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Green roofs for hot and dry climates: Interacting effects of plant water use, succulence and substrate

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ABSTRACT

Green roofs are increasingly being constructed in urban environments to provide a range of environmental benefits. However, little is known about how they will perform in hot and dry climates where water is often limiting and drought tolerance determines plant survival. We evaluated the effects of severe drought (113 days without water) on growth, water use and survival of five succulent species (*Sedum pachyphyllum*, *S. clavatum*, *S. spurium*, *Disphyma crassifolium* and *Carpobrotus modestus*) planted in three different green roof substrates (growing media) differing in water holding capacity. Plants survived 12 days longer in substrates with higher water holding capacity. Water use determined survival under severe drought with species with higher water use (*D. crassifolium* and *C. modestus*) dying at least 15 days earlier than *Sedum* species which were conservative water users. Increased survival was not related to increased leaf succulence but was related to reduced biomass under drought. Under well-watered conditions, water use was greatest in species with lower leaf succulence in substrates with increased water holding capacity. To maximise survival, green roofs in year round or seasonally hot and dry climates should be planted with species that have high leaf succulence and low water use in substrates with high water holding capacity.

1. Introduction

Green roofs are increasingly being built to provide a diverse range of environmental benefits. These include energy conservation through improved building insulation and energy efficiency (Sailor, 2008), mitigation of the urban heat island effect (Bass and Baskaran, 2003), noise attenuation (Van Renterghem and Botteldooren, 2009), biodiversity habitat provision (Brenneisen, 2006) and urban stormwater management (Berndtsson, 2010; VanWoert et al., 2005). Green roofs are constructed profiles made up of layers including water-proofing, drainage (gravel or proprietary system) and substrate (growing media) layers in which plants are grown. Weight loading restrictions on buildings limit the depth of substrate (often <20 cm) on retrofitted green roofs. This makes green roofs difficult environments for plant growth and survival as water availability fluctuates dramatically between rain events (Nagase and Dunnett, 2010; Oberndorfer et al., 2007). Consequently, survival during drought periods determines plant species suitability for green roofs (Bousselot et al., 2011), especially in hot and dry climates.

Survival on green roofs is determined by substrate depth and physical properties, particularly water holding capacity. Drought tolerance of *Sedum* species in response to substrate depth has been widely investigated, with increased survival in greater depths (Durhman et al., 2007; Getter and Rowe, 2009; VanWoert et al., 2005). However, there has been little comparison of species performance under drought conditions in different substrates with different physical properties. For long term success, green roof substrates need to balance a number of competing and sometimes contrasting properties. Good aeration and low bulk density are needed to ensure the substrate is free draining, lightweight and facilitates plant respiration, yet this must be balanced against sufficient water retention for plant growth and survival (Nektarios et al., 2004; Rowe et al., 2006; Thuring et al., 2010). These properties can be achieved with light weight components; however, many components, particularly organic materials, shrink and/or decompose over time, therefore green roof substrates are largely mineral based. Mineral based substrate composition differs according to local availability and cost, and many include recycled or waste products to maximise the environmental benefits of green roofs (Molineux et al., 2009). Most green roof substrates are developed according to specified performance guidelines and standards, notably the widely used German FLL guidelines (FLL 2008) or the more recent American Standard Testing Methods (ASTM 2009a,b,c, ASTM 2010). Both specify value ranges and limits for different substrate properties and the required testing methodologies.

The plants most commonly used on European and North American green roofs in temperate climates are succulents from the

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genus *Sedum* (Oberndorfer et al., 2007; Snodgrass and Snodgrass, 2006). *Sedum* species are considered ideal for green roofs due to their low spreading habit, providing good lateral cover, and drought tolerance (Nagase and Dunnett, 2010; VanWoert et al., 2005). Their drought tolerance is largely due to high leaf succulence and physiological adaptations such as CAM (Crassulacean Acid Metabolism) photosynthesis (Butler, 2012; Durhman et al., 2006). CAM plants have greater water use efficiency than C3 plants as transpiration per unit CO_2 fixed is reduced due to stomata opening at night for CO_2 uptake (Sayed, 2001). Some *Sedum* species are also considered facultative CAM (Kluge, 1977), shifting from C3 to CAM photosynthesis under stressful conditions such as drought, salinity or elevated temperature (Sayed, 2001). Leaf succulence enables plants to survive periodic drought by providing usable water when soil water conditions prevent uptake by roots (von Willert, 1992). Many *Sedum* species used on green roofs have been selected from alpine areas for their frost tolerance and enhanced survival during winter (Durhman et al., 2007), including *Sedum album*, *S. acre*, *S. reflexum* and *S. spurium*. As a consequence of higher frost tolerance, these species exhibit reduced leaf succulence (Osmond et al., 1975; Teeri et al., 1981). As the degree of leaf succulence directly influences drought tolerance (von Willert, 1992), these *Sedum* species may be less suitable in hot and dry climates than species with greater succulence (Williams et al., 2010b).

Despite widespread implementation in cooler northern hemisphere climates, there are very few extensive green roofs in hot and dry climates (Williams et al., 2010b). Successful implementation of green roofs in hot and dry climates is important as the environmental benefits are likely to be far greater in than in temperate climates (Alexandri and Jones, 2008). However, it is problematic to rely on temperate northern hemisphere green roof practices without scientific testing (Williams et al., 2010b), due to climatic differences, access to suitable substrate and plants and limited information on plant performance under drought conditions (Bousselot et al., 2011). To date little research has been done to determine drought tolerance of green roof succulents and the suitability of different substrates in year round or seasonally hot and dry climates.

This paper describes an experiment that determined the effects of drought on plant growth, survival and water use of five succulent species, with varying degrees of leaf succulence, grown in three different substrates that were developed according to the FLL guidelines. This drought experiment had two objectives: (i) to determine how substrate water holding capacity affects plant water use and survival; and (ii) to determine whether leaf succulence affects plant survival.

2. Materials and methods

Five succulent species were evaluated, three introduced *Sedum* species (*S. pachyphyllum* Rose, *S. clavatum* Clausen and *S. spurium* Marshall von Bieberstein) and two Australian species (*Carpobrotus modestus* S.T. Blake and *Disphyma crassifolium* L.) (Table 1). The Sedum species are likely to be obligate CAM plants, however little is known about their CAM strategies. Butler (2012) found that although *S. spurium* showed nocturnal CO_2 accumulation they did not show nocturnal CO_2 uptake. The two Australian species are facultative CAM plants when water is limiting (Winter et al., 1981). Three month-old cuttings of each species were planted on December 1, 2010 into 200 mm diameter pots containing one of the three substrates (160 mm deep substrate). As Cuttings had been grown in commercial potting mix, as much of this mix as possible was removed prior to planting to reduce the effects of this media on the water holding capacity of the green roof substrates. These were comprised of 80% readily available mineral components, either scoria, crushed roof tiles or bottom ash from coal fired power stations and 20% horticultural grade coir (Rayner et al., unpublished data). Table 2 shows the aggregate sizes of the mineral components for the three green roof substrates. Scoria and crushed roof tile components were sourced locally from Melbourne, Victoria, while the bottom ash was sourced from coal-fired power stations in New South Wales. Whilst conforming to the FLL guidelines (2008), the three growing media differed in physical and chemical properties (Table 2), including water holding capacity (WHC). Bottom ash had a significantly higher WHC than either scoria or roof tile. Low WHC of the substrates was related to a higher air-filled porosity (AFP) in scoria but not in roof tile, which has a similar AFP to bottom ash.

As the three substrates differed in bulk densities, substrates were added by weight to pots to ensure the same volume (equivalent oven dried weight = 2702.8 g scoria; 3904.6 g roof tile; and 2051.2 g bottom ash substrate). This diameter pot approximates planting density on established green roofs in Melbourne (25 plants m^{-2}). Fine mesh squares were placed in the bottom of pots to prevent loss of substrate. One month post-planting 12 g of slow release fertiliser (Osmocote® plus, Scotts Australia Pty Ltd.; 16 nitrogen (N):1.3 phosphorus (P):9.1 potassium (K)) was added to the surface of each pot.

2.1. Experimental design

The drought experiment ran for 113 days (25 January to 17 June, 2011) and was conducted in a temperature controlled glasshouse at The University of Melbourne's Burnley campus, Melbourne, Australia (−37.828472, 145.020883). Daytime temperature ranged between 6 and 49 °C with a mean of 21.4 °C, and night-time temperatures ranged between 6 and 28 °C with a mean of 15.7 °C. We used a factorial randomised block design with substrate and watering regime (drought or well-watered) as treatments, with five replicates. All plants were watered weekly until the start of experiment (25 January 2011) when they were considered well established. Plants were considered well established when above ground growth was sufficient to cover the pot's surface. Two treatments were implemented: well-watered (WW) and droughted (D). Well-watered plants were watered once a week to pot capacity from days 1 to 85, then fortnightly until day 113 as evaporative demand declined. Droughted plants were watered to pot capacity at the start of the experiment then received no further watering.

2.2. Plant growth, biomass, leaf succulence and survival

At the start of the experiment, five plants of each species were harvested to determine initial biomass (root and shoot mass). During the experiment plant survival was determined by visual assessment. Plants were considered dead when all leaves were dry and shrivelled. They were then harvested to determine plant biomass. Fallen leaves were retained and added to shoot biomass. On June 17 (day 113) all surviving plants were harvested to determine total plant, shoot and root masses. Root mass was determined by thoroughly washing substrate away from plant roots over a sieve to ensure minimal root loss. Any substrate still adhering to roots was removed after drying roots in the oven. Dry weights were determined after oven drying samples at 70 °C to a constant weight. Dry weights were used to determine shoot to root ratio (g shoot g^{-1} root). Ten leaves from well-watered plants of each species were sampled to determine leaf succulence, determined as: Leaf succulence = water content of leaf/surface area of leaf (Jones, 2011). Leaf areas of individual leaves were measured using ImageJ 1.43 software (NIH, USA).