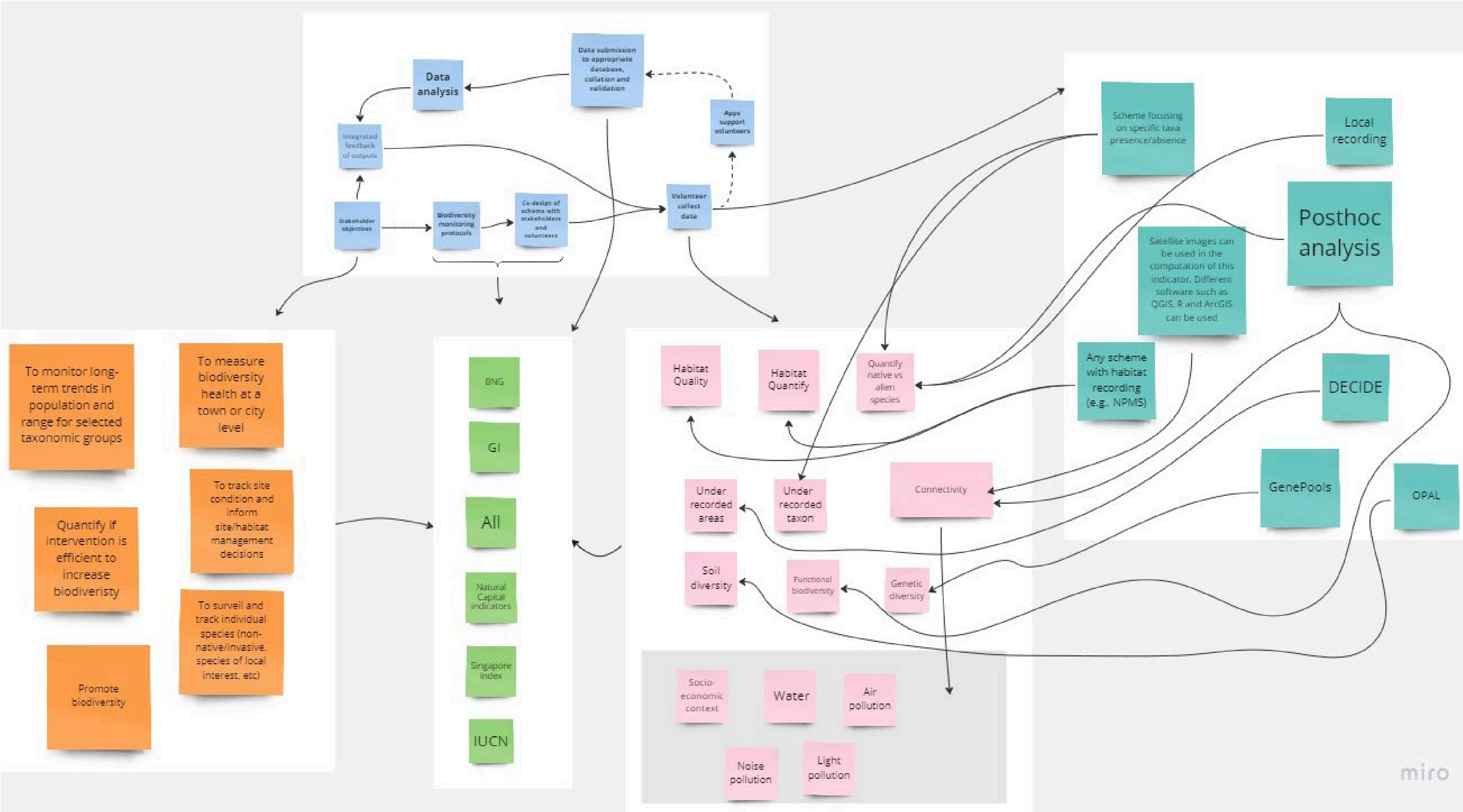

Figure 4: An example of the connections between different survey components and how each part of the potential framework incorporating indicators could operate. Orange: Objectives, Green: Indicators/Framework, Blue: Data cycle, Pink: part of urban biodiversity to assess, Blue: Example of citizen science monitoring. (BNG= Biodiversity Net Gain, GI= Green Infrastructure, IUCN= International Union for Conservation of Nature, DECIDE= Delivering Enhanced Biodiversity Information with Adaptive Citizen Science and Intelligent Digital Engagements, NPMS = National Plant Monitoring Scheme, GenePools = partnership that investigating life in ponds in urban areas, OPAL = Open Air Laboratories)

6.3 Role of CS in collecting data in urban areas

Based on the above, we have identified specific ways in which CS can contribute to urban areas monitoring. In Appendix 1, we highlight which kind of schemes can support this. By focusing on these aspects, we can enhance our overall understanding of biodiversity in urban areas while utilising the indicators and frameworks presented earlier. We also outline the necessary steps to achieve this:

Generate robust, long-term indicators of species' abundance in urban areas: Current CS studies are vital to developing an accurate understanding of species distribution, trends and abundance. Supporting existing monitoring schemes such as the ones presented in section 4 in urban areas will help with enhancing data collection efforts. Here, we presented how CS data, along with other data sources, can be utilised to apply existing indicators. It is worth noting that CS data can also be used more directly. For example, instead of incorporating CS data into the BNG, Cooper *et al.* (2023) demonstrated how bird counts from the BBS can predict the impact of different land uses and inform urban development plans.

Monitoring a broad range of urbanisation impacts: This entails expanding surveys to study impacts beyond species counts, such as behavioural shifts or reproductive success. However, obtaining robust estimate of species abundance and distribution in urban area should remain the priority.

Genetic diversity and functional diversity: Supporting and developing surveys that focus on other components of diversity to gain a comprehensive understanding of the drivers of diversity in urban areas.

Monitoring habitat quality and quantity: Existing schemes without habitat surveys need to consider ways to incorporate habitats in their assessment, while schemes already including habitat surveys could incorporate the monitoring of habitat quality by using habitat quality indicators and collaborating with remote sensing (EO) work through ground-truthing. A recent unpublished survey has highlighted volunteers' interest in monitoring habitat.

Data collection on species with low record numbers: Identifying the taxa that require specific attention and collecting data on them in particular areas. The needs may vary depending on the local context, and local surveys can provide valuable information about specific taxa.

Soil biodiversity: Identifying methods to assess soil biodiversity in urban areas and determining key points of study, such as microbiota and soil structure.

Data collection on drivers impacting biodiversity: Monitoring schemes can incorporate additional data recording, such as gathering feedback about certain areas. It is also crucial for various schemes to provide accurate sampling locations to facilitate post-hoc analysis and understand the drivers of biodiversity patterns.

Increasing data collection in under-recorded habitats/areas: Supporting data flow between different schemes to prioritize survey efforts at a local scale, identifying areas that require more attention.

Monitoring areas with interventions versus non-interventions and conducting pre- and post-intervention assessments to evaluate their effectiveness:

By focusing on these areas and implementing the suggested steps, we can leverage CS to improve urban areas monitoring and enhance our knowledge of urban biodiversity. However, in the following steps of this work, it is important to consider and assess the willingness of CS volunteers to take part in the different aspects mentioned above. For example, it is unclear if volunteers will be interested in the outputs arising from frameworks. Prioritising volunteers' interests is essential to keep them engaged in their respective schemes.

6.4 Take home messages and next steps

This report is the first step in understanding urban biodiversity and its current state. However, it is essential to acknowledge that this work remains theoretical, and further steps are needed to facilitate widespread implementation of urban biodiversity initiatives.

We suggest that the following key points need to be addressed for successful implementation:

- **Identify urban stakeholders and their objectives:** Given the high population density in urban areas, a variety of stakeholders interested in monitoring biodiversity and indicators/frameworks can be identified. It is crucial to determine the most effective way to support stakeholders' objectives concerning indicators and frameworks and how CS can contribute to achieving their goals.
- **Address different spatial scales:** Monitoring efforts occur at various scales, from local to international, driven by specific objectives and funding availability. Understanding how data collected at different scales can be utilised across all levels will provide a more comprehensive overview of urban biodiversity in both spatial and temporal dimensions.
- **Incorporate different taxonomic groups:** Local and national monitoring activities often focus on specific taxonomic groups. To achieve a holistic view of biodiversity in urban areas, it is necessary to collate and integrate information across all taxonomic groups, not just at the species level.
- **Enhance data quality and reproducibility:** To comprehend biodiversity across urban areas and taxonomic groups effectively, it is imperative to adopt a more standardised and reproducible approach to biodiversity monitoring. While CS is an excellent engagement tool for promoting biodiversity conservation, efforts should be made to ensure scientifically meaningful data collection by refining/standardising sampling designs and methods.
- **Improve data mobilisation and accessibility:** Despite the broad collection of data from CS monitoring and other sources, the accessibility and flow of these data are still limited. It is essential to improve data availability, flow, and accessibility for different species and scales, enabling multiple sampling efforts to contribute effectively to biodiversity conservation.
- **Identify an inclusive framework:** To address the above points, an inclusive framework should be identified that considers:
  (i) the objectives of various stakeholders,
  (ii) different spatial scales,
  (ii) diverse taxonomic groups,
  (iv) enhanced data mobilisation.

  This framework could be an adaptation of existing frameworks/indicators and CS protocols, or a newly designed framework specifically tailored to address urban biodiversity in the UK. The latter option requires building upon current knowledge of urban monitoring, learning from local successes, failures, and needs.

- **Conduct local pilots for success:** It is essential to conduct local pilot projects to test and refine the identified framework. These pilot challenges and the data mobilization, help understand challenges, and adapt strategies to unforeseen circumstances.

By addressing these points, we can lay the foundation for effective urban biodiversity management, incorporating the valuable contributions of CS while meeting the diverse needs of stakeholders and maintaining ecological conservation as a priority.

7. References

Amano, T., Lamming, J.D.L. & Sutherland, W.J. 2016. Spatial Gaps in Global Biodiversity Information and the Role of Citizen Science. *BioScience* 66, 393–400. https://doi.org/10.1093/biosci/biw022

Andrianjara, I., Bordenave-Jacquemin, M., Roy, V., Cabassa, C., Federici, P., Carmignac, D., Marcangeli, Y., Rouhan, G., Renard, M., Nold, F., Lata, J.-C., Genet, P. & Planchais, S. 2021. Urban tree management: Diversity of Tilia genus in streets and parks of Paris based on morphological and genetic characteristics. *Urban For. Urban Green*. 66, 127382. https://doi.org/10.1016/j.ufug.2021.127382

Aronson, M.F.J., 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., La Sorte, F.A., Williams, N.S.G., Zipperer, W., 2016. Hierarchical filters determine community assembly of urban species pools. *Ecology* 97, 2952–2963. https://doi.org/10.1002/ecy.1535

Baker, P.J., Harris, S., 2007. Urban mammals: what does the future hold? An analysis of the factors affecting patterns of use of residential gardens in Great Britain. *Mammal Rev*. 37, 297–315. https://doi.org/10.1111/j.1365-2907.2007.00102.x

Barbato, D., Benocci, A., Caruso, T., Manganelli, G., 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

Beumer, C., Martens, P., 2015. Biodiversity in my (back) yard: towards a framework for citizen engagement in exploring biodiversity and ecosystem services in residential gardens. *Sustain. Sci*. 10, 87–100.

Blair, R.B., Launer, A.E., 1997. Butterfly diversity and human land use: Species assemblages along an urban grandient. *Biol. Conserv*. 80, 113–125. https://doi.org/10.1016/S0006-3207(96)00056-0

Blanchong, J.A., Sorin, A.B., Scribner, K.T., 2013. Genetic diversity and population structure in urban white-tailed deer. *J. Wildl. Manag*. 77, 855–862. https://doi.org/10.1002/jwmg.521

Bolund, P., Hunhammar, S., 1999. Ecosystem services in urban areas. Ecol. Econ. 29, 293–301. https://doi.org/10.1016/S0921-8009(99)00013-0

Bone, J., Archer, M., Barraclough, D., Eggleton, P., Flight, D., Head, M., Jones, D.T., Scheib, C., Voulvoulis, N., 2012. Public Participation in Soil Surveys: Lessons from a Pilot Study in England. *Environ. Sci. Technol.* 46, 3687–3696. https://doi.org/10.1021/es203880p

Borowy, D., Swan, C.M., 2020. A Multi-Trait Comparison of an Urban Plant Species Pool Reveals the Importance of Intraspecific Trait Variation and Its Influence on Distinct Functional Responses to Soil Quality. *Front. Ecol. Evol.* 8.

Callaghan, C.T., Ozeroff, I., Hitchcock, C., Chandler, M., 2020. Capitalizing on opportunistic citizen science data to monitor urban biodiversity: A multi-taxa framework. *Biol. Conserv.* 251, 108753. https://doi.org/10.1016/j.biocon.2020.108753

Callaghan, C.T., Poore, A.G.B., Major, R.E., Rowley, J.J.L., Cornwell, W.K., 2019. Optimizing future biodiversity sampling by citizen scientists. *Proc. R. Soc. B Biol. Sci.* 286, 20191487. https://doi.org/10.1098/rspb.2019.1487

Chace, J.F. & Walsh, J.J. 2006. Urban effects on native avifauna: a review. *Landsc. Urban Plan*. 74, 46.

Chamberlain, S., Foster, Z., Bartomeus, I., LeBauer, D., Black, C. & Harris, D. 2020. traits: Species Trait Data from Around the Web.

Chan, L., Hillel, O., Werner, P., Holman, N., Coetzee, I., Galt, R. & Elmqvist, T. 2021. Handbook on the Singapore Index on Cities' Biodiversity (also known as the City Biodiversity Index). Montr. Secr. Conv. Biol. Divers. Singap. Natl. Parks Board Singap. 70.

CIEEM. 2016. Biodiversity Net Gain: Good Practice Principles for Development. CIEEM, CIRIA, IEMA.

Cooper, J.E.J., Plummer, K.E. & Siriwardena, G.M. 2023. Using species-habitat models to predict bird counts from urban development plans. *Landsc. Urban Plan*. 230, 104629. https://doi.org/10.1016/j.landurbplan.2022.104629

Courter, J.R., Johnson, R.J., Stuyck, C.M., Lang, B.A. & Kaiser, E.W. 2013. Weekend bias in Citizen Science data reporting: implications for phenology studies. *Int. J. Biometeorol*. 57, 715–720. https://doi.org/10.1007/s00484-012-0598-7

Cowie, R.H., Bouchet, P. & Fontaine, B. 2022. The Sixth Mass Extinction: fact, fiction or speculation? *Biol. Rev*. 97, 640–663. https://doi.org/10.1111/brv.12816

Davies, L., Kwiatkowski, L., Gaston, K.J., Beck, H., Brett, H., Batty, M., Scholes, L., Wade, R., Sheate, W.R., Sadler, J., Perino, G., Andrews, B., Kontoleon, A., Bateman, I. & Harris, J.A. 2011. UK National Ecosystem Assessment: Technical Report - Chapter 10.

Enloe, H.A., Lockaby, B.G., Zipperer, W.C. & Somers, G.L. 2015. Urbanization effects on leaf litter decomposition, foliar nutrient dynamics and aboveground net primary productivity in the subtropics. Urban Ecosyst. 18, 1285–1303. https://doi.org/10.1007/s11252-015-0444-x

Evans, K.L., Newson, S.E. & Gaston, K.J. 2009. Habitat influences on urban avian assemblages. *Ibis* 151, 19–39. https://doi.org/10.1111/j.1474-919X.2008.00898.x

Faeth, S.H., Bang, C. & Saari, S. 2011. Urban biodiversity: patterns and mechanisms. *Ann. N. Y. Acad. Sci*. 1223, 69–81. https://doi.org/10.1111/j.1749-6632.2010.05925.x

Faivre, N., Fritz, M., Freitas, T., de Boissezon, B. & Vandewoestijne, S. 2017. Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges. *Environ. Res*. 159, 509–518. https://doi.org/10.1016/j.envres.2017.08.032

Farinha-Marques, P., Lameiras, J.M., Fernandes, C., Silva, S. & Guilherme, F. 2011. Urban biodiversity: a review of current concepts and contributions to multidisciplinary approaches. *Innov. Eur. J. Soc. Sci. Res*. 24, 247–271. https://doi.org/10.1080/13511610.2011.592062

Feldman, M.J., Imbeau, L., Marchand, P., Mazerolle, M.J., Darveau, M. & Fenton, N.J. 2021. Trends and gaps in the use of citizen science derived data as input for species distribution models: A quantitative review. *PLOS ONE* 16, e0234587. https://doi.org/10.1371/journal.pone.0234587

Fenoglio, M.S., Rossetti, M.R. & Videla, M. 2020. Negative effects of urbanization on terrestrial arthropod communities: A meta-analysis. *Glob. Ecol. Biogeogr*. 29, 1412–1429. https://doi.org/10.1111/geb.13107

Fusco, N.A., Pehek, E. & Munshi-South, J. 2021. Urbanization reduces gene flow but not genetic diversity of stream salamander populations in the New York City metropolitan area. *Evol. Appl.* 14, 99–116. https://doi.org/10.1111/eva.13025

Gaston, K.J. & Spicer, J.I. 2013. Biodiversity: An Introduction. John Wiley & Sons.

Germaine, S.S. & Wakeling, B.F. 2001. Lizard species distributions and habitat occupation along an urban gradient in Tucson, Arizona, USA. *Biol. Conserv.* 97, 229–237. https://doi.org/10.1016/S0006-3207(00)00115-4

Giam, X. 2017. Global biodiversity loss from tropical deforestation. *Proc. Natl. Acad. Sci. U. S. A.* 114, 5775–5777. https://doi.org/10.1073/pnas.1706264114

Gionata, B. 2015. TR8: an R package for easily retrieving plant species traits. *Methods Ecol. Evol*. 6, 347–350.

Hall, D.M., Camilo, G.R., Tonietto, R.K., Ollerton, J., Ahrné, K., Arduser, M., Ascher, J.S., Baldock, K.C.R., Fowler, R., Frankie, G., Goulson, D., Gunnarsson, B., Hanley, M.E., Jackson, J.I., Langellotto, G., Lowenstein, D., Minor, E.S., Philpott, S.M., Potts, S.G., Sirohi, M.H., Spevak, E.M., Stone, G.N. & Threlfall, C.G. 2017. The city as a refuge for insect pollinators. *Conserv. Biol.* 31, 24–29. https://doi.org/10.1111/cobi.12840

Hassall, K.L., Dailey, G., Zawadzka, J., Milne, A.E., Harris, J.A., Corstanje, R. & Whitmore, A.P. 2019. Facilitating the elicitation of beliefs for use in Bayesian Belief modelling. *Environ. Model. Softw.* 122, 104539. https://doi.org/10.1016/j.envsoft.2019.104539

Hill, M.O., Preston, C.D., Bosanquet, S.D.S. & Roy, D.B. 2007. BRYOATT – Attributes of British and Irish Mosses, Liverworts and Hornworts.

Hope, D., Gries, C., Zhu, W., Fagan, W.F., Redman, C.L., Grimm, N.B., Nelson, A.L., Martin, C. & Kinzig, A. 2003. Socioeconomics drive urban plant diversity. *Proc. Natl. Acad. Sci.* 100, 8788–8792. https://doi.org/10.1073/pnas.1537557100

Hyseni, C., Heino, J., Bini, L.M., Bjelke, U. & Johansson, F. 2021. The importance of blue and green landscape connectivity for biodiversity in urban ponds. *Basic Appl. Ecol*. 57, 129–145. https://doi.org/10.1016/j.baae.2021.10.004

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., Rowe, R., Valentine, L.E. & Kendal, D. 2016. Cities are hotspots for threatened species. *Glob. Ecol. Biogeogr.* 25, 117–126. https://doi.org/10.1111/geb.12404

Jones, E.L. & Leather, S.R. 2012. Invertebrates in urban areas: A review. *Eur. J. Entomol.* 109, 463–478. https://doi.org/10.14411/eje.2012.060

Kolbert, E. 2014. The Sixth Extinction: An Unnatural History. A&C Black.

Krauss, J., Bommarco, R., Guardiola, M., Heikkinen, R.K., Helm, A., Kuussaari, M., Lindborg, R., Öckinger, E., Pärtel, M., Pino, J., Pöyry, J., Raatikainen, K.M., Sang, A., Stefanescu, C., Teder, T., Zobel, M. & Steffan-Dewenter, I. 2010. Habitat fragmentation causes immediate and time-delayed biodiversity loss at different trophic levels. *Ecol. Lett.* 13, 597–605. https://doi.org/10.1111/j.1461-0248.2010.01457.x

LaPoint, S., Balkenhol, N., Hale, J., Sadler, J. & van der Ree, R. 2015. Ecological connectivity research in urban areas. *Funct. Ecol.* 29, 868–878. https://doi.org/10.1111/1365-2435.12489

Lepczyk, C.A., Aronson, M.F.J., Evans, K.L., Goddard, M.A., Lerman, S.B. & MacIvor, J.S. 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

Luck, G.W. & Smallbone, L.T. 2010. Species diversity and urbanisation: patterns, drivers and implications, in: Gaston, K.J. (Ed.), Urban Ecology. Cambridge University Press, pp. 88–119. https://doi.org/10.1017/CBO9780511778483.006

Lusardi, J., Rice, P., Waters, R.D. & Craven, J. 2018. Natural Capital Indicators: for defining and measuring change in natural capital (Research Report No. 076). Natural England.

Manchester, S.J. & Bullock, J.M. 2000. The impacts of non-native species on UK biodiversity and the effectiveness of control. *J. Appl. Ecol.* 37, 845–864. https:/doi.org/10.1046/j.1365-2664.2000.00538.x

Marcotullio, P.J., Braimoh, A.K. & Onishi, T. 2008. The Impact of Urbanization on Soils, in: Braimoh, A.K., Vlek, P.L.G. (Eds.), Land Use and Soil Resources. Springer Netherlands, Dordrecht, pp. 201–250. https://doi.org/10.1007/978-1-4020-6778-5_10

Marzluff, J.M. 2005. Island biogeography for an urbanizing world: how extinction and colonization may determine biological diversity in human-dominated landscapes. *Urban Ecosyst.* 8, 157–177. https://doi.org/10.1007/s11252-005-4378-6

McCaffrey, R.E. 2005. Using Citizen Science in Urban Bird Studies 3.

McDonald, R., Colbert, M., Hamann, M., Simkin, R., Walsh, B. & Ascensão, F. 2018. Nature in the Urban Century: A global assessment of important areas for safeguarding biodiversity and human well-being.

McDonnell, M.J. & Hahs, A.K. 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

McIntyre, N.E. 2000. Ecology of Urban Arthropods: A Review and a Call to Action. *Ann. Entomol. Soc. Am.* 93, 825–835. https://doi.org/10.1603/0013-8746(2000)093[0825:EOUAAR]2.0.CO;2

McKinney, M.L. 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

McKinney, M.L. 2006. Urbanization as a major cause of biotic homogenization. *Biol. Conserv*. 127, 247–260. https://doi.org/10.1016/j.biocon.2005.09.005

McKinney, M.L. 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

Miles, L.S., Rivkin, L.R., Johnson, M.T.J., Munshi-South, J. & Verrelli, B.C. 2019. Gene flow and genetic drift in urban environments. *Mol. Ecol*. 28, 4138–4151. https://doi.org/10.1111/mec.15221

Morawitz, D.F., Blewett, T.M., Cohen, A. & Alberti, M. 2006. Using NDVI to Assess Vegetative Land Cover Change in Central Puget Sound. *Environ. Monit. Assess*. 114, 85–106. https://doi.org/10.1007/s10661-006-1679-z

Moss, M. 2021. England Green Infrastructure Mapping Database: Beta version 1.1 user guide. Natural England, United Kingdom.

NatureScot. 2023. Nature-based solutions: Urban [WWW Document]. NatureScot. URL https://www.nature.scot/climate-change/nature-based-solutions/nature-based-solutions-urban (accessed 8.29.23).

Nikula, S., Vapaavuori, E. & Manninen, S. 2010. Urbanization-related changes in European aspen (*Populus tremula* L.): Leaf traits and litter decomposition. *Environ. Pollut.*, 158, 2132–2142. https://doi.org/10.1016/j.envpol.2010.02.025

Oliveira Hagen, E., Hagen, O., Ibáñez-Álamo, J.D., Petchey, O.L. & Evans, K.L. 2017. Impacts of Urban Areas and Their Characteristics on Avian Functional Diversity. *Front. Ecol. Evol*. 5.

Patenković, A., Tanasković, M., Erić, P., Erić, K., Mihajlović, M., Stanisavljević, L. & Davidović, S. 2022. Urban ecosystem drives genetic diversity in feral honey bee. *Sci. Rep*. 12, 17692. https://doi.org/10.1038/s41598-022-21413-y

Pescott, O.L., Walker, K.J., Harris, F., New, H., Cheffings, C.M., Newton, N., Jitlal, M., Redhead, J., Smart, S.M. & Roy, D.B. 2019. The design, launch and assessment of a new volunteer-based plant monitoring scheme for the United Kingdom. *PLOS ONE* 14, e0215891. https://doi.org/10.1371/journal.pone.0215891

Pierce, J.R., Barton, M.A., Tan, M.M.J., Oertel, G., Halder, M.D., Lopez-Guijosa, P.A. & Nuttall, R. 2020. Actions, indicators, and outputs in urban biodiversity plans: A multinational analysis of city practice. *PLOS ONE* 15, e0235773. https://doi.org/10.1371/journal.pone.0235773

Pinho, P., Casanelles-Abella, J., Luz, A.C., Kubicka, A.M., Branquinho, C., Laanisto, L., Neuenkamp, L., Alós Ortí, M., Obrist, M.K., Deguines, N., Tryjanowski, P., Samson, R., Niinemets, Ü. & Moretti, M. 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

Plummer, K.E., Gillings, S. & Siriwardena, G.M. 2020. Evaluating the potential for bird-habitat models to support biodiversity-friendly urban planning. *J. Appl. Ecol*. 57, 1902–1914. https://doi.org/10.1111/1365-2664.13703

Pocock, M.J.O., Chapman, D.S., Sheppard, L.J. & Roy, H.E. 2014. Choosing and Using Citizen Science: a guide to when and how to use citizen science to monitor biodiversity and the environment. Centre for Ecology & Hydrology.

Pocock, M.J.O. & Marlowe, C. 2022. Patterns of biodiversity citizen science recording in urban regions in England.

Ravetz, J. 2015. The future of the urban environment and ecosystem services in the UK.

Rawlins, B.G., Harris, J., Price, S. & Bartlett, M. 2015. A review of climate change impacts on urban soil functions with examples and policy insights from England, UK. *Soil Use Manag*. 31, 46–61. https://doi.org/10.1111/sum.12079

Rega-Brodsky, C.C., Aronson, M.F.J., Piana, M.R., Carpenter, E.-S., Hahs, A.K., Herrera-Montes, A., Knapp, S., Kotze, D.J., Lepczyk, C.A., Moretti, M., Salisbury, A.B., Williams, N.S.G., Jung, K., Katti, M., MacGregor-Fors, I., MacIvor, J.S., La Sorte, F.A., Sheel, V., Threfall, C.G. & Nilon, C.H. 2022. Urban biodiversity: State of the science and future directions. *Urban Ecosyst.* 25, 1083–1096. https://doi.org/10.1007/s11252-022-01207-w

Rimlinger, A., Avana, M.-L., Awono, A., Chakocha, A., Gakwavu, A., Lemoine, T., Marie, L., Mboujda, F., Vigouroux, Y., Johnson, V., Vinceti, B., Carrière, S.M. & Duminil, J. 2021. Trees and their seed networks: The social dynamics of urban fruit trees and implications for genetic diversity. *PLOS ONE* 16, e0243017. https://doi.org/10.1371/journal.pone.0243017

Ritzel, K. & Gallo, T. 2020. Behavior Change in Urban Mammals: A Systematic Review. *Front. Ecol. Evol*. 8.

Robinson, M.L. & Strauss, S.Y. 2018. Cascading effects of soil type on assemblage size and structure in a diverse herbivore community. *Ecology* 99, 1866–1877. https://doi.org/10.1002/ecy.2406

Roman, L.A., Scharenbroch, B.C., Östberg, J.P.A., Mueller, L.S., Henning, J.G., Koeser, A.K., Sanders, J.R., Betz, D.R. & Jordan, R.C. 2017. Data quality in citizen science urban tree inventories. *Urban For. Urban Green*. 22, 124–135. https://doi.org/10.1016/j.ufug.2017.02.001

Seress, G. & Liker, A. 2015. Habitat urbanization and its effects on birds. *Acta Zool. Acad. Sci. Hung.* 61, 373–408. https://doi.org/10.17109/AZH.61.4.373.2015

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. https://doi.org/10.1525/bio.2010.60.3.6

Tait, C.J., Daniels, C.B. & Hill, R.S. 2005. Changes in Species Assemblages Within the Adelaide Metropolitan Area, Australia, 1836–2002. *Ecol. Appl.* 15, 346–359. https://doi.org/10.1890/04-0920

Tangcharoensathien, V., Yamamoto, N., Suphanchaimat, R., Sukbut, H. & Chotchoungchatchai, S. 2022. Impact of climate change on biodiversity, agriculture and health: a call for papers. *Bull. World Health Organ*. 100, 238. https://doi.org/10.2471/BLT.22.288219

Taylor, P.D., Fahrig, L., Henein, K. & Merriam, G. 1993. Connectivity Is a Vital Element of Landscape Structure. *Oikos* 68, 571–573. https://doi.org/10.2307/3544927

Theodorou, P., Radzevičiūtė, R., Lentendu, G., Kahnt, B., Husemann, M., Bleidorn, C., Settele, J., Schweiger, O., Grosse, I., Wubet, T., Murray, T.E. & Paxton, R.J. 2020. Urban areas as hotspots for bees and pollination but not a panacea for all insects. *Nat. Commun*. 11, 576. https://doi.org/10.1038/s41467-020-14496-6

Tresch, S., Frey, D., Le Bayon, R.-C., Zanetta, A., Rasche, F., Fliessbach, A. & Moretti, M. 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

Trumbo, D.R., Salerno, P.E., Logan, K.A., Alldredge, M.W., Gagne, R.B., Kozakiewicz, C.P., Kraberger, S., Fountain-Jones, N.M., Craft, M.E., Carver, S., Ernest, H.B., Crooks, K.R., VandeWoude, S. & Funk, W.C. 2019. Urbanization impacts apex predator gene flow but not genetic diversity across an urban-rural divide. *Mol. Ecol*. 28, 4926–4940. https://doi.org/10.1111/mec.15261

United Nation. 2018. URL https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html (accessed 10.3.23).

Vanden Broeck, A., Cox, K., Melosik, I., Maes, B. & Smets, K. 2018. Genetic diversity loss and homogenization in urban trees: the case of *Tilia × europaea* in Belgium and the Netherlands. *Biodivers. Conserv*. 27, 3777–3792. https://doi.org/10.1007/s10531-018-1628-5

Villaseñor, N.R., Tulloch, A.I.T., Driscoll, D.A., Gibbons, P. & Lindenmayer, D.B. 2017. Compact development minimizes the impacts of urban growth on native mammals. *J. Appl. Ecol.* 54, 794–804. https://doi.org/10.1111/1365-2664.12800

Walker, J.S., Grimm, N.B., Briggs, J.M., Gries, C. & Dugan, L. 2009. Effects of Urbanization on Plant Species Diversity in Central Arizona. *Front. Ecol. Environ*. 7, 465–470.

Wandeler, P., Funk, S.M., Largiadèr, C.R., Gloor, S. & Breitenmoser, U. 2003. The city-fox phenomenon: genetic consequences of a recent colonization of urban habitat. *Mol. Ecol*. 12, 647–656. https://doi.org/10.1046/j.1365-294x.2003.01768.x

Westgate, M.J., Scheele, B.C., Ikin, K., Hoefer, A.M., Beaty, R.M., Evans, M., Osborne, W., Hunter, D., Rayner, L. & Driscoll, D.A. 2015. Citizen Science Program Shows Urban Areas Have Lower Occurrence of Frog Species, but Not Accelerated Declines. *PLOS ONE* 10, e0140973. https://doi.org/10.1371/journal.pone.0140973

Williams, R.L., Stafford, R. & Goodenough, A.E. 2015. Biodiversity in urban gardens: Assessing the accuracy of citizen science data on garden hedgehogs. *Urban Ecosyst.* 18, 819–833. https://doi.org/10.1007/s11252-014-0431-7

Wood, D.A., Rose, J.P., Halstead, B.J., Stoelting, R.E., Swaim, K.E. & Vandergast, A.G. 2020. Combining genetic and demographic monitoring better informs conservation of an endangered urban snake. *PLOS ONE* 15, e0231744. https://doi.org/10.1371/journal.pone.0231744

Yan, Y., Jarvie, S., Zhang, Q., Zhang, S., Han, P., Liu, Q. & Liu, P. 2021. Small patches are hotspots for biodiversity conservation in fragmented landscapes. *Ecol. Indic.* 130, 108086. https://doi.org/10.1016/j.ecolind.2021.108086

Zerbe, S., Maurer, U., Schmitz, S. & Sukopp, H. 2003. Biodiversity in Berlin and its potential for nature conservation. *Landsc. Urban Plan*. 62, 139–148. https://doi.org/10.1016/S0169-2046(02)00145-7