GREEN CITIES IN THE WORLD

Progression Innovation Organization

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CHAPTER 6
THE POTENTIAL OF GREEN ROOFS TO SUPPORT URBAN BIODIVERSITY

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ABSTRACT

Loss of biodiversity, including loss of ecosystems, species, and genes, has been documented at alarming rates with urbanization identified as one of the most influential causes. Biodiversity in urban areas is now more homogenous across cities and unique specialist species are rare. In the face of enormous habitat changes, initial studies suggest that green roofs have the potential to support greater biodiversity by creating unique habitats, providing ecosystem services and expanding urban corridors. However, the work to date has focused at the species level and the full scope of biodiversity on green roofs has yet to be realized. Recommendations are made in this chapter for encouraging the inclusion of biodiversity at all levels into green roof design and city planning.

KEY WORDS
Biodiversity, conservation, diversity, green infrastructure, green roof, urbanization.

1. BACKGROUND: THE NEED TO CONSERVE BIODIVERSITY IN URBAN AREAS

1.1. Biodiversity

In cities around the world the argument that green roofs enhance urban biodiversity is increasingly being used to attract funding and public support for their construction. However, the term 'biodiversity' is not always used correctly or with the full realization of the complexities encompassing its various measures. In order to encourage more widespread adoption of biodiversity conservation on green roofs, it is first essential to develop a working understanding of all that encompasses biodiversity.

The term biodiversity was used for the first time in 1986 at the National Forum on BioDiversity in Washington, D.C. (Harper & Hawsworth 1994). The term has grown in popularity since then and is now used extensively in academic publications and throughout the general media.
1.2. Effects of urbanization on biodiversity

Human activities have contributed to a greater loss of biodiversity on Earth over the past 50 years than at any other time period in human history (Millennium Ecosystem Assessment 2005). Current projections reveal alarming scenarios for increased rates of biodiversity loss around the world (Millennium Ecosystem Assessment 2005). Urbanization has both direct and indirect effects on local, regional, and global biodiversity, the largest and most direct being the transformation and loss of natural habitat (Sala et al. 2000; Millennium Ecosystem
Assessment 2005; Hahs et al. 2009; Gregor et al. 2012; McDonald et al. 2013). Land transformation removes natural vegetation and fragments communities (Güneralp et al. 2013; Müller et al. 2013). Remaining habitat fragments generally have altered microclimate characteristics, such as increased edge effects, changes in disturbance regimes, altered nutrient cycling and perturbations in population dynamics (Hahs et al. 2009; Solecki & Marcotullio 2013). Over the next few decades, land conversion is expected to displace thousands of plant and animal species, including hundreds already on the International Union for Conservation of Nature Endangered or Critically Endangered Lists (Seto et al. 2012). In addition to global species extinctions, many other species will also become endangered and/or locally extinct (extripated).

In addition to the loss of species and habitat, the resulting increase in heterogeneously arranged habitat fragments can disrupt ecological pathways (Müller et al. 2013) such as migration, seed dispersal and gene flow (McDonald et al. 2013). Land use changes also indirectly affect communities by contributing to climate change and urban heat islands (Millennium Ecosystem Assessment 2005; Elmqvist, et al. 2013; Güneralp et al. 2013; Müller et al. 2013; Solecki & Marcotullio 2013). Increased pollution, dominance of invasive species and overexploitation of resources (Millennium Ecosystem Assessment 2005), as well as changes in hydrology and soil biogeochemistry (Güneralp et al. 2013) make urban habitats difficult living environments for many organisms. The combination of the many direct and indirect consequences of urbanization can ultimately decrease the robustness and resiliency of biodiversity worldwide.

Urbanization is projected to expand over the next few decades and pose an intensified threat to biodiversity (McKinney 2002). Compared to 2000, the extent of global urban
land cover is projected to increase by up to 185% by 2030 (Secretariat of the Convention on Biological Diversity 2012; Seto et al. 2012). Recent estimates suggest that the number of people living in urban areas globally will double between 2000 and 2030 and urban land area will triple in order to accommodate the high demand for living space (Elmqvist et al. 2013). This is particularly true in areas considered to have the highest amount of biodiversity (hotspots) and in rapidly developing regions of Asia (Miller & Hobbs 2002; McKinney 2006; Seto et al. 2012; Secretariat of the Convention on Biological Diversity 2012; Güneralp et al. 2013). The opportunity exists now for all nations to incorporate explicit biodiversity conservation goals for novel urban habitats into their future plans.

1.3. Biodiversity in urban landscapes

The Millennium Ecosystem Assessment stresses that the need for conservation of biodiversity must extend beyond nature reserves to include all urban areas (Millennium Ecosystem Assessment 2005). While it is generally known that urbanization affects global biodiversity, only recently have researchers begun to understand the ecological processes that support biodiversity within cities (Millennium Ecosystem Assessment 2005). It is clear that urbanization negatively influences biodiversity by supporting more exotic species and promoting global homogenization of plants and animals. However, cities also harbor distinctly urban habitats, such as green roofs, which may support many species with unique traits.

Globally, cities have experienced high extinction rates of many plant species (McKinney 2006; Hahs et al. 2009; Duncan et al. 2011). A decrease in native flora in urban habitats can lead to further cascades of species loss for both above and below-ground fauna at local and regional spatial scales (Faeth et al. 2005; Chace & Walsh 2006; Tallamy 2007; Blair & Johnson 2008; Walker et al. 2009; Faeth et al. 2011). For example, the proportion of native plants in urban and suburban tends to be positively correlated with the diversity of native birds (Munyenyembe et al. 1989; French et al. 2005; Chace & Walsh 2006; Burghardt et al. 2009) and insects (Crisp et al. 1998; Burghardt et al. 2009). Pollinating insects can be particularly affected because they may be able to use the pollen and nectar resources more effectively from native plant species than from non-native species (Corbet et al. 2001). In addition to loss of species, loss of genetic diversity within populations can threaten ecosystem resiliency by decreasing the number of species able to survive or recolonize after predation, disease or environmental stressors which cause local extinction events; a problem intensified in highly disturbed urban environments (Olden et al. 2004).

One common trend observed in cities associated with a decreased proportion of native species is a corresponding increase in non-natives (Secretariat of the Convention on Biological Diversity 2012). The high taxonomic richness observed in many cities is inflated by common non-native urban species (McKinney 2006; McKinney 2008; Shochat et al. 2010; Gregor et al. 2012; McDonald et al. 2013), which is the
reason urban centers can have higher species richness of plants and animals than surrounding areas (Walker et al. 2009; Faeth et al. 2011). A commonly found set of non-native plant and animal species is now found in cities across the world (for example, the common urban rat, *Rattus norvegicus*, and city pigeon, *Columbia livia*), a pattern called biotic homogenization (Olden et al. 2004). Non-native species richness increases along gradients of both disturbance and urbanization, a trend exacerbated by the globalization of horticultural trade (Müller et al. 2013). In some cities, up to 50% of the species in the urban core or city center are non-native (McKinney 2002; Dunn & Heneghan 2011; McDonald et al. 2013). For example, about a third of all plant species in New York City, Tianjin and Warsaw were found to be non-native and about 50% of plant species were non-native in Dublin, Boston and London (Dunn & Heneghan 2011). Though conservation of common species in cities is important, increased consideration must be given to the species that have or are becoming rare in their natural ranges due to the pressures imposed by urbanization.

2. USING GREEN ROOFS TO ACHIEVE BIODIVERSITY CONSERVATION GOALS

As cities around the world continue to develop technology and infrastructure using environmentally conscious materials and methods (Blaustein 2013), vegetated surfaces have the potential to play an increasingly important role in reconciliation ecology and urban biodiversity conservation (Francis & Lorimer 2011). The principles of reconciliation ecology encourage the design of anthropogenically-dominated landscapes to include considerations for a wide variety of organisms (Rosenzweig 2003). Each year, more urban habitats are designed following these principles, providing a wider variety of ecosystem services and increasing public awareness of biodiversity (Miller 2005). Extensive green roofs, or buildings designed specifically to incorporate a shallow layer of growing media and plants, continue to become more numerous and widely distributed globally (Greenroofs.com 2013). Recent studies in urban ecology suggest that although small habitat patches in cities are subject to extreme environmental stressors, they have the potential to support many elements of biodiversity and should not be overlooked for their conservation value (Miller & Hobbs 2002). Green roofs represent novel habitats in the urban environment and can contribute to the goals of reconciliation ecology by increasing the availability of living space for a variety of organisms (Francis & Lorimer 2011).
2.1. Ecosystem diversity

When green roofs are installed, they create unique habitats on what is often otherwise unutilized space (Francis & Lorimer 2011). It is clear that these novel systems provide a variety of environmental benefits including stormwater capture and retention (Getter & Rowe 2006; Mentens et al. 2006; Carter & Butler 2008; Dunnett, Nagase, Booth, et al. 2008; MacIvor et al. 2011; Schroll et al. 2011; Nagase & Dunnett 2012), pollution abatement (Rowe 2011), thermal insulation of buildings (Getter & Rowe 2006; Carter & Butler 2008; Spala et al. 2008), and mitigation of the urban heat island effect through evaporative cooling. These beneficial aspects of green roofs can indirectly support a variety of organisms in the urban environment.

Green roofs can also directly support organisms by providing unique habitat. Conditions on green roofs are hotter, drier and windier compared to the ground level (Monterusso et al. 2005; Carter & Butler 2008; Nagase & Dunnett 2010; MacIvor et al. 2011). The particular ecosystem on green roofs therefore represents an extreme of local conditions, which can benefit a subset of local species. By supporting small communities, green roofs can serve as an important component of a larger heterogeneous meta-community, increasing the total richness and diversity of species that can use the urban landscape. Some green roofs are now designed to mimic natural habitats which share similar harsh environmental properties in hopes of providing alternatives to in situ conservation of some species (Lundholm 2004; Catalano et al. 2013). This type of design allows green roofs to support unique plant and animal species that would not otherwise be found in the urban environment. If designed with specific ecological goals in mind, green roofs have the potential to support an even greater diversity of local native organisms and processes ex situ, thereby slowing biodiversity loss (McKinney 2006).

2.2. Species diversity

Genetic homogenization can threaten ecosystem resiliency by decreasing the number of species able to survive or recolonize after predation, disease, or environmental stressors which cause local extinction events; a problem intensified in highly disturbed urban environments (Olden et al. 2004). In ecology, the widely known theory of island biogeography states that patch (habitat) area often affects species diversity and abundance, with an expectation that smaller patches will have lower taxonomic diversity than larger patches (MacArthur & Wilson 1967). As many green roofs are small compared to city parks or preserved areas, species diversity on roofs is assumed to be low. However, distinctly urban habitats such as preserves, wastelands and vacant lots can significantly contribute to species diversity and richness (Lawson et al. 2008; Müller et al. 2013) and in some cases may even be optimal for population persistence or species survival (McCarthy et al. 2006). In contrast to principles suggested by island biogeography theory, the richness of usable urban habitats has been found to be a more important predictor of bird diversity than patch shape or patch size (Donnelly & Marzluff 2006). Comprehensive studies thus far reveal...
no correlation between green roof size and species abundance or diversity (Braaker et al. 2013), suggesting that green roofs of all sizes have the potential to sustain high species diversity in cities.

2.3. Genetic diversity

Extinction of species can occur due to a loss of genetic diversity, which tends to be lower in small populations (Spielman et al. 2004). Genetic diversity can be particularly important to species on green roofs, where environmental pressures can be even more extreme than on the ground and local extinction events are likely (Lundholm 2004; Monterusso et al. 2005; Getter & Rowe 2006; Maclvor et al. 2011; Rowe et al. 2012). Low genetic diversity is particularly an issue when green roofs are planted with nursery-grown species, which generally have low genetic diversity and may even be clonal in the case of vegetatively-propagated varieties. Scientific research has yet to demonstrate that plant populations on green roofs possess the genetic diversity needed to respond to severe environmental stressors.

Although few urban gardens and even fewer green roofs are designed with habitat connectivity in mind (Quigley 2011), urban planners could encourage installation of vegetated roofs on buildings near larger green spaces, directly supporting ecological land-use connectivity designs (Colding 2007; Jim 2013). Green roof organisms likely contribute to urban metapopulations, being colonized by individuals from the larger urban population as well as colonizing other nearby areas. With an increased focus on ecology in urban planning, structures could be arranged intentionally to encourage interaction between patches and promote gene flow and migration, thereby increasing habitat resilience and supporting all aspects of urban biodiversity: ecosystem, species, and genetic diversity. Cities that already have expansive green networks, such as Singapore (Tan 2006), could easily incorporate green roofs into their strategies for habitat
Connectivity and biodiversity support. Connectivity through gene flow may be a way of preventing genetic decline and promote long-term reproductive success of small fragmented populations (Frankham et al. 2007; González-Varo et al. 2009). Consequently, a well-connected network of urban patches is important to maintain genetic diversity within populations and build community resiliency. Previous studies of urban gardens and backyards have found that small patches can form habitat networks (Elle et al. 2012; Rudd et al. 2002) which allow small populations to possess increased genetic diversity from pollen movement or migration (McIntyre 2000). Patch connectedness can provide stepping-stone habitats for foraging insects which can, in turn, increase total gene flow (Van Rossum & Triest 2012). Increased green roof connectivity could allow a larger variety of organisms with limited mobility to contribute to genetically diverse populations. As the number of green roofs across a city increases, each site has the potential to be part of well-connected urban corridors and metapopulations.

2.4. Challenges

Although there is great potential for green roofs to promote biodiversity, achieving this goal may not be easy. Access to best practices for utilizing green infrastructure to conserve biodiversity is only now becoming more widely available (Sandström et al. 2006; Müller et al. 2013). More importantly, most green roofs are not designed with biodiversity considerations as main objectives (Quigley 2011). While green roofs provide an increase in floral habitat compared to a traditional shingled or tar roof, green roofs are likely to be planted with non-native species (Snodgrass & Snodgrass 2006) which lack genetic diversity and may not provide adequate
resources to support larger faunal communities. Despite increasing local taxonomic plant diversity, green roofs can contribute to biotic homogenization and therefore decrease biodiversity on a global scale when installed without concern for biodiversity. This could be particularly problematic as many green roofs are not taxonomically diverse, often consisting mainly of succulent orpine species (Crassulaceae), or even species exclusively from the genus Sedum (Dunnett & Kingsbury 2004; Snodgrass & Snodgrass 2006). Quickly spreading succulents can contribute to ecological function by facilitating the growth of neighboring forbs with high ecological value (Butler & Orians 2011) and providing quick protection of important soil biota, such as springtails (Collembolans) (Schrader & Böning 2006). Designing roofs dominated by a few plant families may also meet the need to provide an aesthetically-pleasing visual display and ecosystem services such as stormwater retention. However, green roofs planted with a low diversity of species does not necessarily contribute to biodiversity, particularly as many of the “tried and true” species or varieties used globally are rarely locally endemic. As green roof technology continues to develop, more green roofs are being designed to include a wider variety of native plant species (Butler et al. 2012), echoing the current trend of using more native plants in urban landscaping in general (Müller et al. 2013). Some locally native species may not be appropriate for use on green roofs due to an increased risk of drought, higher wind, and decreased winter soil temperature (Monterusso et al. 2005; Carter & Butler 2008; Nagase & Dunnett 2010; Maclvor et al. 2011). However, despite these limitations, there are numerous species that thrive under natural conditions similar to those encountered on green roofs and can be used to overcome the limitations of monocultures or low-diversity communities. For example, several species from coastal barrens, cliff faces and rock outcrops thrive on green roofs in Canada (Lundholm & Richardson 2010; Maclvor et al. 2011) and Australia (Farrell et al. 2012; Farrell et al. 2013) and many species from dry prairies thrive on green roofs in the central United States (Dvorak & Carroll 2008; Dvorak & Volder 2010; Dvorak et al. 2012). Planting green roofs with plants of high functional, taxonomic and genetic diversity on green roofs is one way to begin achieving biodiversity conservation goals.

Contrary to common assumptions that vegetated roofs adequately support higher trophic levels and all aspects of biodiversity (Oberndorfer et al. 2007), not all instances of plants growing on green roofs ensure a rich and diverse faunal community. Principles of restoration ecology dictate that compositional and functional diversity will not necessarily self-assemble if one simply provides the physical structure (Quigley 2011), a prevalent notion described as the field of dreams myth (i.e. “if you build it, they will come”) (Hilderbrand et al. 2005). Furthermore, many building owners expect that their green roof will retain all of the qualities of function and aesthetics over the life-span of the roof, ignoring any natural ecological successional processes. As with other urban ecosystems, floral, faunal, fungal and microbial communities will develop through various stages of ecological successional, particularly because many green roofs are undisturbed habitats (Collins et al. 2000; McKinney 2002). But when these natural processes are suppressed by weeding, watering, addition or movement of certain species, changing out of growing media, or simply by designing the habitat to support a limited number of species (e.g. Sedum), it is unlikely that more complex ecosystems will develop. Creating the correct physical conditions on a green roof which support all aspects of biodiversity is an important first step which must be followed by encouraging colonization by a taxonomically and genetically diverse assemblage of species. Habitat creation is not a simple task but, over time, the dynamic system can change in response to external pressures and the overall community structure can develop into one that helps mitigate biodiversity loss and/or contributes to its conservation.
2.5. Current findings of green roof biodiversity research

Studies regarding green roof biodiversity are now more common and widespread, at least at the level of species diversity. In the absence of intense management, green roof plant diversity can increase over time as species colonize from the surrounding environment (Köhler 2006; Dunnett, Nagase & Hallam 2008; Köhler & Poll 2010; Bates et al. 2013). Increased plant diversity is likely to correspond to an increase in arthropod diversity (McIntyre 2000). When plants with a wide breadth of functional diversity are used, green roofs can provide a higher degree of ecosystem services (Cook-Patton & Bauerle 2012) including better building cooling and insulation (Lundholm et al. 2010), a higher reduction in harmful nitrogenous runoff from roofs (Aitkenhead-Peterson et al. 2010), and greater capture and retention of stormwater (Dunnett, Nagase, Booth, et al. 2008; Anderson et al. 2010; Lundholm et al. 2010; Nagase & Dunnett 2012). Although general urban ecology research suggests that a positive relationship between plant diversity and overall biodiversity exists (Andow 1991; Siemann et al. 1998; Haddad et al. 2001), this relationship has yet to be directly demonstrated on green roofs (Cook-Patton & Bauerle 2012).

In a recent review, Cook-Patton and Bauerle (2012) identified three specific ways in which increasing the structural and functional diversity of plants on green roofs could directly enhance urban biodiversity: (1) the increase in primary productivity of plant species creates a larger food web base, thereby supporting greater faunal abundance and richness; (2) more rare and specialized fauna are supported by unique plant species; and (3) greater temporal availability of food sources supports a wider variety of resource-dependent faunal species, such as pollinators. The first two points highlight opportunities to increase taxonomic diversity while the third highlights contributions to ecosystem functions; in the case of pollination, longer periods of resource availability supports increased foraging and therefore higher genetic diversity. More research is needed to confirm these hypotheses and move beyond knowledge of the mere presence of plant and animal species to a broader, more comprehensive understanding of the ecological processes occurring on green roofs and to determine if patterns observed in natural systems are found in the green roof environment as well.

To begin assessing the current state of biodiversity conservation on green roofs, research regarding faunal taxonomic diversity is now being carried out in many regions. Green roof habitats are used by a variety of mobile organisms including many native and non-native species of birds (Burgess 2004; Baumann 2006; Grant 2006; Fernandez-Canero & Gonzalez-Redondo 2010; Ishimatsu & Ito 2013; Livingroofs.org 2013). For example, in the United Kingdom, green roofs have been incorporated into the London Biodiversity Action Plan to help provide nesting sites for the rare black redstart *Phoenicurus ochruros* which can use the many herbaceous roofs for nesting as well as foraging (Burgess 2004; Gedge & Kadas 2005; Ishimatsu & Ito 2013, Livingroofs.org 2013). Food sources for the black redstart as well as many other bird species include fruits and seeds provided by the diverse vegetation as well as insects and other invertebrates such as mollusks (Kadas 2006). An increase in plant species diversity on green roofs has the potential to provide a temporally-expanded variety of resources to many different foragers.

In addition to vertebrates, a large variety of invertebrates visits and colonizes green roofs (Mecke & Grimm 1997; Mann 1998; MacIvor & Lundholm 2010; Coffman & Waite 2011; Schindler et al. 2011; Braaker et al. 2013; Madre et al. 2013). Though the research is still nascent, evidence suggests that arthropod species abundance and diversity is influenced by abiotic properties of the roof such as substrate depth and structure (Jones 2002). Vegetation strata may also affect patterns of invertebrate colonization (Madre et al. 2013), although it is difficult in some cases to separate the influence...
of abiotic variables completely from the influence of vegetation (Kaupp et al. 2004). For example, greater invertebrate species diversity has been found on green roofs designed to mimic brownfields compared to green roofs planted with mostly Sedum (Kadas 2006). Similarly, vegetation cover (Schindler et al. 2011) and complexity (Madre et al. 2013) are both positively correlated with arthropod species diversity and abundance on green roofs. While rigorous analyses and conclusions regarding the functional or genetic diversity of invertebrate communities are yet unknown, a taxonomic overview now provides information about the types of organisms that use green roofs.

Over the past decade, several investigations of green roofs throughout Europe and North America have confirmed the presence of hundreds of species of beetles (Mecke & Grimm 1997; Jones 2002; Maclvor & Lundholm 2010; Coffman & Waite 2011; Schindler et al. 2011; Braaker et al. 2013; Madre et al. 2013; Meierhofer 2013) and spiders (Brenneisen & Hänggi 2006; Kadas 2006; Madre et al. 2013; Braaker et al. 2013), including species that are rare, endangered or previously unknown to the region (Jones 2002; Kaupp et al. 2004; Gedge & Kadas 2005; Brenneisen & Hänggi 2006). Few studies have also investigated the properties of the roofs or the vegetation that influence the arthropod community diversity but those that have, reveal that site characteristics are important in shaping beetle and spider communities (Braaker et al. 2013). For example, Kaupp et al. (2004) found that beetle species richness was correlated with the successional stage of the vegetation community on green
roofs, whereby both beetle species richness and activity level was highest on old, grass-dominated roofs compared to young, sparsely vegetated roofs or older roofs colonized primarily by Sedum species. Furthermore, this study revealed that vegetation cover alone does not predict beetle species richness on green roofs and that having a mosaic of both vegetated and non-vegetated areas supports a larger variety of fauna, including more rare and endangered species.

Not surprisingly, many species of pollinating wasps and bees, including rare and endangered species (Brenneisen 2005) also make use of green roofs (Mann 1998; Colla et al. 2009; MacIvor & Lundholm 2010; Coffman & Waite 2011; Schindler et al. 2011; Toni et al. 2011; Ksiazek et al. 2012; Braaker et al. 2013; Madre et al. 2013; MacIvor 2013; Ksiazek et al. 2014). Although more research is needed to determine which of these very mobile species use these habitats for nesting as well as foraging, it appears that physical properties of the roof as well as availability of floral resources (pollen and nectar) influence the number of visiting and nesting pollinators. For example, MacIvor (2013) found that green roofs on lower buildings and those surrounded by more green space were colonized by a greater diversity of solitary nesting bees. Additionally, Madre et al. (2013) reported that bee richness was correlated with functional diversity of vegetation and Brenneisen (2005) found that roofs planted with mostly Sedum species attracted only half as many wild bee species as herbaceous roofs. Further investigations are needed to elucidate pollinator response to various components of green roofs, as recent studies in North America suggest that green roofs support a high proportion of non-native bee species rather than local specialists that some plants require for successful pollination (Colla et al. 2009; MacIvor 2013; Ksiazek et al. 2014). Increasing knowledge about pollinator activity on green roofs is especially important as pollination can increase genetic connectivity of habitats and improve the stability and resilience plant communities not only on green roofs (Ksiazek et al. 2012) but also in the overall urban environment (Colla et al. 2009).

In addition to macrofauna, the microinvertebrates and microorganisms living in green roof growing media are critical to the ecological functioning of the roof, aiding in nutrient cycling, organic matter decomposition and food web structure (Rumble & Gange 2013). The non-living components of green roof growing media change over time (Schrader & Böning 2006; Köhler & Poll 2010) and the
taxonomic diversity of the critically important microarthropod and fungal communities have recently begun to be investigated. Studies in North America provide evidence that microarthropods, such as springtails (Collembola) colonize green roof growing media (Maclvor & Lundholm 2010; Schindler et al. 2011). Over time, the community composition of collembolans and other pioneer species becomes increasingly variable (Schrader & Böning 2006). The structure of the plant community as well as environmental factors such as moisture and temperature can affect the species diversity and abundance of microarthropods. For example, species abundance and diversity is low on green roofs containing primarily Sedum and mosses (Rumble & Gange 2013). A recent comprehensive investigation has also documented the presence of a robust fungal community on green roofs (McGuire et al. 2013). It is yet unknown exactly how green roof fungal assemblages, unique from other urban habitats, influence floral and faunal diversity. Clearly, much more research is needed to understand how the biodiversity of the overlooked soil-dwelling organisms impacts green roof ecosystems and contributes to urban biodiversity at broader spatial scales.

As green roof communities continue to experience successional changes, they have the potential to develop complex ecological interactions and make increasing contributions to urban biodiversity. Though few investigations have been carried out over long time periods, both floral (Köhler 2006) and faunal (Jones 2002) diversity increase over time and green roofs with high plant species and functional diversity gain invertebrate species as the system develops (Kadas 2006). Future investigations carried out over multiple field seasons are needed to elucidate the factors that impact long-term development, persistence, and growth of complex communities on green roofs. Increasing monitoring and management of all urban habitats, including green roofs, will help ensure that the unique biodiversity of cities is supported and conserved.

2.6. Examples

Because green roofs are entirely engineered habitats, considerations should be taken at each step of the design process in order to ensure that the variety of functions provided by green roofs is maximized (Gedge & Kadas 2005). More green roofs around the world are now built with broad ecological goals such as biodiversity conservation in mind. Below, a few examples are highlighted to illustrate different methods being used to help green roofs support high levels of urban biodiversity in temperate climates (Table 1). While there is certainly no one method that is appropriate for use on all green roofs, there are many ways that ecosystem, species and genetic diversity can be enhanced.
These few examples demonstrate that a larger variety of techniques can be used to encourage biodiversity on shallow-media green roofs. These methods are summarized in Table 2. In general, varying the non-living components of a green roof to increase habitat variety will help promote greater ecosystem diversity which can provide habitat for a larger number of species. Planting or inoculating roofs with genetically diverse floral, fungal and microbial communities and/or allowing for natural colonization and ecological succession can expand the range of species and genetic diversity. There is also great potential for biodiversity enhancement in other regions including tropical climates as green roof technology continues to become more widespread (Ishimatsu & Ito 2013). While the methods summarized in in Table 2 represent a variety of practical suggestions that could be implemented on most green roofs, many fundamental questions about the practicalities of incorporating green roofs into conservation goals still remain unanswered.

2.7. Recommendations

In these early days of investigating green roof ecology, empirical research determining the potential of various techniques to support all components of biodiversity is still needed. Management intensity, initial construction, and plant selection will influence floral and faunal occurrence and community performance on green roofs as it does in all urban habitats (Müller et al. 2013). As green roof technology and techniques continue to develop around the world, other strategies for biodiversity conservation may become apparent. For example, the use of green facades to connect green roofs with ground-level habitats could assist in migration and colonization of many species which have limited mobility (Braaker et al. 2013). Designing green roofs with intentional ground-roof connections may therefore prove to be a beneficial and commonly used biodiversity strategy in the future. Opportunities for green roofs to enhance biodiversity should not be squandered, particularly due to lack of knowledge, communication, or collaboration. Improvement in three fundamental areas could help realize the potential of green roofs to increasingly support urban biodiversity.
### Table 1. Examples of Green Roofs from the United States and Europe That Have Used Techniques that Promote Biodiversity

<table>
<thead>
<tr>
<th>City</th>
<th>Site</th>
<th>Year Built</th>
<th>Approx. Size (m²)</th>
<th>Location</th>
<th>Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berlin, Germany</td>
<td>Nature Center Ökowerk</td>
<td>circa 1920</td>
<td>600</td>
<td>A small one-story building located within a nature center surrounded by a forest preserve and a variety of educational gardens containing both non-native and local native plants.</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>The roof of this old water-purification facility was originally covered with a thin layer of sand to insulate the building. No plants were installed and the roof was allowed to colonize naturally for approximately 100 years. In 2006, the roof needed repairs and the entire biotic layer, from substrate to plant layer was carefully removed and returned with additional fresh sand added. Recent vegetation surveys demonstrate that the majority of plant species survived reconstruction. Over 100 species are now present, including rare lichens. (See chapter by M. Köhler, this edition)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>UfaFabrik International Culture Center</td>
<td>1986</td>
<td>350</td>
<td>Several one and two-story buildings clustered in an urban neighborhood surrounded by many street trees, other green roofs and private gardens.</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Three green roofs were installed as an artistic display in the 1980s before engineered growing media was popular. Other roofs at this complex were added over the years, as recently as 2012. A mixture of succulent and non-succulent species were planted, including seeds collected from the European Alps. The growing media consisted of mostly garden soil with 10% expanded clay (Köhler 2006). The roofs are not irrigated and maintenance is minimal, usually including removal of weeds and dried plant material once a year. (Figure 2, C)</td>
<td></td>
</tr>
<tr>
<td>Munich, Germany</td>
<td>Paper Technology Foundation</td>
<td>circa 1990s</td>
<td>800</td>
<td>Located on a 2nd story walkout of a factory and office building within a somewhat industrialized region, surrounded by paved parking and small private gardens with other green roofs nearby.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>This roof was an experimental concept, created as a garden to add a diversity of species to the site. Non-living materials were used to create a shallow water-retention area running the length of the roof. A wide variety of plant forms were included in the original design including several native forbs and woody shrub species. Maintenance is minimal and natural colonization is generally allowed. There are currently over 100 plant species found here, including a variety of aquatic species. (Figure 2, D)</td>
<td></td>
</tr>
<tr>
<td>Basel, Switzerland</td>
<td>University Hospital Basel, Klinikum 2</td>
<td>2003</td>
<td>3000</td>
<td>In the heart of the city, near a large river, surrounded by many other buildings with green roofs and several private gardens which include native plantings.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A variety of substrates were installed, including sand, gravel, shingle, and topsoil (Brenneisen 2005). Substrate coverage varied not only in composition but also in arrangement and depth. A variety of plant species were planted and others were brought in as seed with the meadow topsoil that was mixed in with the other components of growing media.</td>
<td></td>
</tr>
</tbody>
</table>
Increased communication and collaboration among stakeholders

With the dramatic rise of urbanization over the next two decades, communication must be enhanced between industry practitioners, scientists, politicians and urban planners. Green roofs can meet the needs of many organisms when expertise in design,
FIGURE 2. BIODIVERSITY GOALS WERE CONSIDERED DURING THE DESIGN OF THESE EXTENSIVE GREEN ROOFS.

A: Several plants, lichen, insects and fungi use a decaying log on the Laban Dance Centre, London, United Kingdom. B: Over half of the green roof is devoted to evaluation of native prairie species at the Chicago Botanic Garden, Glencoe, IL, USA. C: Two coccinellid beetles use a green roof for mating habitat at the UfaFabrik Cultural Center, Berlin, Germany. D: Small ponds and a variety of algae, shrubs, grasses and forbs provide unique habitat on the green roof at the Paper Technology Foundation, Munich, Germany.

TABLE 2. MANY DESIGN AND/OR MAINTENANCE TECHNIQUES USED ON GREEN ROOFS CURRENTLY SUPPORT URBAN BIODIVERSITY GOALS

<table>
<thead>
<tr>
<th>METHOD</th>
<th>BIODIVERSITY ASPECT SUPPORTED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vary substrate composition</td>
<td>Ecosystem, Species</td>
</tr>
<tr>
<td>Vary substrate depth</td>
<td>Ecosystem, Species</td>
</tr>
<tr>
<td>Create micro-habitats</td>
<td>Ecosystem, Species</td>
</tr>
<tr>
<td>Irrigate when needed</td>
<td>Ecosystem, Species</td>
</tr>
<tr>
<td>Remove aggressive species</td>
<td>Species</td>
</tr>
<tr>
<td>Plant/inoculate with a variety of species</td>
<td>Species, Genetic</td>
</tr>
<tr>
<td>Use organic materials from the natural environment</td>
<td>Species, Genetic</td>
</tr>
<tr>
<td>Allow for colonization and succession</td>
<td>Species, Genetic</td>
</tr>
</tbody>
</table>
construction, ecological processes, writing policies and implementing guidelines are brought together. National and international conferences exist in which members of various fields come together to discuss new methods, products and discoveries. However, annual meetings can be cost prohibitive and do not always have the capacity or time to facilitate necessary discussions. So, how can stakeholders from all fields bring their relevant knowledge to the table? Scientists can make suggestions based on ecological theory gathered from other systems and, more importantly, test these theories within the urban and engineered framework of green roofs. Where possible, scientists should write transparent and easily accessible reports of their scientific findings specifically to inform the green roof industry. Architects and engineers can determine the practical limitations of green roof technology and implement realistic solutions that combine the best ecological and technical practices. Politicians and urban planners can assure that when environmental regulations are written, especially in urban areas, they contain specific guidelines for helping conserve and promote biodiversity on all green roofs. Together the knowledge of the community can be used to achieve high yet realistic goals.

Understanding the full breadth of ecological interactions on green roofs

Research regarding ecological processes on green roofs is still new or nonexistent in most regions. The full scope of community interactions that take place between fungi, plants, animals, and microorganisms on green roofs is yet unknown. In this engineered habitat, what factors limit achievement of goals that would support all aspects of biodiversity? Green roofs will never replace natural habitat, so what are reasonable expectations for ecological processes in these systems? Are there a set of common biodiversity targets that can be applied to green roofs globally? A great opportunity exists for scientists to use what is already known about biodiversity conservation from other habitats to begin to answer these questions. Ecologists should expand the scope of their research beyond green roof taxonomic diversity and should look for ways to collaborate at regional, national and international levels. As more is known about the community and ecosystem-level processes which occur on green roofs, these innovative habitats will have even greater potential to support all facets of biodiversity.

Connecting green roofs to the larger urban environment

Beyond the potential of green roofs to provide habitat and resources to a small number of organisms that live within their confines, these small habitat patches may have the ability to make larger contributions within urban environments. Little research has been conducted in this area but will likely be necessary in the future to determine how green roofs interact with other urban green spaces and other green infrastructure to form larger metapopulations. Are green roof plants a seed source for nearby natural areas? How should green roofs be designed and managed to ensure that they do not become havens for pests or invasive species? Do green roofs act as stepping stones for mobile species and contribute to urban corridors? A recent investigation has now demonstrated that connectivity in the landscape shapes arthropod communities on green roofs (Braaker et al. 2013). Further ecology research incorporating a network approach is necessary to understand the ways that organisms on green roofs are functioning within the larger urban community (Elle et al. 2012). Urban planners could strive to incorporate green roofs with high ecosystem, taxonomic and genetic diversity into city-wide conservation strategies, particularly by including these habitats as part of linear landscape elements and linear greenway sites (Jim & Chen 2003; Jim 2004; Van Rossum & Triest 2012). This strategy would support local and regional biodiversity by providing resources to transitory species such as migratory birds or highly mobile pollinating insects that move through the landscape.
3. CONCLUSIONS

As the number of green roofs continues to rise globally, so does the potential of this technology to contribute to both local and global biodiversity support. Conservation efforts that enhance biodiversity on individual green roofs can contribute to larger collective and systematic efforts to create connected habitats and encourage overall genetic, species and ecosystem diversity in cities (Savard et al. 2000; Millennium Ecosystem Assessment 2005; Van Heezik et al. 2012). As with biodiversity conservation in all habitats, urban planners and policy makers will need to set both specific short-term targets as well as long-term goals in order to ensure that biodiversity is sustained in the future (Millennium Ecosystem Assessment 2005). Solutions which focus on a single aspect of green roof habitat such as abiotic components (Quigley 2011) or species diversity, will likely not be enough to adequately create resilient, robust communities and thwart the loss of biodiversity (Cook-Patton & Bauerle 2012).

Research addressing the use of green roofs to conserve complex biodiversity will need to be multi-faceted. As stated in the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2005), no single component – ecosystems, species or genes – is consistently a sufficient indicator of overall biodiversity because these components can vary independent from one another and across space and time. The needs of every city are unique but biodiversity conservation can be achieved on green roofs when their design and management is incorporated into multi-scale and multi-stakeholder planning (Henry & Frascaris-Lacoste 2012). Research regarding biodiversity on green roofs thus far has made great strides in a short period of time and has contributed to the current understanding of the complexity of green roof ecology. Additional studies will allow scientists and practitioners alike to explore the full potential of green roofs and their contributions to the conservation of biodiversity at all levels.

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