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Amount of water runoff from different vegetation types on extensive green roofs: Effects of plant species, diversity and plant structure

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ABSTRACT

Increased stormwater runoff from impervious surfaces is a major concern in urban areas and green roofs are increasingly used as an innovative means of stormwater management. However, there are very few studies on how different vegetation types affect the amount of water runoff. This paper describes an experiment that investigates the influence of plant species and plant diversity on the amount of water runoff from a simulated green roof. Twelve species were selected from the three major taxonomic and functional plant groups that are commonly used for extensive green roofs (forbs, sedum and grasses). Four species were chosen from each group and planted in combinations of increasing diversity and complexity: monocultures, four-species mixtures and twelve-species mixtures. The results showed that there was a significant difference in amount of water runoff between vegetation types; grasses were the most effective for reducing water runoff, followed by forbs and sedum. It was also shown that the size and structure of plants significantly influenced the amount of water runoff. Plant species with taller height, larger diameter, and larger shoot and root biomass were more effective in reducing water runoff from simulated green roofs than plant species with shorter height, smaller diameter, and smaller shoot and root biomass. The amount of water runoff from *Sedum* spp. was higher than that from bare ground. Species richness did not affect the amount of water runoff in this study.

1. Introduction

Increased stormwater runoff from impervious surfaces is a major concern in urban areas (Scholz, 2004) where the sewage systems cannot cope with heavy storms. However, upgrading to a larger system capable of quickly rerouting the water would not only be costly, but would also pose a risk of flooding downstream and reduced efficiency of water treatment installations (White, 2002). Hence, water runoff management has attracted much interest in recent years. In the United States, Stormwater Best Management Practices (BMPs) are primarily designed to lessen the impact of urban development and drainage by increasing stormwater storage areas across a watershed, therefore slowing the flow of water into a receiving water body, and/or replacing impervious surfaces with permeable areas that allow stormwater infiltration (Carter & Jackson, 2007). Effective management practices include stormwater planting (aboveground planting containers that intercept water diverted from a roof), open channels (concave, vegetated conveyance systems), wetlands, and green roofs (vegetated roof surfaces) (Dunnett & Clayden, 2007). Green roofs are one of the most important BMPs given the lack of land in urban areas. A number of large cities have established water management policies to encourage the construction of green roofs. For example, in Portland, Oregon, developers who install impervious surfaces exceeding an area of 46.5 m^2 must allow for onsite stormwater management. If conditions onsite do not permit full water quality treatment and flow rate control, the developer must either build an offsite facility, or pay an ‘in lieu’ fee for municipal stormwater management. Additionally, in areas where zoning regulations limit a building’s height-to-floor-area ratio, by greening all or part of a roof, a developer can add as many as three additional square metres to the building height for every square metre of green roof (Liptan, 2005).

The management of water runoff is a highly active area of green roof research and many studies have shown that green roofs can significantly reduce the amount of water runoff compared to black roofs (Carter & Jackson, 2007; Getter, Rowe, & Andresen, 2007; Schroll, Lambrinos, Righetti, & Sandrock, 2011; Teemusk & Mander, 2007; VanWoert et al., 2005).Mentens, Raes, and Hermy (2006), summarised German studies from 1987 to 2003 and reported that the estimated annual rainfall-retention capability ranges from 75% for intensive green roofs (median substrate depth: 150 mm) to 45% for extensive green roofs (median substrate depth: 100 mm). Green

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roofs influence runoff water in a number of ways. Water that falls on the roof can be absorbed into pore spaces in the substrate or can be taken up by absorbent materials in the substrate. It can also be taken up by the plants and either stored in plant tissues or transpired back into the atmosphere. Some water may lodge on plant surfaces and subsequently evaporate (Dunnett & Kingsbury, 2008). During a short storm, water in excess of the field capacity is temporarily stored in the soil and vegetation, which means that the peak runoff is delayed and reduced (Bengtsson, Grahn, & Olsson, 2005).

Green roof vegetation can affect the amount of water runoff depending on each plant's capacity for water interception, water retention and transpiration. The amount of water runoff from a green roof is given by the following formula (Koehler, 2004): water runoff = precipitation − (water interception + water retention + transpiration from plants + evaporation from soil). Greater water interception by plants may effectively reduce water runoff from green roofs. Clark (1937, 1940) compared the interception of rainfall by different types of plants and concluded that low-growing or mat-forming plants did not intercept as much rain as taller plants because of the smaller surface area that was exposed. In addition, the belowground plant structure is important for water management since water retention in the soil may also be affected by the plant root structure. MacIvor and Lundholm (2011) showed that plant species that formed extremely dense fibrous roots captured the least amount of water runoff from green roofs because they reduced the porosity of the growing medium and the volume of space in which water could be retained. Not only water interception and water retention, but also a higher transpiration rate could lead to a greater reduction of water runoff (Lundholm, MacIvor, MacDougall, & Ranalli, 2010). Species that can evapotranspire more water from the growing medium will create more space for water capture in subsequent rain events (MacIvor & Lundholm, 2011). Plants are divided into three types in terms of their photosynthetic mechanism: C3 plants (to which the majority of plants belong), C4 plants (mainly grasses) and Crassulacean acid metabolism (CAM) plants (mainly succulents). C4 plants tend to show a high transpiration rate, and their growth rate is higher than that of C3 and CAM plants (Larcher, 2003). On the contrary, CAM plants generally have higher water-use efficiency and retain more water in the substrate than C3 and C4 plants. As the stomata of CAM plants are closed during the day, plant gas exchange occurs at night, thus reducing transpirational water loss (Gravatt & Martin, 1992). It was previously hypothesized that C3 and C4 plants are more effective at reducing water runoff from green roofs compared to CAM plants because C3 and C4 plants use more water than CAM plants.

In addition to the above characteristics of individual plants, vegetation diversity might also influence the hydrological performance of green roofs. The amount of water runoff can be reduced if the vegetation contains many species and a variety of structural types according to the following reasons. Rixen and Mulder (2005) pointed out that the increase in water absorption with greater species richness may be explained by two different mechanisms. Firstly, it may be a sampling effect: there is a greater probability of including at least one species with a very high absorption capacity in high-diversity plots. Secondly, the inclusion of more species results in a greater diversity of architectures. The inclusion of taller species may result in a lower rate of evaporation, while mat species that are in contact with the soil may release more moisture from the soil into the subcanopy space. Lamont and Bergl (1991) pointed out that many species of contrasting growth form behave differently in their use of soil water. Different rooting patterns or phenologies in these species create a type of belowground niche separation. This facilitates coexistence by allowing differential exploitation of the soil profile either spatially or temporally.

Although previous studies have shown that the amount of water runoff is influenced by the design of a green roof, such as the roof slope (Getter et al., 2007), substrate depth (VanWoert et al., 2005), and roof structural components (Berndtsson, 2010), as well as the rainfall intensity (MacMillan, 2004), studies on the role of green roof vegetation in the management of runoff water have been limited (Lundholm et al., 2010). Previous green roof studies tended to use *Sedum* spp. (Monterusso, Rowe, Rugh, & Russell, 2004; VanWoert et al., 2005) or a mixture of perennial plants (Teemusk & Mander, 2007) and different vegetation was not compared. However, some recent papers address the effect of plant species and functional group combinations on green roof ecosystem functions (Bulter & Orians, 2011; Dunnett, Nagase, Booth, & Grime, 2008; Lundholm et al., 2010; MacIvor & Lundholm, 2011; Nagase & Dunnett, 2010; Wolf & Lundholm, 2008). Bulter and Orians (2011) showed that *Sedum* spp. could facilitate the growth of neighbouring plants during water stress, but acted as a competitor when water was abundant. Lundholm et al. (2010) studied green roof systems planted with monocultures or mixtures containing one, three, or five forms to quantify water capture, and they showed that some mixtures outperformed the best monocultures for water capture and evapotranspiration. Although the abovementioned studies demonstrated that the composition of vegetation affected both the amount of water retained and released from green roofs, detailed information was not explicitly provided on factors such as the role of the plant structure.

In the present study, we investigated how vegetation and plant diversity affect runoff reduction from green roofs. Understanding the hydrological performance of different vegetation makes it possible to choose the appropriate plants to maximize the benefit of reduced water runoff from green roofs. This study followed up on the previous study by Dunnett et al. (2008), who compared two experiments to show the role of vegetation composition on green roof function in regard to rainwater runoff. Their two experiments were (a) an outdoor lysimeter experiment that investigated the quantity of runoff from trays containing 100 mm of growing medium and combinations of grasses and forbs, together with bare substrate, and (b) a greenhouse experiment using simulated rainfall to estimate the amount of rainfall intercepted by different vegetation types. The latter experiment comprises only part of our experiment and it is necessary to show additional information to discuss how vegetation and plant diversity affect water runoff from green roofs. In this study, the results of water runoff from modules planted with species in monocultures and mixtures experiencing simulated rain intensity of 50 mm/h are shown and discussed whereas the same modular setup experienced 100 mm/h simulated rain intensity in Dunnett et al. (2008). Our first goal was to examine how different plant species and vegetation in mixtures and in monocultures affect the reduction of water runoff from green roofs. Our second goal was to examine how plant structure affects the amount of water runoff.

2. Methods

The experiment was carried out in a greenhouse in order to maintain a constant volume and intensity of simulated rain. We selected one of the greenhouses of the experimental garden at the University of Sheffield, UK. This greenhouse was heated when the outside temperature fell below 20 °C; the inside temperature was kept at more than 20 °C. Twelve plant species were used to create a vegetation cover of the same plant density but differing species composition. The twelve species were chosen from sedum (*Sedum acre* 'Minor', *Sedum album* 'Coral Carpet', *Sedum rupestre*, *Sedum spurium* 'Coccineum'), grasses (*Anthoxanthum odoratum*, *Festuca ovina*, *Koeleria macrantha*, *Trisetum flavescens*), and herbaceous plants other than grass and sedum, referred to as forbs in this study