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Influence of plant composition and water use strategies on green roof stormwater retention

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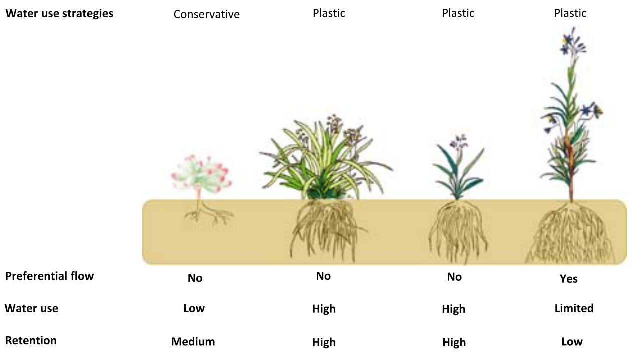
HIGHLIGHTS

- We evaluated how plant water use strategies influenced ET and stormwater retention.
- ET and retention were greatest in plants with high water use and drought tolerance.
- Plant roots reduced retention and soil water content due to preferential flow.
- Preferential flow overwhelmed the influence of water use strategies.

GRAPHICAL ABSTRACT



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ABSTRACT

Green roofs are increasingly being considered a promising engineered ecosystem for reducing stormwater runoff. Plants are a critical component of green roofs and it has been suggested that plants with high water use after rainfall, but which are also drought tolerant, can improve rainfall retention on green roofs. However, there is little evidence to show how plants with different water use strategies will affect green roof retention performance, either in monocultures or in mixed plantings. This study tested how monocultures and a mixture of herbaceous species (*Dianella admixta*, *Lomandra longifolia* and *Stypandra glauca*) affected rainfall retention on green roofs. These species were chosen based on their water use strategies and compared with a commonly used succulent species (*Sedum pachyphyllum*) with conservative water use. We measured retention performance for 67 rainfall events, quantifying all components of the water balance. We also compared growth for species in monocultures and mixtures. We found that monocultures of *L. longifolia* had the greatest stormwater retention and ET. Although *S. glauca* has a similar water use strategy to *D. admixta*, it had the lowest stormwater retention and ET. In both the mixture and as a monoculture, *S. glauca* created preferential flow pathways, resulting in lower substrate water contents which reduced ET and therefore rainfall retention. This species also dominated performance of the mixture, such that the mixture had lower ET and retention than all monocultures (except *S. glauca*). We suggest that root traits and their interaction with substrates should be considered alongside water use strategies for rainfall retention on green roofs.

1. Introduction

Impervious surfaces in urban areas increase the frequency, volume and peak flow of stormwater runoff compared with natural areas

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which degrades urban aquatic ecosystems (Walsh et al., 2005). As roofs comprise a large proportion of impermeable surfaces, green roofs are being used as a tool to manage urban runoff (Li and Babcock, 2014; Elliott et al., 2016). Although they provide other ecosystem services, such as air purification, noise reduction and urban cooling, reducing stormwater runoff is often considered the major benefit provided by green roofs and is one of the main reasons they are legislated or incentivised in cities worldwide (Oberndorfer et al., 2007; Carter and Fowler, 2008).

Green roofs reduce stormwater runoff by storing water during rainfall events, delaying peak runoff (attenuation through the substrate) and removing water from the substrate to the atmosphere through evapotranspiration (ET) (Stovin et al., 2013). Following rainfall, a portion of the detained water drains from the roof and the amount of rainfall corresponding to substrate storage capacity is retained (Bengtsson et al., 2005). This retained water will then either evaporate or be transpired by plants which dries out the substrate and regenerates retention capacity before the next rainfall event (Berretta et al., 2014; Poë et al., 2015). The rate at which water stored in the substrate is used by plants is an important determinant of how a green roof responds to the next rainfall event (Villarreal and Bengtsson, 2005). The most commonly planted species on green roofs are succulents in the genus *Sedum*. These plants are ideal for survival in green roof systems, because their shallow root system and conservative water use strategy means that they can withstand frequent periods of drought on green roofs when the shallow substrates dry out (VanWoert et al., 2005; Getter and Rowe, 2009). However, these characteristics also mean that they may not sufficiently dry out substrates via transpiration between rain events to provide significant stormwater retention (Farrell et al., 2013). To optimise rainfall retention and plant survival on green roofs, plants need to have high transpiration when water is available after rainfall, but also be able to survive dry substrates between rainfall events by limiting their transpiration (Wolf and Lundholm, 2008; Farrell et al., 2013). These water use strategies have been found in rock outcrop plants evaluated for green roofs, but their potential for reducing stormwater runoff has not yet been evaluated (Farrell et al., 2013).

It has been suggested that a diverse mixture of plant functional groups will improve the function and resilience of green roofs (Lundholm et al., 2010). Studies in both natural and engineered ecosystems have found positive relationships between plant diversity and the provision of ecosystem services, including: maintaining hydrologic cycles, cleaning air and water and the storing/cycling of nutrients (Christensen et al., 1996; Quijas et al., 2010; Johnson et al., 2016). Two principal mechanisms are thought to drive the positive relationships between species diversity and ecosystem function: (1) transgressive overyielding, where mixtures of plant species produce more biomass than monocultures due to complementarity in resource utilization (Schmid et al., 2008; Prieto et al., 2015); and (2) selection effect, where there is a greater possibility of including the best-performing species in a mixture which enhances resource use efficiency (Chapin III et al., 1997). Species which have similar effects on ecosystem processes (water and nutrient dynamics, trophic interactions, or disturbance regime), but differ in response to environmental conditions, can also provide stability (resistance and resilience) under changing environmental conditions (Chapin III et al., 2000). Consequently, if one species is lost from a diverse ecosystem, there is the potential for other functionally similar species to compensate, making the ecosystem more resilient to environmental changes (Ehrlich and Ehrlich, 1981).

Applying biodiversity and ecosystem theory to improve the performance of green roofs has been gaining traction, with several studies evaluating how plant diversity affects rainfall retention (Dunnett et al., 2008; Lundholm et al., 2010). However, most of these studies have evaluated diversity in terms of mixtures of life-forms or species richness, rather than by mixing species with known functionality, such as the water use strategy. While these studies hypothesised that mixtures would out-perform monocultures in terms of retention, the results have not been straight forward. For example, Lundholm et al. (2010) reported that while mixtures of grasses and succulents had greater retention than monocultures of either life-form, their retention was less than bare substrate. The effects of life-form diversity are likely complicated by differences in biomass and rainfall interception. For example, Dunnett et al. (2008) found there was no significant improvement in retention with life-form diversity, but that the highest retention was from tall plants with high root biomass. This is consistent with Franzaring et al. (2016) which showed that, compared with monocultures of legumes, herbs, small shrubs and succulents, mixtures of these life-forms retained less water than monocultures of grasses. While species richness seems to be positively related to productivity, it may not relate to rainfall retention (Nagase and Dunnett, 2012; Johnson et al., 2016).

These results are consistent with ecological research that shows that not all metrics of biodiversity are related to improved nutrient and water uptake, biomass production and transpiration rate (Díaz and Cabido, 2001; Lavorel and Garnier, 2002). It has been suggested that functional diversity and functional trait diversity may be the most important drivers for specific ecosystem services (Petchey and Gaston, 2002; Cadotte et al., 2011). Consequently, green roof experiments assessing the role of diversity on the basis of life-forms or species richness may not have included the necessary functional or physiological traits to improve water retention. This leads us to consider whether biodiverse green roofs designed on the basis of functional diversity or functional trait diversity could achieve the trade-off between hydrological performance and plant survival. We therefore suggest that green roofs planted with mixtures of species with appropriate water use strategies will improve rainfall retention performance without compromising plant survival (Farrell et al., 2013).

In this study, we tested how mixtures and monocultures of species chosen on the basis of plant water use strategies affect rainfall retention on green roofs, relative to a commonly used succulent species. We evaluated three species (*Lomandra longifolia*, *Dianella admixta* and *Stypandra glauca*) known to have water use plasticity, i.e. they have high evapotranspiration when water is available and reduced water use under drought conditions to avoid drought stress (Farrell et al., 2013). We predicted that: (1) green roof modules planted with monocultures of species with water use plasticity would retain more water via greater evapotranspiration than modules planted with the succulent species with conservative water use and (2) mixtures would retain more rainfall due to complementarity in aboveground biomass and water use, resulting in greater evapotranspiration.

2. Materials and methods

2.1. Experimental design

We used a randomized block design with six 'vegetation' treatments and three replicates: (1) bare substrate (as a control), (2) monoculture of *Sedum pachyphyllum* (as a reference for common green roof plantings), (3) monoculture of *Lomandra longifolia*, (4) monoculture of *Dianella admixta*, (5) monoculture of *Stypandra glauca* and (6) mixture of *Lomandra longifolia*, *Dianella admixta* and *Stypandra glauca*. These four species were chosen based on two types of water use strategies, (1) conservative water use: *S. pachyphyllum* and (2) plastic water use: *L. longifolia*, *D. admixta* and *S. glauca* (Table 1) (Farrell et al., 2013).

The experiment was located at the Burnley Campus of The University of Melbourne, Australia (−37.828472, 145.020883). Melbourne has monthly average maximum and minimum temperatures of 19.9 and 10.2 °C (Melbourne Regional Office; site 086071; Australian Bureau of Meteorology). We used 18 modules (6 treatments with 3 replicates per treatment) with dimensions 1.15 × 1.15 m, placed in an open-ended rainfall exclusion shelter (i.e., a poly tunnel; 28 m long × 2.6 m high). Modules were constructed with drainage, geotextile and substrate layers to simulate a typical green roof structure. Modules were filled by weight with 105 kg of a scoria-based substrate to a depth of