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Review

Potential benefits of plant diversity on vegetated roofs: A literature review

Susan C. Cook-Patton [a,*], Taryn L. Bauerle [b]

[a] Ecology and Evolutionary Biology, E145 Corson Hall, Cornell University, Ithaca, NY 14853, USA
[b] Horticulture, 134A Plant Science Building, Cornell University, Ithaca, NY 14853, USA

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ABSTRACT

Although vegetated green roofs can be difficult to establish and maintain, they are an increasingly popular method for mitigating the negative environmental impacts of urbanization. Most green roof development has focused on maximizing green roof performance by planting one or a few drought-tolerant species. We present an alternative approach, which recognizes green roofs as dynamic ecosystems and employs a diversity of species. We draw links between the ecological and green roof literature to generate testable predictions about how increasing plant diversity could improve short- and long-term green roof functioning. Although we found few papers that experimentally manipulated diversity on green roofs, those that did revealed ecological dynamics similar to those in more natural systems. However, there are many unresolved issues. To improve overall green roof performance, we should (1) elucidate the links among plant diversity, structural complexity, and green roof performance, (2) describe feedback mechanisms between plant and animal diversity on green roofs, (3) identify species with complementary traits, and (4) determine whether diverse green roof communities are more resilient to disturbance and environmental change than less diverse green roofs.

1. Introduction

By 2050 almost 9 billion people are predicted to inhabit the Earth and two-thirds of those are expected to live in urban areas (United Nations, 2009). Urbanization triggers a suite of negative environmental impacts, including elevated pollution and temperatures ("urban heat islands"), degraded streams and watersheds, and loss of native biodiversity (Grimm et al., 2008; Pickett et al., 2011). Incorporating diverse forms of vegetation into cities may help alleviate these problems by restoring ecosystem services (Bowler et al., 2010; Goddard et al., 2009; McKinney, 2002).

Vegetated green roofs (Box 1), which integrate vegetation into underutilized urban spaces, are growing in popularity (Dunnett and Kingsbury, 2004a; Oberndorfer et al., 2007). However, selecting appropriate plant species for green roofs remains a challenge because species must tolerate extreme temperature fluctuations, thin soils, and high winds (Dunnett and Kingsbury, 2004a; Snodgrass and Snodgrass, 2006). Tests of candidate species have focused primarily on identifying those that best tolerate rooftop conditions, resulting in a limited flora of a few drought-resistant *Sedum* species on many green roofs (Dunnett and Kingsbury, 2004a; Snodgrass and Snodgrass, 2006). Yet, by limiting the number and type of species in these systems, we may fail to treat green roofs as ecological communities and constrain the short- and long-term functioning of green roofs.

Although a strong positive link between plant biodiversity and ecosystem functioning has been well-established in the ecological literature (Hooper et al., 2005) and diverse green roof communities have been created (e.g., Dewey et al., 2004; Dvorak, 2003; Hauth and Liptan, 2003; Köhler, 2006), the empirical research linking plant biodiversity with green roof performance is limited. Thus, it is not surprising that green roof designers infrequently stray from *Sedum*-dominated planting schemes. Here, we combine the green roof and biodiversity-ecosystem functioning literatures to explore ecological dynamics on green roofs. We generate testable predictions (Table 1) about how positive interactions among plant species may improve green roof performance (Section 3), how diverse green roof plantings may support more abundant and diverse fauna (Section 4), and how diverse green roofs may be less vulnerable to change (Section 5). Finally, we conclude with a discussion of the types of species to test in diverse green roof communities (Section 6). While other reviews have included abbreviated discussions of these topics (e.g., Dvorak and Volder, 2010; Francis and Lorimer, 2011; Oberndorfer et al., 2007; Ranalli and Lundholm, 2008) our review provides a more rigorous examination of the potential links between ecological biodiversity research and green roof design, and suggests an explicit research agenda for future green roof studies.

* Corresponding author. Tel.: +1 607 254 4255; fax: +1 607 255 8088.
E-mail address: scc56@cornell.edu (S.C. Cook-Patton).

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Box 1. Definitions of key terms and concepts.

Green roofs are vegetated rooftops that consist of several layers including waterproofing, drainage, and insulation with soil substrate and actively growing plants on top (F.L.L., 2008).

Intensive green roofs have soil substrates usually >15 cm deep and require more maintenance, whereas **extensive green roofs** have thinner soil and require less maintenance (Getter and Rowe, 2006). Many more species, including small trees and shrubs, can survive on intensive roofs, but only small herbaceous species can survive on extensive roofs (Dunnett and Kingsbury, 2004b; Dvorak and Volder, 2010; Snodgrass and Snodgrass, 2006).

Diversity is a general term that can be defined at multiple levels and encompasses variation within and among species. **Richness** refers to the number of species or genotypes present in an assemblage, but does not describe the differences among these units. **Functional group diversity** distinguishes species by broad morphological or physiological characteristics (C3 grasses, C4 grasses, succulents, legumes, *etc.*) whereas **functional trait diversity** directly quantifies differences in trait means among species. Because it is often hard to know what traits are relevant and to measure them in all species, **phylogenetic diversity** can be measured instead of functional trait diversity. This metric quantifies relatedness among species, assuming that more distantly related species will have more variable traits, compete less, use the total resource pool more completely, and function better in diverse mixtures (Burns and Strauss, 2011; Cavender-Bares and Wilczek, 2003; Darwin, 1859). Indeed, a recent meta-analysis showed that phylogenetic diversity was a better predictor of plant productivity than either species richness or functional group classifications (Cadotte et al., 2008).

Functional plant traits are traits that contribute to a green roof's ability to provide services to an urban area. Candidate functional traits for green roof plants are related to drought tolerance, phenology, and morphology (Dunnett and Kingsbury, 2004b). Potential drought traits include mat or cushion growth forms, succulence, leaf trichomes (hairs) or waxes, a dormant life stage (*i.e.,* tubers) during harsh conditions, and low tissue maintenance costs during periods of low resource availability (Dunnett and Kingsbury, 2004b; Eissenstat and Yanai, 1997; Grime, 2001). Dense trichomes reflect sunlight and increase the boundary layer around the leaf, helping to prevent water loss (Grime, 2001). Also, increased endo- and exodermis layers in roots reduce water loss back to the environment (Enstone et al., 2002). Phenological traits are also important – annuals may work as an accent, but perennials improve the longevity of the planting (Snodgrass and Snodgrass, 2006). Variation in flowering may help sustain animal communities (Dixon, 2009; Menz et al., 2011).

Structural complexity has been implicated as important in roof insulation (Kolb and Schwarz, 1986), rainwater retention (Dunnett et al., 2008a) and plant survival (Mulder et al., 2001), which suggests that variation in plant height, branching, and leafiness should also be considered when selecting green roof species.

2. Methods

We searched ISI Web of Science, Cornell University's library resources, and Google Scholar for relevant literature. Our search revealed five peer-reviewed articles in the green roof literature that explicitly manipulated plant diversity (Dunnett et al., 2008a; Kolb and Schwarz, 1986; Lundholm et al., 2010; MacIvor et al., 2011; Nagase and Dunnett, 2010). In contrast, there are hundreds of papers relating plant biodiversity to ecosystem function in the ecological literature, so we drew information from reviews and a subset of the relevant empirical work. Mostly, we used peer-reviewed articles, but include some papers from the annual Greening Rooftops for Sustainable Communities Conference when no relevant peer-reviewed articles existed.

3. Positive interactions among plant species may improve green roof performance

Plant species differ in how they utilize resources such as soil nutrients, water, and sunlight. Diverse communities composed of species with complementary resource use are expected to utilize total resources more completely and efficiently (Macarthur and Levins, 1967; Tilman et al., 1996). This can lead to increased nutrient uptake, more efficient water usage and overall higher productivity (Darwin, 1859; Hooper et al., 2005; Rixen and Mulder, 2005; Tilman et al., 1996), and these effects may improve the ecosystem services provided by green roofs (Table 1).

3.1. Plant productivity, cooling, insulation, and rainwater retention on green roofs

There is some evidence that diverse green roof communities are more productive than monocultures (Lundholm et al., 2010) and an increase in biomass may enhance multiple green roof services (Table 1). For example, Kolb and Schwarz (1986) found that temperatures below diverse green roof communities were cooler than below monocultures and suggested that the increased height and structural complexity (Box 1) found in diverse mixtures formed air pockets that increased the roof insulation. Similarly, a large ecological experiment that manipulated plant species diversity in a field habitat found that temperatures in diverse plots were lower than in monocultures, although the cooling in this case was attributed to increased evapotranspiration (Verheyen et al., 2008). Previous green roof research also linked higher biomass production to decreased water runoff, although the relationship between diversity and rainwater retention is ambiguous. Teemusk and Mander (2007) compared runoff on either side of a roof and found higher water retention on the side with denser vegetation (although they did not manipulate plant diversity). Dunnett et al. (2008a) manipulated plant diversity in green roof mesocosms, using a pool of four *Sedum* spp., four forbs and four grasses planted in monocultures, single functional group mixtures, or 12-spp. mixtures. The authors found a negative relationship between plant height and water runoff, but no clear relationship between plant diversity and rainwater retention. They hypothesized that structural complexity was more important than diversity. This merits further investigation because increasing plant diversity can increase structural diversity if functionally and morphologically different species are tested together (Spehn et al., 2000).

The above examples highlight the importance of distinguishing between biomass production and structural complexity. These two variables are likely frequently related, though not necessarily. Given that the amount of biomass suitable for green roofs is constrained by wind sheer, limited nutrient availability, load-bearing capacity, fire hazards, and ease of maintenance (Snodgrass and Snodgrass, 2006), it may be important to identify combinations of plants that optimize structural complexity rather than biomass *per se*.