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Understanding and applying ecological principles in cities: Comparative urban ecology views from the UK and Brazil

Heather Rumble, Fabio Angeoletto, Stuart P. Connop, Mark A. Goddard and Caroline Nash.

Abstract

Renaturing cities requires a thorough understanding of how plants and animals interact with the urban environment and humans. But cities are a challenging environment for ecologists to work in, with high levels of heterogeneity and rapid rates of change. In addition, the hostile conditions often found in cities, such as extremes of heat and drought, mean that each city has a unique geographical context.

In this chapter, we present case study countries, the UK and Brazil, to demonstrate the contrasting challenges and approaches needed to renature cities. The UK has a long history of urbanisation and well established urban ecological research, which could be valuable to a rapidly urbanising Brazil, seated within a biodiversity hotspot. In addition, we present methods for applying this ecological knowledge to cities, so called "Ecological Engineering", in particular by discussing ecomimicry. By reading the ecological landscape in which urban developments sit and applying tailored green infrastructure solutions to new developments, cities may be able to decline the rate at which extinction debt is accumulated.

1. Why is Urban Ecology Important for Renaturing?

Constanza et al., (2014) determined that natural ecosystems provide $125 trillion of ecosystem service provision to human beings per year, more than twice as much as global GDP. Nature provides us with the essential functions needed to support human life, from oxygen to climate regulation. Humans also share an intrinsic, deep relationship with nature; the biophilia hypothesis (Wilson 1984) outlines that our reliance on nature, as hunter gatherers and agronomists, means that our love of nature is part of our DNA. For example, evidence shows that regular contact with nature lowers stress-levels (Hartig et al. 2014). Yet whilst cities can support surprisingly diverse natural communities, urbanisation processes generally cause native species and natural habitats to decline. As more people move into cities, it is essential that we renature cities effectively.

The impacts of renaturing cities are far-reaching. "The pigeon paradox" (Dunn et al. 2006) proposes three simple assertions: (1) current conservation actions are insufficient, (2) people are more prone to engage in conservation measures when they have direct experiences with the natural world, (3) as the majority of humans live in cities, humans primarily experience biodiversity through contact with urban nature. If these assertions are correct, future incentives for biological conservation, whether in urban environments or outside of them, will depend on people's interactions with urban ecosystems. With the electorate and environmental leaders concentrated in cities, if these key decision-makers do not experience nature, they are less likely to champion it.

To renature cities effectively, it is essential to understand how plants and animals interact with the urban environment. In their current form, cities pose a unique and hostile environment for many species, with extremes of climate and high levels of disturbance. Some species can thrive, exploiting new niches, escaping predation and, sometimes, forming relationships with humans – so called 'synurbic' species. A great many more cannot, meaning that cities display a net extinction debt (Hahs et al. 2009). Only by understanding the underlying ecological principles that drive or prevent urban colonisation will we be able to determine how to enable species to live in cities, which species we wish to form a basis for this renaturing and how to ensure ecological balances are in place to produce the ecosystem function we need to thrive.

Urban habitats are also a challenging environment to study because of their spatial heterogeneity and fast rate of change (Cadenasso et al. 2007). They are generally understudied compared to non-urban environments (Martin et al. 2012). Also, a city's geographical location influences the strategies and methodologies we may wish to employ to renature. Each city has a unique mix of social and physical factors, meaning that solutions are not universally applicable. We present two case study countries, the UK and Brazil, to demonstrate the contrasting challenges and approaches needed to renature. In both the UK and Brazil, the challenge is to understand how to conserve and enhance populations of existing species and how to encourage species to return to cities. Each country has its own challenges; In Brazil there is a need to reconcile rapid urbanisation with the maintenance of habitats and species of conservation concern in a biodiversity hotspot. Contrastingly, the UK has a long history of urbanisation and is at the forefront of biodiversity planning and providing resources and policy to do so, despite having relatively impoverished ecosystems.

By understanding urban ecological processes, we can engineer aspects of the urban fabric to maximise colonisation of the urban environment. This chapter also discusses methods used to apply ecological knowledge to urban design ("Ecological Engineering"), to develop vibrant, biodiverse ecosystems and conserve key species. We focus on ecomimicry as a learning-by-doing approach to increase our knowledge of urban ecosystem processes, bringing us closer to developing resilient and effective methods for renaturing.

2.1. Urban Ecology in the UK

Urbanisation and Urban Greenspace in the UK

The UK has a long history of urbanisation. The proportion of people living in cities has changed little in the past half century, from 78% in 1960 to 83% in 2016, a rise of only 5% (The World Bank 2017). Urban and developed land is the fifth most dominant land cover, equating to just over 10% of land cover in the UK (Nafilyan 2015). Within cities, urban greenspaces are important land covers, occupying between 17% and 41% of the total urban area in some English cities (Dallimer et al. 2011). However, many of these cities are witnessing a reduction in greenspace coverage, a trend that reflects land use policy, which encourages compact urban development and densification (Ibid.).

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Urban Nature Conservation and Planning in the UK

The UK has always been at the forefront of the urban nature conservation movement (Goode 1989; Adams 2005). The London Natural History Society (LNHS) can trace its roots to a group of Victorian lepidopterists as far back as 1858, with the society itself being created in 1913 (Edgington 2008). The LNHS produced the seminal work London's Natural History (Fitter 1945), and other notable contributions by urban naturalists (e.g. Gilbert, 1989; Mabey, 2010). By the 1970s and 1980s urban wildlife groups and programmes were commonplace across the UK, and ecological issues were increasingly integrated into urban planning and design (Goode 1989, 2014). Local authorities are now required to include biodiversity within their local plans with the result that the UK is in the vanguard of planning for urban biodiversity and ecosystem services (Evans 2004; Nilon et al. 2017).

Urban Ecology as an Academic Discipline

Academic ecologists began to turn their attention to UK towns and cities in the 1970s as the importance of urban and industrial areas for wildlife conservation became clear (Davis 1976). One of the earliest research programmes to be established focused on the demographics of the urban red fox (*Vulpes vulpes*) (e.g. Harris 1977). Concurrently, research on the impact of urbanisation on other fauna emerged, most notably on birds (Batten 1972, 1973; Cramp 1980). Starting with Salisbury's observations of the flora of bombed areas (Salisbury 1943), UK urban vegetation and habitats have been particularly well researched, with seminal studies on domestic gardens (e.g. Thompson et al. 2003; Loram et al. 2008; Owen 2010), brownfield land (Gilbert 1983) and green roofs (Dunnett and Kingsbury 2004), in addition to pioneering work on urban land restoration (Bradshaw and Chadwick 1980). Over time, urban ecological studies have become increasingly comprehensive and systematic. For example, Baldock et al., (2015) surveyed representative triplicates of urban habitats, farmland and nature reserves in and around 12 UK cities to determine the relative importance of urban areas for pollinating insects such as bees. Public engagement also became an important element of British urban ecological research. In recent years, urban ecologists have drawn upon 'citizen science' to assist with data collection for a range of taxa, making a valuable contribution to our understanding of UK urban ecosystems (e.g. Cannon et al. 2005; Lye et al. 2008; Southon et al. 2017). Building on Kettlewell's groundbreaking selection experiments on industrial melanism in the Peppered Moth, *Biston betulari* (Kettlewell 1955), we have also seen an increase in experimental ecology in an attempt to elucidate some of the mechanisms underlying urban ecosystem function (Bonnington et al. 2013; Bennie et al. 2018).

Since the publication of the Millennium Ecosystem Assessment (MEA 2005) and the popularisation of the ecosystem services concept, there has been an ever increasing emphasis on the goods and services provided by urban ecosystems (Gaston et al. 2013). UK researchers have examined the relationship between urban form and ecosystem services (Tratalos et al. 2007), seeking to quantify a range of city-scale urban ecosystem services, including carbon storage (Davies et al. 2011) and microclimatic regulation (Edmondson et al. 2016). The contribution of urban greenspace and its biodiversity to 'cultural services' linked to human health and well-being has recently emerged as an active research area (e.g. Dallimer et al., 2012; Southon et al., 2017). The emergence of the ecosystem services paradigm in urban ecology has been concomitant with the realisation that urban green infrastructure (UGI) should be 'multifunctional' such that there is a need to maximise synergies and minimise trade-offs between beneficial services (e.g. Bellamy et al., 2017; Connop et al., 2016) . Building on its formative roots in the UK and elsewhere, urban ecology is now mainstream research that seeks to implement global sustainability goals relating to climate action, urbanisation and biodiversity (United Nations 2015a, 2016). Achieving these lofty goals requires a holistic understanding of the patterns and drivers of biodiversity and ecosystem service provision in cities worldwide, founded upon collaborative and comparative research that transcends national boundaries (Aronson et al. 2016).

2.2. Urban Ecology in Brazil

Urbanisation and Urban Greenspace in Brazil

Contrasting the 5% rise in UK urban populations since 1960, Brazil has seen rapid urbanisation: a 40% increase in urban populations since 1960 (The World Bank 2017). Today, 83% of Brazilians live in cities, which occupy less than 1% of the country's land mass (Farias 2017). The inputs and outputs of these urban ecosystems are immense, because urban planning and management are precarious and consumption patterns increasingly resemble those of the cities of the northern hemisphere. Moreover, environmental legislation may not protect areas that are most important for biodiversity in urban areas (Guadagnin and Gravato 2009).

Brazilian cities are also characterised by particularly high levels of environmental injustice, with vegetation cover lower in areas of lower social class. This pattern has been observed in cities such as Sao Paulo (Lombardo 1985); Presidente Prudente (Gomes and Amorim 2002); Maringá and Sarandi (Angeoletto et al. 2017) and Rondonópolis (Duarte et al. 2017). Consequently, inhabitants of these areas experience less contact with nature and lower provision of ecosystem services, such as the amelioration of the urban heat island (Lombardo 1985).

Urban Nature Conservation and Planning in Brazil

Most global biodiversity is concentrated in countries in the southern hemisphere, which also account for most of today's urban growth. Expanding knowledge about the ecology of cities in megadiverse countries, and applying it to actions to increase and improve urban green spaces for nature and people is an urgent task. Despite this, urban biodiversity has only recently been considered in Brazilian urban planning and ecology is not fully incorporated into Brazilian urban, territorial and economic governance planning (Angeoletto et al. 2016). A broader understanding of urban ecosystems is needed (Pauleit and Duhme 2000). This must be embedded in planning through interdisciplinary working practices (Terradas 2001).

A lack of research on the ecology of Brazilian cities contributes to the scarcity of planning for biodiversity. Less than 10% of urban ecology studies have been conducted outside of Europe or the United States (Secretariat of the Convention on Biological Diversity 2012). Research conducted on urban ecology in Brazil indicates a luxuriant biodiversity. Hundreds of plant species inhabit the urban backyards of Brazilian cities (Angeoletto et al, 2017), as do species-rich bird communities (Reis et al. 2012). Mammals are also increasingly being studied in urban environments; a recent study by Nunes et al., (2017) highlighted that a high proportion of Brazil's bat species (47%) have been recorded in cities.

There is also increasing research into the mechanisms controlling biodiversity in Brazilian cities. Several papers have investigated the relationship between bird diversity, vegetation cover and urban characteristics. Mirroring results from UK cities, most concluded that complexity of vegetation cover is the strongest predictor of avian biodiversity (Toledo and Donatelli 2010; Fontana et al. 2011; Lessi et al. 2016). Similar results have also been reported for Hymenoptera, with complex vegetation supporting higher species richness (Antonini et al., 2013). The inclusion of native plant species and connected spaces have also been shown to be important for urban Hymenoptera (Pacheco and Vasconcelos, 2007). These studies emphasise the importance of appropriate vegetation in cities for supporting higher trophic levels.

2.3 Best Practice in Global Urban Ecological Research

These examples highlight the rich ecology and habitats that occur in Brazilian and UK cities and the contrasting pressures and challenges involved in studying, conserving and restoring biodiversity in each location. Whilst urban ecological research is gaining traction in the Southern Hemisphere, urban ecological research remains biased to Northern Hemisphere studies, such that conclusions from this work may not be applicable in places where it is most urgently needed (i.e. biodiversity hotspots experiencing rapid urbanisation). Additionally, whilst more resources have traditionally been available for UK urban biodiversity, this is only recently on the agenda of a Brazilian planning. Knowledge exchange of experiences and methodologies between the two countries should unlock some of the socio-political barriers preventing more widespread renaturing of cities.

International urban ecological knowledge transfer projects that engage key policy and decision-makers are likely to be most successful at achieving these aims. There is increasing support to achieve this. An example was the recent Newton Fund UK/Brazilian symposium "Renaturing Cities", from which this book emerged. Ecologists, architects and urban planners discussed the application of renaturing, with the involvement of local policy makers. From this a Biodiversity of Rondonópolis Project emerged, that aims to share knowledge internationally by bringing together researchers from Brazil (Angeoletto) and the UK (Connop, Goddard, Nash and Rumble), with scientists from the Complutense University of Madrid, the University of Rome "La Sapienza", the University of Presov (Slovakia) and the University of Poznan (Poland). The project aims to generate understanding of ecology and biodiversity in Rondonópolis, a medium-sized Brazilian city experiencing rapid urbanization. Key policy makers are integral to the project, with knowledge applied in planning and management, through institutional partnerships with the Municipal Department of Environment and other government agencies of the municipality.

Examples of transferable methodologies from this project comprise the remainder of this chapter:

3.1 Applying Urban Ecology to Cities: Ecological Engineering

The importance of undertaking basic ecological research in cities to understand their form and function is the first step to increasing urban biodiversity. The question is then, how do we best utilise that knowledge? The term "ecological engineering" in its broadest definition encompasses some of the techniques that we may employ to achieve this. Ecological engineering describes the method of designing ecosystems to benefit both humans and non-humans (Mitsch 2012). It is particularly important when discussing renaturing cities.

Ecological engineering can encompass habitat restoration or remediation, but arguably it's most exciting angle comes from the notion of starting with a blank canvas. Cities provide this blank canvas because of their uniqueness as a habitat for which there is no simple "natural" proxy for ecosystem engineers to draw upon, or pose challenges that require a deeper understanding of these natural environments than we currently have. Whilst "renaturing cities" suggests restoring cities to some baseline natural state, in reality, ecological engineers can and must apply creativity and imagination to the renaturing that is applied in cities within the parameters and conditions that make a city a city. These conditions encompass the physical and social (e.g. economy, urban morphology, cultural and political issues) environment, creating a complex set of limitations (Grimm et al., 2000).

There are many examples of ecological engineering being implemented and used effectively to renature cities. At one end of the spectrum, providing multiple ecosystem services, are "naturalistic" examples, such as ecomimicry (taking inspiration from the local ecological landscape to maximise urban biodiversity and ecosystem service provision). This technique is discussed later in the chapter as an example of best practice. Whilst ecomimicry aims to recreate the ecological functions provided by semi-natural and natural habitats, ecological engineering is much broader. It encompasses large and small-scale projects with narrower ecosystem service provision, often falling under the subdivisions of ecotechnology and bioengineering. For example, the large scale Burlington Eco Park (Vermont) integrates multiple ecologically engineered units to treat wastewater and grow crops (Todd et al. 2003). Smaller scale examples include the localised use of plants to uptake heavy metal contamination in composts and soils (Zhao et al. 2011).

Creating novel ecosystems that provide functionality for humans and non-humans shows great promise and poses significant challenges. To recreate a habitat or design a new one, one must understand how this habitat works. For instance, what are the key abiotic and biotic conditions that allow a habitat to function and flourish? There are still many non-urban habitats for which these questions remain. Soil ecology is a good example. Many plants form symbiotic relationships with fungi called mycorrhizas. In theory, mycorrhizas can alleviate the effects of drought on a plant (Ruiz-Lozano et al. 2016), enhance ability to withstand pests and diseases (Song et al. 2015) and gain competitive advantage over other plants (Averill et al. 2014), all desirable functions for application in urban ecosystems. Numerous examples exist of applying this fungi in cities to (in theory) benefit ecology. One of the most notable being the California Academy of Sciences green roof, which utilised coconut coir trays impregnated with mycorrhizal fungi in its construction (Peck, 2017). Whilst we know that different types/species of these fungi provide these functions to different degrees (Averill et al. 2014) and that this can be affected by specific plant/fungi pairings (Lekberg et al. 2015), the technology needed to apply this knowledge is in its infancy. This example is one of many that demonstrate that the key to ecological engineering is an in-depth understanding of the ecosystems involved, gained from both the study of organisms in cities and detailed "traditional" ecological studies.

From naturalistic ecomimicry approaches to the almost alien Supertrees of Singapore, ecological engineering can be applied in different ways to provide benefit. As a predominantly human habitat, it is vital that social benefits are embedded in this design process. This process marks out ecological engineering as a special area of ecology ensuring renaturing is accepted and appreciated by the public.

3.2. Enhancing Urban Habitats for Biodiversity

Ecological engineering can provide diverse habitats or narrowly focused elements of nature. The "gold standard" is to achieve both. UGI can vary considerably in terms of biodiversity value. For instance urban greenery that contains native species and is analogous to, or composed of, remnant natural habitat, has been shown to support greater diversity than cultivated and manicured greenspace (Chong et al. 2014). Nonetheless, long-established approaches to landscaping have resulted in much UGI across the globe having a homogenous character, typically comprising short, frequently mown grass and manicured, ornamental trees (Lepczyk et al. 2017). This widespread urban 'blandscaping' has largely been motivated by cultural services (primarily aesthetics/recreation) and economics, and the simplified habitat structure offers insufficient complexity to support multiple taxa, contributing to biotic homogenisation (McKinney 2008). If a renaturing cities strategy is to maximise ES provision and UGI multifunctionality, including supporting biodiversity as an ecosystem service in its own right (Mace et al. 2012), ecological functionality should be the foundation for UGI design and implementation. This is because biodiversity loss negatively impacts ecosystem functioning, and the multiple services that human populations derive from ecosystems (Hector and Bagchi 2007). Consequently, relying on assumed intrinsic benefits from UGI by default, rather than ensuring benefits to biodiversity by design, can constrain ES performance (Collier et al. 2013). Balancing ecological functionality, aesthetics and multifunctionality is one of the emerging challenges for nature-based solution innovators (Figure 1; Connop et al., 2016).

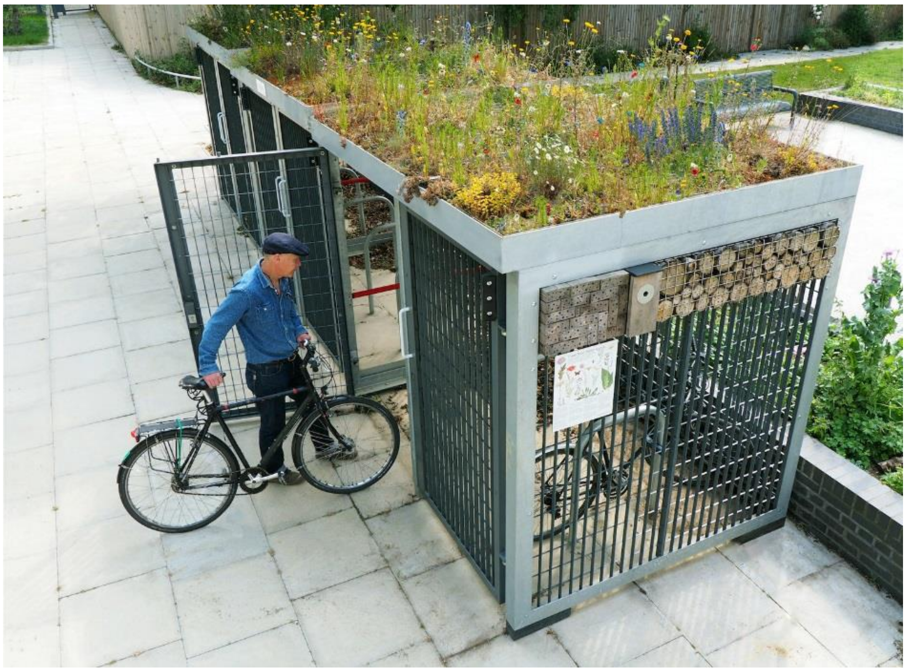

Fig. 1. A green roof shelter (Grass Roof Company) showcasing how innovative Nature-based Solutions can balance ecological functionality, aesthetics and multifunctionality. This shelter provides safe storage for bicycles, habitat for biodiversity, alleviates problems with stormwater and adds greenspace for community health and wellbeing. ©Grass Roof Company.

As with natural ecosystems, communities that develop on UGI will be a function of the niches embedded into the design, as demonstrated by the increased species richness found in complex tree communities in Brazilian cities (Sect. 2.2). Newly created, suitably designed UGI can offer unexploited resources for urban biodiversity. The 'habitat heterogeneity hypothesis' (MacArthur and MacArthur 1961), proposes that structurally complex habitats provide a greater range of niches and resources, enhancing species diversity. As habitat heterogeneity can contribute positively to biodiversity (Tews et al. 2004), this should be a key consideration for UGS design. Additionally, to restore locally-attuned, ecologically functioning UGI into cities, it is essential to consider regional context (Connop et al. 2016). This will ensure UGI compatibility with the local climate and regional biodiversity, and contribute to retention of locally-distinctive habitats, potentially assuaging processes of biotic homogenisation (McKinney 2006). 'Ecomimicry' (Marshall 2007) offers a mechanism to achieve this approach; developed from the biomimicry ideology (Benyus 2002), ecomimicry considers local ecology as the basis for design and innovation. This is because flora, fauna and ecosystems characteristic of a region will have co-evolved with, and be adapted to, local conditions, and as such would be the most resilient to local environmental challenges (Marshall 2007). Adopting an ecomimicry approach to UGS design can enable locally-contextualised, biodiversity-focused UGS implementation that contributes to the functioning and resilience of urban areas through restoration of heterogeneous habitat resources.

3.3 Applying Ecomimicry: The Barking Riverside Wetland Green Roof Case Study

The concept of ecomimicry has been used to mitigate the loss of valuable brownfield sites to development in London, UK. In the London and East Thames Corridor region, brownfield sites (previously-developed land) have become important reservoirs for biodiversity that can no longer find suitable resources in the 'natural landscape' due to habitat loss or degradation (Harvey 2000). Their heterogeneous edaphic conditions and lack of frequent management result in unique habitat mosaics that are flower-rich and structurally diverse. Invertebrates particularly benefit from this as typically they need several habitat resources in close proximity to complete their complex lifecycles (Gibson 1998). Many species from deteriorating natural ecosystems, including nationally rare and scarce invertebrates, now depend on brownfield mosaics for their persistence because these can provide ecologically analogous functions to declining natural and semi-natural habitats such as chalk grassland and seasonal wetlands (Eversham et al. 1996). The conservation importance of biodiverse brownfield sites was recognised when Open Mosaic Habitat was designated a UK Biodiversity Action Plan Priority Habitat (Maddock 2010).

Despite increasing recognition of their nature conservation value, planning policy in the UK continues to target brownfield sites for redevelopment to meet the demands of growing urban communities (Robins et al. 2013). To help urban developments meet sustainability goals (United Nations 2015b), and ensure no-net-loss of biodiversity and ES (The European Commission 2012) in this development process, researchers are partnering developers to investigate targeted UGI solutions to compensate for the loss of brownfield habitat mosaics.

One such development is Barking Riverside, in the London Borough of Barking and Dagenham. Barking Riverside is a housing development being constructed on a large brownfield site of high biodiversity value. In recognition of this, planning consent for the development required conservation of key biodiversity through innovative UGI creation, in particular through provision of extensive green roofs (EGR). Such consent is linked to the Mayor of London guidance recommending green roofs on major developments for stormwater management and no-net-loss of biodiversity. The site was considered to be of regional importance for invertebrates, and these were a target faunal group for habitat compensation at roof level. As part of the EU FP7 project TURAS (http://www.turas-cities.org/), a Knowledge Transfer Partnership was established to trial biodiverse green roofs using a targeted brownfield habitat mosaic ecomimicry approach to design. Previous research indicated that green roofs designed using ecomimicry can perform as well as, or outperform, industry standard generic green roof systems for ES provision (Connop et al. 2013).

In order to apply ecomimicry, data from an extensive study of brownfield invertebrate assemblages on local brownfield sites was analysed using a pioneering invertebrate analysis tool (Webb and Lott 2006). This characterised the local habitat and identified key features of value to species in the region. The process identified ephemeral wetland as a key habitat niche for creation on EGRs to enhance their value for regionally important brownfield invertebrates (Figure 2).

Fig. 2. The brownfield mosaic ecomimicry extensive green roof included locally typical substrates to create heterogeneous thermal, moisture and organic conditions and encourage habitat mosaic development (a). These were applied in varied depths to create microtopography and structural diversity, to increase niches for plants and provide refugia for biota during hot, dry or cold spells. Locally-attuned, diverse wildflower assemblages were planted (b) to provide a broad range of foraging resources, and enhance habitat heterogeneity through structurally complex plant architecture. In addition, innovative drainage mechanisms were used to recreate seasonally wet brownfield habitat niches (c).

Within two years of construction, there were significant differences in plant development in the various habitat niches created by the ecomimicry design (Nash 2017). This approach made a positive contribution to creating a habitat mosaic with a novel wetland component. Almost half the invertebrate species recorded on the EGRs were designated as national nature conservation priorities, many being characteristic of the pre-development brownfield site at Barking Riverside. Using ecomimicry to read the local landscape and incorporating ecological understanding into the design made it possible to create locally-contextualised UGI of value to target biodiversity, and expand the range of habitat niches provided by standard EGR design approaches.

Whilst the design used for this case study may not be appropriate for all locations, the process of incorporating the floral diversity and habitat heterogeneity of locally important habitats into UGI design is universally applicable. Locally-contextualised and adapted UGI for locally important biodiversity is a successful renaturing strategy, making cities more permeable to biodiversity and conserving habitat connectivity and ES provision.

3.4 Summary

UGI represents a unique opportunity to improve the sustainability of our cities and the well-being of our communities (European Commission 2012), and to ensure that the urban fabric represents a rich source habitat for biodiversity (Pulliam 1988). This opportunity can be realised through a combination of creating networks of new UGS (e.g. green roofs, green walls, pocket parks and Sustainable Drainage Systems), and improving the multifunctionality of existing UGS (e.g. making better use of low value ecological/ES-providing open space in cities). It is not sufficient, however, to provide 'greenery' and assume that biodiversity benefits and associated ES will ensue (Connop et al. 2016). To unlock the full potential of such spaces, informed design must be used to create functioning ecosystems underpinned by broad biodiversity. From ecomimicry to ecotechnology, the range of tools provided by an ecological engineering approach represent mechanisms to achieve this potential.

Embedding such knowledge into UGI design by engineering a balance of art, ecology, aesthetics, and multifunctionality is now the great challenge facing nature-based solutions innovators. Such pioneering approaches coupled with financially sustainable models and co-creational method-ologies are beginning to emerge from a series of EU Horizon 2020 innovation projects such as CONNECTING Nature (www.connectingnature.eu). These projects provide a mechanism for transferring knowledge about nature-based solutions between the EU and other cities globally, ensuring the international outlook necessary for transferring the application of “renaturing”.

References

Adams LW (2005) Urban wildlife ecology and conservation:A brief history of the discipline. Urban Ecosyst 8:139–156 . doi: 10.1007/s11252-005-4377-7

Angeoletto F, Santos JWMC, Ruiz Sanz JP, et al (2016) Tipología socio-ambiental de las ciudades medias de Brasil: aportes para un desarrollo urbano sostenible. urbe Rev Bras Gestão Urbana 8:272–287 . doi: 10.1590/2175-3369.008.002.AO08

Angeoletto F, Sanz JPR, Albertin RM, Silva FF da (2017) The grass is always greener on the other side of the fence: the flora in urban backyards of different social classes. Ambient Soc 20:1–20 . doi: 10.1590/1809-4422asoc141293v2012017

Antonini Y, Martins RP, Aguiar LM, Loyola RD (2013) Richness, composition and trophic niche of stingless bee assemblages in urban forest remnants. Urban Ecosyst 16:527–541 . doi: 10.1007/s11252-012-0281-0

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

Averill C, Turner BL, Finzi AC (2014) Mycorrhiza-mediated competition between plants and decomposers drives soil carbon storage. Nature 505:543–545 . doi: 10.1038/nature12901

Baldock KCR, Goddard MA, Hicks DM, et al (2015) Where is the UK's pollinator biodiversity? The importance of urban areas for flower-visiting insects. Proceedings Biol Sci 282:20142849 . doi: 10.1098/rspb.2014.2849

Batten LA (1972) Breeding bird species diversity in relation to increasing

urbanisation. Bird Study 19:157–166 . doi: 10.1080/00063657209476337
Batten LA (1973) Population dynamics of suburban blackbirds. Bird Study 20:251–258 . doi: 10.1080/00063657309476389
Bellamy CC, van der Jagt APN, Barbour S, et al (2017) A spatial framework for targeting urban planning for pollinators and people with local stakeholders: A route to healthy, blossoming communities? Environ Res 158:255–268 . doi: 10.1016/j.envres.2017.06.023
Bennie J, Davies TW, Cruse D, et al (2018) Artificial light at night alters grassland vegetation species composition and phenology. J Appl Ecol 55:442–450 . doi: 10.1111/1365-2664.12927
Benyus JM (2002) Biomimicry: innovation inspired by nature, 2nd edn. Harper Collins, New York
Bonnington C, Gaston KJ, Evans KL (2013) Fearing the feline: Domestic cats reduce avian fecundity through trait-mediated indirect effects that increase nest predation by other species. J Appl Ecol 50:15–24 . doi: 10.1111/1365-2664.12025
Bradshaw AD, Chadwick MJ (1980) The restoration of land: The ecology and reclamation of derelict and degraded land. Blackwell Scientific Publications, Berkeley
Cadenasso ML, Pickett STA, Schwarz K (2007) Spatial heterogeneity in urban ecosystems: reconceptualizing land cover and a framework for classification. Front Ecol Environ 5:80–88 . doi: 10.1890/1540-9295(2007)5[80:SHIUER]2.0.CO;2

Cannon AR, Chamberlian DE, Toms MP, et al (2005) Trends in the use of private gardens by wild birds in Great Britain 1995-2002. J Appl Ecol 42:659–671 . doi: 10.1111/j.1365-2664.2005.01050.x

Chong KY, Teo S, Kurukulasuriya B, et al (2014) Not all green is as good: Different effects of the natural and cultivated components of urban vegetation on bird and butterfly diversity. Biol Conserv 171:299–309 . doi: 10.1016/J.BIOCON.2014.01.037

Collier MJ, Nedović-Budić Z, Aerts J, et al (2013) Transitioning to resilience and sustainability in urban communities. Cities 32:S21–S28 . doi: 10.1016/J.CITIES.2013.03.010

Connop S, Gedge D, Kadas G, et al (2013) TURAS green roof design guidelines: Maximising ecosystem service provision through regional design for biodiversity. University of East London, London

Connop S, Vandergert P, Eisenberg B, et al (2016) Renaturing cities using a regionally-focused biodiversity-led multifunctional benefits approach to urban green infrastructure. Environ Sci Policy 62:99–111 . doi: 10.1016/J.ENVSCI.2016.01.013

Constanza R, de Groot R, Sutton P, et al (2014) Changes in the global value of ecosystem services. Glob Environ Chang 26:152–158 . doi: 10.1016/J.GLOENVCHA.2014.04.002

Cox DTC, Hudson HL, Shanahan DF, et al (2017) The rarity of direct experiences of nature in an urban population. Landsc Urban Plan 160:79–84 . doi: 10.1016/J.LANDURBPLAN.2016.12.006

Cramp S (1980) Changes in the breeding birds of Inner London since 1900. In: Symposium on Urbanization.
Dallimer M, Irvine KN, Skinner AMJ, et al (2012) Biodiversity and the feel-good factor: Understanding associations between self-reported human well-being and species richness. Bioscience 62:47–55 . doi: 10.1525/bio.2012.62.1.9
Dallimer M, Tang Z, Bibby PR, et al (2011) Temporal changes in greenspace in a highly urbanized region. Biol Lett 7:763–766 . doi: 10.1098/rsbl.2011.0025
Davies ZG, Edmondson JL, Heinemeyer A, et al (2011) Mapping an urban ecosystem service: quantifying above-ground carbon storage at a city-wide scale. J Appl Ecol 48:1125–1134 . doi: 10.1111/j.1365-2664.2011.02021.x
Davis BNK (1976) Wildlife, urbanisation and industry. Biol Conserv 10:249–291 . doi: 10.1016/0006-3207(76)90002-1
Duarte TEP, Angeoletto FHS, Correa Santos JWM, et al (2017) O Papel da Cobertura Vegetal nos Ambientes Urbanos e sua Influência na Qualidade de Vida nas Cidades. Desenvolv em Questão 15:175 . doi: 10.21527/2237-6453.2017.40.175-203
Dunn RR, Gavin MC, Sanchez MC, Solomon JN (2006) The Pigeon Paradox: Dependence of Global Conservation on Urban Nature. Conserv Biol 20:1814–1816 . doi: 10.2307/4124710
Dunnett N, Kingsbury N (2004) Planting Green Roofs and Living Walls.

Timber Press, Portland (OR)
Edgington J (2008) Lepidopterists through the lens: portraits from the first fifty years of the LNHS. London Nat 87:123–132
Edmondson JL, Stott I, Davies ZG, et al (2016) Soil surface temperatures reveal moderation of the urban heat island effect by trees and shrubs. Sci Rep 6:33708 . doi: 10.1038/srep33708
European Commission (2012) The Multifunctionality of Green Infrastructure. Brussels
Evans J (2004) What is local about local environmental governance? Observations from the local biodiversity action planning process. Area 36:270–279 . doi: 10.1111/j.0004-0894.2004.00224.x
Eversham BC, Roy DB, Telfer MG (1996) Urban, industrial and other manmade sites as analogues of natural habitats for Carabidae. Ann. Zool. Fennici 33:149–156
Farias AR (2017) Identificação, mapeamento e quantificação das áreas urbanas do Brasil. In: Embrapa Gestão Territorial-Comunicado Técnico (INFOTECA-E)
Fitter RSR (1945) London’s Natural History. Collins, London
Fontana CS, Burger MI, Magnusson WE (2011) Bird diversity in a subtropical South-American City: effects of noise levels, arborisation and human population density. Urban Ecosyst 14:341–360 . doi: 10.1007/s11252-011-0156-9
Frearson A (2012) Gardens by the Bay by Grant Associates and Wilkinson

Eyre Architects. Dezeen Mag.
Gaston KJ, Ávila-Jiménez ML, Edmondson JL (2013) REVIEW: Managing urban ecosystems for goods and services. J Appl Ecol 50:830–840 . doi: 10.1111/1365-2664.12087
Gibson CWD (1998) Brownfield: red data – the values artificial habitats have for uncommon invertebrates. English Nature Research Report No. 273. Peterborough
Gilbert O (1989) The ecology of urban habitats. Chapman and Hall, London
Gilbert O (1983) The wildlife of Britain's wasteland. New Sci 67:824–829
Gomes MAS, Amorim MCCTA (2002) As pracas publicas de Presidente Prudente/SP:dinamica socio-espacial e caracterizacao da vegetacao. Geogr em Atos 1:21–37
Goode DA (1989) Urban Nature Conservation in Britain. J Appl Ecol 26:859 . doi: 10.2307/2403697
Goode DA (2014) Nature in towns and cities. William Collins, New York
Grimm NB, Grove JG, Pickett STA, Redman CL (2000) Integrated approaches to long-term studies of urban ecological systems: Urban ecological systems present multiple challenges to ecologists—pervasive human impact and extreme heterogeneity of cities, and the need to integrate social and ecological approach. Bioscience 50:571–584 . doi: 10.1641/0006-3568(2000)050[0571:IATLTO]2.0.CO;2
Guadagnin DL, Gravato ICF (2009) Value of Brazilian environmental

legislation to conserve biodiversity in suburban areas. A case study in Porto Alegre, Brazil. Nat Conserv 7:133–145
Hahs AK, McDonnell MJ, McCarthy MA, et al (2009) A global synthesis of plant extinction rates in urban areas. Ecol Lett 12:1165–1173 . doi: 10.1111/j.1461-0248.2009.01372.x
Harris S (1977) Distribution, habitat utilization and age structure of a suburban fox (Vulpes vulpes) population. Mamm Rev 7:25–38 . doi: 10.1111/j.1365-2907.1977.tb00360.x
Hartig T, Mitchell R, de Vries S, Frumkin H (2014) Nature and Health. Annu Rev Public Health 35:207–228 . doi: 10.1146/annurev-publhealth-032013-182443
Harvey PR (2000) The East Thames Corridor: A nationally important invertebrate fauna under threat. Br Wildl 91–98
Hector A, Bagchi R (2007) Biodiversity and ecosystem multifunctionality. Nature 448:188–190 . doi: 10.1038/nature05947
Kettlewell HBD (1955) Selection experiments on industrial melanism in the Lepidoptera. Heredity (Edinb) 9:323–342 . doi: 10.1038/hdy.1955.36
Lekberg Y, Rosendahl S, Olsson PA (2015) The fungal perspective of arbuscular mycorrhizal colonization in “nonmycorrhizal” plants. New Phytol 205:1399–1403 . doi: 10.1111/nph.13118
Lepczyk CA, Aronson MFJ, Evans KL, et al (2017) Biodiversity in the city: Fundamental questions for understanding the ecology of urban green spaces for biodiversity conservation. Bioscience 67:799–807 . doi:

10.1093/biosci/bix079
Lessi BF, Pires JSR, Batisteli AF, MacGregor-Fors I (2016) Vegetation, urbanization, and bird richness in a brazilian peri-urban area. Ornitol Neotrop 27:203–210
Lombardo MA (1985) Ilha de Calor nas Metrópoles: o exemplo de São Paulo. Editora. Hucitec., Sao Paulo
Loram A, Thompson K, Warren PH, Gaston KJ (2008) Urban domestic gardens (XII): The richness and composition of the flora in five UK cities. J Veg Sci 19:321–330 . doi: 10.3170/2008-8-18373
Lye GC, Osborne JL, Park KJ, Goulson D (2008) Using citizen science to monitor Bombus populations in the UK: nesting ecology and relative abundance in the urban environment. J Insect Conserv 12:696–707 . doi: 10.1007/s10841-011-9450-3
Mabey R (2010) The unofficial countryside. Little Toller Books, Dorchester
MacArthur RH, MacArthur JW (1961) On bird species diversity. Ecology 42:594–598 . doi: 10.2307/1932254
Mace GM, Norris K, Fitter AH (2012) Biodiversity and ecosystem services: A multilayered relationship. Trends Ecol Evol 27:19–26 . doi: 10.1016/J.TREE.2011.08.006
Maddock A (2010) UK Biodiversity Action Plan; Priority Habitat Descriptions - Open Mosaic Habitats on Previously Developed Land
Marshall M (2007) The theory and practice of ecomimicry. Working Paper Series: no. 3. Curtin

Martin LJ, Blossey B, Ellis E (2012) Mapping where ecologists work: biases in the global distribution of terrestrial ecological observations. Front Ecol Environ 10:195–201 . doi: 10.1890/110154

McKinney ML (2008) Effects of urbanization on species richness: A review of plants and animals. Urban Ecosyst 11:161–176 . doi: 10.1007/s11252-007-0045-4

McKinney ML (2006) Urbanization as a major cause of biotic homogenization. Biol Conserv 127:247–260 . doi: 10.1016/J.BIOCON.2005.09.005

MEA (2005) Millenium Ecosystem Assessment Synthesis Report. Washington DC

Mitsch WJ (2012) What is ecological engineering? Ecol Eng 45:5–12 . doi: 10.1016/j.ecoleng.2012.04.013

Nafilyan V (2015) UK Natural Capital–Land Cover in the UK. Office for National Statistics. https://www.ons.gov.uk/economy/environmentalaccounts/articles/uknaturalcapitallandcoverintheuk/2015-03-17

Nash C (2017) Brownfield-inspired green infrastructure: a new approach to urban biodiversity conservation. University of East London

Nilon CH, Aronson MFJ, Cilliers SS, et al (2017) Planning for the Future of Urban Biodiversity: A Global Review of City-Scale Initiatives. Bioscience 67:332–342 . doi: 10.1093/biosci/bix012

Nunes H, Rocha FL, Cordeiro-Estrela P (2017) Bats in urban areas of Brazil:

roosts, food resources and parasites in disturbed environments. Urban Ecosyst 20:953–969 . doi: 10.1007/s11252-016-0632-3
Owen J (2010) Wildlife of a garden : a thirty-year study. Royal Horticultural Society
Pacheco R, Vasconcelos HL (2007) Invertebrate conservation in urban areas: Ants in the Brazilian Cerrado. Landsc Urban Plan 81:193–199 . doi: 10.1016/J.LANDURBPLAN.2006.11.004
Pauleit S, Duhme F (2000) Assessing the environmental performance of land cover types for urban planning. Landsc Urban Plan 52:1–20 . doi: 10.1016/S0169-2046(00)00109-2
Peck SW (2017) The Evolution of the Awards of Excellence Winning California Academy of Sciences. Living Archit. Monit. 23–24
Pulliam HR (1988) Sources, Sinks, and Population Regulation. Am Nat 132:652–661 . doi: 10.1086/284880
Reis E, López-Iborra GM, Pinheiro RT (2012) Changes in bird species richness through different levels of urbanization: Implications for biodiversity conservation and garden design in Central Brazil. Landsc Urban Plan 107:31–42 . doi: 10.1016/J.LANDURBPLAN.2012.04.009
Robins J, Henshall S, Farr A (2013) The state of brownfields in the Thames Gateway. Essex Nat 29:77–88
Ruiz-Lozano JM, Aroca R, Zamarreño ÁM, et al (2016) Arbuscular mycorrhizal symbiosis induces strigolactone biosynthesis under drought and improves drought tolerance in lettuce and tomato. Plant Cell Environ

39:441–452 . doi: 10.1111/pce.12631

Salisbury EJ (1943) The flora of bombed areas. Nature 151:462–466

Secretariat of the Convention on Biological Diversity (2012) Cities and biodiversity outlook. Montreal

Song Y, Chen D, Lu K, et al (2015) Enhanced tomato disease resistance primed by arbuscular mycorrhizal fungus. Front Plant Sci 6:786 . doi: 10.3389/fpls.2015.00786

Southon GE, Jorgensen A, Dunnett N, et al (2017) Biodiverse perennial meadows have aesthetic value and increase residents' perceptions of site quality in urban green-space. Landsc Urban Plan 158:105–118 . doi: 10.1016/J.LANDURBPLAN.2016.08.003

Terradas J (2001) Ecología Urbana. Editorial Rubes, Barcelona

Tews J, Brose U, Grimm V, et al (2004) Animal species diversity driven by habitat heterogeneity/diversity: the importance of keystone structures. J Biogeogr 31:79–92 . doi: 10.1046/j.0305-0270.2003.00994.x

The European Commission (2012) The EU Biodiversity Strategy to 2020. doi: 10.2779/39229

The World Bank (2017) World Urbanization Prospects. https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS. Accessed 11 Dec 2017

Thompson K, Austin KC, Smith RM, et al (2003) Urban Domestic Gardens (I): Putting Small-Scale Plant Diversity in Context. J. Veg. Sci. 14:71–78

Todd J, Brown EJG, Wells E (2003) Ecological design applied. Ecol Eng

20:421–440 . doi: 10.1016/J.ECOLENG.2003.08.004
Toledo MCB, Donatelli RJ (2010) Spectral analysis of flowers used by nectar-feeding birds in an urban area in Southeastern Brazil. Braz J Biol 70:729–35
Tratalos J, Fuller RA, Warren PH, et al (2007) Urban form, biodiversity potential and ecosystem services. Landsc Urban Plan 83:308–317 . doi: 10.1016/J.LANDURBPLAN.2007.05.003
United Nations (2015a) Resolution adopted by the General Assembly on 25 September 2015. Transforming our world: the 2030 agenda for sustainable development. New York
United Nations (2016) Draft outcome document of the United Nations Conference on Housing and Sustainable Urban Development (Habitat III). New York
United Nations (2015b) Transforming our world: the 2030 agenda for sustainable development: Sustainable development knowledge platform. New York
Webb JR, Lott DA (2006) The development of ISIS: A habitat-based invertebrate assemblage classification system for assessing conservation interest in England. J Insect Conserv 10:179–188 . doi: 10.1007/s10841-006-6292-5
Wilson EO (1984) Biophilia. Harvard University Press, Cambridge (MA)
Zhao S, Lian F, Duo L (2011) EDTA-assisted phytoextraction of heavy metals by turfgrass from municipal solid waste compost using permeable

barriers and associated potential leaching risk. Bioresour Technol 102:621–626 . doi: 10.1016/J.BIORTECH.2010.08.006