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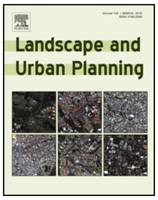

Research Paper

Effects of recycled aggregate growth substrate on green roof vegetation development: A six year experiment

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HIGHLIGHTS

- Drought disturbance was a key environmental driver of green roof plant assemblages.
- Plant recovery from drought disturbance was mediated by the growth substrate type.
- Solid municipal waste incinerator bottom ash was a poor plant growth substrate.
- Recycled building aggregate was better, especially when percentage brick was high.
- Robust conclusions about green roof development require multi-year investigation.

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ABSTRACT

Green roofs have the potential to address several of the environmental problems associated with urbanisation, and can be used as mitigation for habitats lost at ground level. Brown roofs (a type of green roof) can be used to mitigate for the loss of brownfield habitat, but the best way of designing these habitats remains unclear. This paper reports an experiment to test the effects of different types of recycled aggregate on the development of vegetation assemblages on brown roof mesocosms. Five recycled aggregates were tested: (1) crushed brick, (2) crushed demolition aggregate, (3) solid municipal waste incinerator bottom ash aggregate, (4) a 1:1 mix of 1 and 2, and (5) a 1:1 mix of 3 and 2. Each was seeded with a wildflower mix that also included some *Sedum acre* and vegetation development was studied over a six-year period. Species richness, assemblage character, number of plants able to seed, and plant biomass were measured. Drought disturbance was the key factor controlling changes in plant assemblage, but effects varied with substrate treatment. All treatments supported a similar plant biomass, but treatments with a high proportion of crushed brick in the growth substrate supported richer assemblages, with more species able to seed, and a smaller amount of *Sedum acre*. Crushed brick, or recycled aggregates with a high proportion of crushed brick, are recommended as good growth substrate materials for encouraging brown roof plant diversity. This investigation demonstrates the importance of multi-year studies of green roof development for the generation of robust findings.

1. Introduction

A majority of the world's population lives in urban areas, and by 2050 the world population is expected to be 68% urban (United Nations, 2012). This rapid expansion of urban population means that towns and cities continue to grow in number, area and density. Urban development is often achieved through infill of greenspace, so that urban areas become compact (Dallimer et al., 2011; Pauleit, Ennos, & Golding, 2005), and this densification can intensify many of the characteristic environmental problems associated with urban areas. These include changes to: terrestrial ecological systems, such as biotic homogenisation, habitat loss, habitat fragmentation and increased disturbance (Grimm et al., 2008; Pickett et al., 2011); lotic ecological systems, such as increased pollution concentration, and more frequent flow disturbances (Pickett et al., 2011; Walsh et al., 2005); local climate systems, with warming due to the urban heat island effect (Li, Zhang, Liu, & Huang, 2004); and human emotional and physical wellbeing, such as those caused by pollution exposure and lack of access to nature (Hoek, Brunekreef, Goldbohm, Fischer, & van den

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Brandt, 2002; Hofmann, Westermann, Kowarik, & van der Meer, 2012; Lee, Williams, Sargent, Farrell, & Williams, 2014; Sadler, Bates, Hale, & James, 2010). All of these 'urban syndromes' can in part be mitigated by the preservation or creation of green space and vegetation cover in urban areas (Akbari, Pomerantz, & Taha, 2001; Lee et al., 2014; Sadler et al., 2010; Susca, Gaffin, & Dell'Osso, 2011).

Extensive green roofs are building roofs covered with <20 cm deep growth substrate and plants (Oberndorfer et al., 2007). Due to the relative low weight and possibility of retro-fit, extensive green roofs could potentially be widely installed in urban areas, thereby contributing to the alleviation of multiple urban syndromes (Dunnett & Kingsbury, 2004; Getter & Rowe, 2006). The design of a green roof influences the environmental benefits associated with that design, such that maximising one element will often trade-off against another (Bates, Mackay, Greswell, & Sadler, 2009; Rowe, 2011; Simmons, Gardiner, Windhager, & Tinsley, 2008). Nonetheless, extensive green roofs are associated with a range of environmental benefits which include: removal of air pollution, urban cooling, habitat provision, building energy-savings, and reduction of roof storm-water runoff (Bengtsson, 2005; Castleton, Stovin, Beck, & Davison, 2010; Francis & Lorimer, 2011; Mentens, Raes, & Hermy, 2006; Oberndorfer et al., 2007; Rowe, 2011; Rumble & Gange, 2013; Yang, Yu, & Gong, 2008).

In the UK, one kind of extensive green roof that has found favour with wildlife conservationists in particular, are brown or biodiversity roofs (Bates, Sadler, & Mackay, 2013; Gedge, 2003; Grant, 2006; Ishimatsu & Ito, 2013). Brown roofs are a type of extensive green roof, which are designed to replicate brownfield habitats, such as building demolition and post-industrial sites. They represent some of the most ecologically diverse and valuable wildlife habitats in urban areas (Angold et al., 2006; Donovan, Sadler, & Bryson, 2005; Gilbert, 1989; Small, Sadler, & Telfer, 2003; Woodward, Eyre, & Luff, 2003), and are increasingly seen as habitats worth conserving (Donovan et al., 2005; Harrison & Davies, 2002).

In the UK, the general need for housing, the perceived low visual appeal of brownfield sites, and recent government guidelines that have favoured brownfield development, have meant that brownfield habitat has come under increasing development pressure (Dallimer et al., 2011; Harrison & Davies, 2002; Hofmann et al., 2012; Sadler, Bates, Donovan, & Bodnar, 2011; Thornton & Nathanail, 2005). In an attempt to create a win–win scenario, where brownfield habitats are preserved yet development proceeds, the idea of replacing aesthetically displeasing (Lee et al., 2014; White & Gatersleben, 2011) brownfield habitat with brown roofs has gained favour (Gedge, 2003; Grant, 2006). Brown roofs should not be seen as exact like-for-like replacement for brownfield habitat because it is not possible to exactly replicate ground-based habitat on roofs (Olly, Bates, Sadler, & Mackay, 2011; Sadler et al., 2011). However when designed well brown roofs can be associated with rare species and diverse wildlife assemblages, so still have considerable potential as mitigation for habitat lost to development (Brenneisen, 2006; Francis & Lorimer, 2011; Kadas, 2006; Sadler et al., 2011).

Little is known about the best design criteria for brown roofs, partly due to the lack of medium to long-term studies of their ecological function (Ishimatsu & Ito, 2013). However, studies to date have suggested a few key design criteria, such as the importance of: low nutrient levels, diverse substrate types, areas of bare ground, disturbance refugia, a range of substrate depths, and replication of brownfield substrate characteristics (Bates et al., 2009; Brenneisen, 2006; Kadas, 2006; Madre, Vergnes, Machon, & Clergeau, 2014). Different potential brown roof growth substrates have been tested, such as recycled building aggregate (e.g. brick, mortar and concrete) and occasionally industrial waste aggregates (e.g. clay, and sewage sludge pellets), partly to try and replicate conditions in brownfield habitats (Bates et al., 2013; Kadas, 2006; Molineux, Fentiman, & Gange, 2009).

Energy, resources, environmental and monetary costs are associated with creating and transporting the substrate used in green roofs (Peri, Traverso, Finkbeiner, & Rizzo, 2012; Saiz, Kennedy, Bass, & Pressnail, 2006). Costs associated with transportation of substrate materials can be sizeable when materials are transported a long distance from the green roof construction site (Peri et al., 2012). So it is advantageous if locally sourced substrate materials can be used, providing the materials can be shown to compare favourably with substrates obtained from further afield (Molineux et al., 2009). Recycling 'waste' substrate materials also prevents their disposal to landfill (Hansen, 1992; Izquierdo, López-Soler, Ramonich, Barra, & Querol, 2002; Pera, Coutaz, Ambroise, & Chababbet, 1997) and recycled substrates can have lower costs than designed substrates that require manufacture (e.g. expanded clay, expanded slate) (Solano, Ristvey, Lea-Cox, & Cohan, 2012).

The relative advantages and disadvantages of several green roof growth substrates have been tested (Simmons et al., 2008; VanWoert, Rowe, Andresen, Rugh, & Xiao, 2005), but tests of recycled substrates are uncommon (but see Molineux et al., 2009; Solano et al., 2012). Substrate character will influence most of the environmental advantages of green roofs both directly (e.g. field capacity and albedo), and indirectly through its influence on vegetation growth. Vegetation on green roofs takes time to establish, and many vegetation characteristics alter from year to year due to successional processes and drought disturbances (Bates et al., 2013; Dunnett, Nagase, & Hallam, 2008; Köhler & Poll, 2010; Köhler, 2006; Lundholm, Heim, Tran, & Smith, 2014; Nagase & Dunnett, 2010; Rowe, Getter, & Durhman, 2012), so findings over short term investigations have to be interpreted with caution.

This paper describes a six-year experimental test of the effects of different types of recycled growth substrates on the diversity, character and amount of brown roof vegetation. Three recycled substrates were tested: crushed brick, crushed demolition aggregate, and solid municipal waste incinerator bottom ash aggregate. Two mixes of these aggregates were also tested: a 1:1 mix of crushed brick and crushed demolition aggregate, and a 1:1 mix of crushed demolition aggregate and solid municipal waste incinerator bottom ash aggregate. Crushed brick is a fairly standard green roof growth substrate in the UK (Molineux et al., 2009) and was transported from distance to the study site. The other aggregates were locally sourced and are rarely used as green roof growth substrates. This medium-term experiment aimed to assess the relative suitability of five different recycled aggregate mixes for the growth of brownfield-like, wildflower vegetation on green roof mesocosms. Specifically, our objectives were to test the effect of recycled substrate type, time and weather conditions on the: species richness of the forb assemblage, characteristics of that assemblage, ability of plant species to complete their life-cycle (i.e. to seed), structure of the habitat (e.g. coverage of bare ground and moss), and distribution of plant biomass in that assemblage.

2. Methods

2.1. Study roof test array

The study site was at The University of Birmingham, UK (52″27′01.54″ N, 1″55′43.41″ W), which has a temperate maritime climate. The green roof test array was installed on a flat 5-storey building roof and completed in May 2007. The edge of the roof had a solid safety wall of about 1.5 m height, but due to the need to distribute weight through the building support columns, the green roof mesocosms were elevated about 1 m above the roof and so were more directly exposed to wind (Fig. 1). Their elevation meant that each was separated by at least a 50 cm gap, meaning that plants were only able to spread propagules between replicates via wind or