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Drought-avoiding plants with low water use can achieve high rainfall retention without jeopardising survival on green roofs

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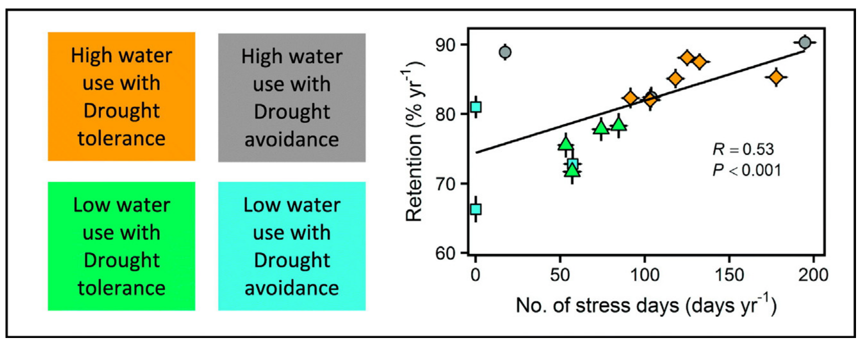
HIGHLIGHTS

- Green roof plant selection is a trade-off between retention and drought risk.
- Rainfall retention and drought stress were modelled over a 30-year climate scenario.
- Low water-using, drought-avoiders achieved high retention and low drought stress.

GRAPHICAL ABSTRACT



Plant water use strategies were compared to assess the trade-off between hydrological performance (rainfall retention) and the number of drought stress days experienced. During a 30-year climate scenario, green roofs with low water-using, drought-avoiding plants achieved high rainfall retention with minimal drought stress. *R* and *P* values were derived from correlation analysis.

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ABSTRACT

Green roofs are increasingly being used among the suite of tools designed to reduce the volume of surface water runoff generated by cities. Plants provide the primary mechanism for restoring the rainfall retention capacity of green roofs, but selecting plants with high water use is likely to increase drought stress. Using empirically-derived plant physiological parameters, we used a water balance model to assess the trade-off between rainfall retention and plant drought stress under a 30-year climate scenario. We compared high and low water users with either drought avoidance or drought tolerance strategies. Green roofs with low water-using, drought-avoiding species achieved high rainfall retention (66–81%) without experiencing significant drought stress. Roofs planted with other strategies showed high retention (72–90%), but they also experienced >50 days of drought stress per year. However, not all species with the same strategy behaved similarly, therefore selecting plants based on water use and drought strategy alone does not guarantee survival in shallow substrates where drought stress can develop quickly. Despite this, it is more likely that green roofs will achieve high rainfall retention with minimal supplementary irrigation if planted with low water users with drought avoidance strategies.

1. Introduction

As cities grow, the amount of impervious area generating stormwater increases. For cities with separate wastewater and drainage networks, this results in large volumes of stormwater degrading the

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ecological value of urban waterways (Walsh et al., 2005). For cities with combined sewer and drainage systems, there are additional health risks associated with the increased frequency of sewer overflows (Passerat et al., 2011). Consequently, water sensitive urban design technologies including swales, constructed wetlands and raingardens are often used to reduce the volume of runoff entering the drainage network. However, options for stormwater control at ground level can be constrained by high competition for space (Berndtsson, 2010). Green roofs have significant potential to contribute to overall runoff reductions, as roofs can represent up to half the effective impervious area in cities (Mentens et al., 2006).

Recent syntheses of green roof hydrological performance suggest that annual rainfall retention varies between ~5 and 85% (Cipolla et al., 2016; Elliott et al., 2016; Li and Babcock, 2014). Restoration of natural hydrological processes requires rainfall retention equivalent to pre-urbanisation levels (Burns et al., 2012). Typically, in natural forests and grasslands, around 60–80% of rainfall is lost to evapotranspiration (Zhang et al., 2001). Consequently, if green roofs are to be effective stormwater control measures, they should aim to achieve a similar level of rainfall retention which is at the upper end of that reported in empirical studies.

The substantial observed variation in green roof hydrological performance can in part be explained by climate, where rainfall retention is lower in cities with a high frequency of large rainfall events followed by periods of low evaporative demand (Elliott et al., 2016; Sims et al., 2016; Stovin et al., 2013; Voyde et al., 2010a). However, variation in rainfall retention can also be attributed to green roof configuration, i.e., the combination of retention layers, substrates and plants (Berndtsson, 2010; VanWoert et al., 2005a). Configuration varies by region and climatic zone, but most green roofs typically have a shallow substrate (<100 mm) with a high hydraulic conductivity to promote drainage, as well as low organic matter content for long-term stability and to prevent the spread of fire (FLL, 2008). Consequently, these substrates have low water availability, such that in hot and dry climates green roofs need to be planted with drought-resistant species which can also survive intense heat and wind exposure (Farrell et al., 2012; Nagase and Dunnett, 2010; Rayner et al., 2016; Savi et al., 2016). Green roof water storage capacity can be manipulated by increasing the depth and water holding capacity of the substrate (Cao et al., 2014; Farrell et al., 2013a; Feitosa and Wilkinson, 2016) any by installing water-retention layers or reservoirs below the substrate (Savi et al., 2013; Simmons et al., 2008). However, these options are often limited by the weight-loading capacity of the roof, particularly in retrofit situations (Castleton et al., 2010). Plant selection is therefore a critical aspect of green roofs designed for stormwater control.

Plants have a major influence on green roof rainfall retention, as evapotranspiration is the main process which restores the storage capacity of the substrate between rain events (Berretta et al., 2014; Poë et al., 2015). Plants with high water use are more likely to create storage between rain events and therefore improve green roof hydrological performance (Poë et al., 2015; Voyde et al., 2010b). However, high water users are also more likely to be exposed to increased drought frequency, intensity and duration, given the limited amount of water stored in shallow substrates (Raimondo et al., 2015; Stovin et al., 2013). Survival during extended periods of drought has therefore been a focus of green roof plant selection in most cities and regions, resulting in a prevalence of succulent species, e.g. *Sedum* spp. (Rayner et al., 2016). Succulents typically survive drought through inherently low rates of water use, coupled with water storage in leaf tissues, allowing them to maintain water status during extended drought (Durhman et al., 2006; Farrell et al., 2012). The disadvantage is that these species will likely do little to replenish the rainfall storage capacity of green roofs between rain events (Nagase and Dunnett, 2012; Wolf and Lundholm, 2008). Using a habitat template approach to green roof plant selection (Lundholm, 2006), Farrell et al. (2013b) showed that some rock outcrop (shallow soil) species have a combination of seemingly conflicting strategies (high water use and drought resistance). However, it is not known whether such strategies could improve hydrological performance of green roofs without introducing substantial drought stress.

Plants resist periods without water by either avoiding or tolerating drought (Blum, 2005; Levitt, 1972). Drought avoiders, or 'isohydric' species, use tight stomatal regulation to rapidly decrease transpiration and therefore maintain their internal water status during drought which comes at the cost of reduced photosynthesis and carbon gain (Tardieu and Simonneau, 1998). In contrast, drought-tolerant, or 'anisohydric' species, allow their internal water status to decrease during drought in order to maintain photosynthesis which also increases the risk of 'hydraulic failure' of the water transport system (Tardieu and Simonneau, 1998). While these definitions help us to describe different drought response strategies and speculate about their behaviour under certain conditions, in reality species sit on a continuum of iso-anisohydry (Franks et al., 2007; Klein, 2014). Both avoidance and tolerance strategies exist in dry environments and across life-forms (McDowell et al., 2008). The suitability of these strategies for green roofs has received little attention (Raimondo et al., 2015).

On green roofs, drought avoidance versus tolerance is a trade-off between maintaining stomatal conductance in drying substrates to increase available storage for rainfall retention and minimising the risk of severe drought stress (MacIvor et al., 2011; Raimondo et al., 2015). In drought-prone ecosystems, a common drought resistance strategy of plants is to develop extensive root systems which access deep soil moisture (Groom, 2004; West et al., 2012). Such strategies are unlikely to work in green roof systems (Raimondo et al., 2015), where access to water is limited due to free-draining, shallow substrates which dry out rapidly after rainfall (Voyde et al., 2010b). In contrast, plants which avoid drought and maintain high water status at stomatal closure are likely to be the best survivors on green roofs (Raimondo et al., 2015); however if these plants use little water then they will not achieve adequate rainfall reduction.

To select appropriate green roof species for local conditions, we need to understand the potential trade-off between rainfall retention performance and the risk of drought stress experienced by plants. In this study, we used a water balance model based on plant physiological relationships derived from a glasshouse experiment to run a 30-year simulation to determine: (i) which plant strategies are more likely to maximise hydrological performance (rainfall retention) without jeopardising survival, (ii) which plant-based parameters are driving this trade-off and (iii) how the trade-off is affected by climatic parameters.

2. Materials and methods

2.1. General description of water balance model

Our water balance model was coded in R, version 3.0.3 (R Core Team, 2014) and the structure follows previous green roof studies (e.g. Stovin et al., 2013; Stovin et al., 2012), according to Eq. (1):

$$\frac{dS}{d_t} = P - R - ET \quad (1)$$

where the change in soil moisture stored in the substrate per unit time (dS/d_t) is equal to precipitation (P; mm) minus runoff (R; mm) and evapotranspiration (ET; mm). Previous green roof modelling studies have described the behaviour of such hydrological flux models (Stovin et al., 2013). Here, we focus on the key points of difference in our model: (i) how ET is calculated and (ii) how fluctuations in soil moisture affect plant drought stress. A brief description of the working of the model follows and detail on each step can be found in subsequent sections.

As a daily time-step rainfall retention model, the order of operations begins with the depth of water stored in the substrate on the previous