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Plant establishment on a green roof under extreme hot and dry conditions: The importance of leaf succulence in plant selection

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A B S T R A C T

Plant selection for extensive green roofs has largely been based on cool, temperate climate research. However, as green roof implementation in hotter and drier climates increases, there is a need to evaluate plant performance under these climatic conditions. Succulents have been shown to be successful in hot and dry green roofs, although survival differs between species and the role of leaf succulence in survival has not been fully explored. For non-succulent plants, habitats with conditions similar to green roofs ('habitat templates') have been used to select plants, although few studies have discussed the performance of these selections under green roof conditions. Therefore, we evaluated establishment of 32 plant species on an unirrigated extensive (125 mm deep) green roof in Melbourne, Australia over a 42 week period (from winter through summer into autumn). Plants were selected on the basis of life-form, succulence, appropriate habitat templates and/or successful use on green roofs internationally. Climatic conditions during the experiment were often extreme, with evaporation regularly exceeding rainfall and a hot and dry summer (mean maximum air temperature 35 °C and 80.6 mm total rainfall), leading to roof temperatures of 65 °C. After 42 weeks, only succulent plants remained alive and only three of the succulent species had 100% survival. Survival was positively related to the degree of leaf succulence ($g\,H_2O$ leaf area cm^{-1}) making this a useful trait for plant selection for unirrigated green roofs in hot, dry climates. The failure of most species, despite being chosen from appropriate habitats, demonstrates the need to evaluate potential plants on green roofs under extreme climatic conditions. Supplementary irrigation may be essential to sustain non-succulent species during extreme weather in hot and dry climates.

1. Introduction

In cities worldwide, green roofs are increasingly being constructed because of their multiple environmental, social and economic benefits, including improved stormwater management, increased longevity of roof membranes, reductions in building heat loads, contributions to wildlife habitat provision and reduced noise and air pollution (Oberndorfer et al., 2007; Rowe, 2011). The vegetation used in lightweight, shallow extensive green roofs is generally restricted to low growing and shallow rooted perennial species with multiple tolerances to drought, heat, cold, wind and pests and diseases (Snodgrass and Snodgrass, 2006).

Plant selection for extensive green roofs has largely been based around experience, observation and research from temperate regions of Europe and North America (Dvorak and Volder, 2010; Oberndorfer et al., 2007) where drought periods are measured in weeks rather than months, and where ambient air temperatures rarely exceed 35 °C (Lundholm et al., 2010; Nagase and Dunnett, 2010). However, as green roof implementation in hotter and drier climates is expanding, there is a need to evaluate plant establishment on green roofs in these regions (Benvenuti and Bacci, 2010; Bousselot et al., 2011; Papafotiou et al., 2013; Van Mechelen et al., 2014). This is important as plant failure has been identified as a major barrier to developing successful green roofs in these regions, particularly where the green roof industry is still in its infancy (Williams et al., 2010) and plant growth conditions on green roofs are often harsher than in green roof modules at ground level or in pot-based experiments (Dvorak and Volder, 2010). Differences in climate and plant availability mean it is not appropriate to assume that the same plant species will be universally suitable (Williams et al., 2010).

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Traditionally two approaches for plant selection have been used: the plant trait approach and the habitat template approach. The plant trait approach uses traits such as succulence to select drought tolerant plants for green roofs. To date, the most common plants used on green roofs worldwide are succulents, principally *Sedum* species (Getter and Rowe, 2008; Monterusso et al., 2005; Snodgrass and Snodgrass, 2006). They achieve drought tolerance through low water use, leaf water storage (Farrell et al., 2012) and often Crassulacean Acid Metabolism (CAM) (Butler et al., 2011; Durhman et al., 2006). CAM leads to greater water use efficiency through opening of stomata at night for CO_2 uptake, greatly reducing water lost through transpiration per unit CO_2 fixed (Sayed, 2001). Leaf water storage, or succulence, (expressed as g water cm^{-2} leaf area) enables plants to survive dry conditions by providing water that can be used to maintain plant function when water is unavailable for uptake by roots (von Willert, 1992). Generally, plants with greater succulence are able to survive longer periods without water (von Willert, 1992), however, many common green roof *Sedum* species such as *Sedum acre* and *Sedum album* exhibit reduced succulence, enabling these species to also tolerate winter frosts and sub-zero temperatures in temperate climates (Osmond et al., 1975; Teeri et al., 1981). Consequently, *Sedum* species with low succulence may be less suitable for green roofs in hot and dry climates than species with greater succulence (Williams et al., 2010). The habitat template approach is based on selecting plants from habitats analogous to extensive green roofs, such as rocky barrens or outcrops (Farrell et al., 2013; MacIvor and Lundholm, 2011), prairies or grasslands (Sutton et al., 2012), and annual and perennial wildflowers from agricultural systems and roadside environments (Benvenuti, 2014). For example in an analysis of species from shallow soil habitats in southern France, Van Mechelen et al., (2014) identified 28 plant species as being potentially suitable for hot and dry Mediterranean green roofs. However, as demonstrated in a number of green roof experiments, theoretical suitability does not guarantee survival in hot and dry conditions (Benvenuti and Bacci, 2010; Vestrella et al., 2015; Zhang et al., 2014), confirming the need to evaluate new potential species in green roofs. Differences in the performance and survival of these plants under water limitation often reflect differences in plant traits (Lundholm et al., 2015) and physiological strategies for dealing with water stress (Farrell et al., 2013; Raimondo et al., 2015).

While researchers have evaluated plant establishment through summer on green roofs with species chosen using the habitat template approach, few have looked at extreme conditions, where elevated temperatures and rainfall deficits of several months create extremely hostile conditions for plant survival. Further, although succulence has been used extensively as a trait to select plants for green roofs, the influence of the degree of succulence on plant survival has not been investigated. Therefore, we evaluated plant establishment over 42 weeks in an extensive green roof in Melbourne, Australia. Thirty two plant species were selected on the basis of leaf succulence (succulent species only), appropriate green roof habitat templates or use on green roofs internationally. The objectives of the study were to (1) compare and evaluate plant health, vigour and survival of the 32 species and (2) explore the effects of differences in life-forms and degree of leaf succulence on plant establishment.

2. Materials and methods

2.1. Study location and climate

A 20 m^2 extensive green roof was constructed on a 6.6 m high brick building at the Burnley Campus of The University of Melbourne, Australia (37°47′S; 144°58′E). Melbourne's climate is characterised by cool, wet winters and dry, hot summers. Melbourne's mean annual rainfall is 648.4 mm (1855 to 2015), with 153.9 mm falling in summer months (Bureau of Meteorology, 2014). Mean annual temperatures range between 10.2 and 19.9 °C with maximum mean temperatures in January (25.9 °C) and minimum mean temperatures in July (6.0 °C) (Bureau of Meteorology, 2014).

2.2. Experimental green roof

A square galvanised steel frame (200 mm high) was placed on the flat, bitumen sealed roof to support the green roof profile 20 m^{-2} which comprised, from base to top: a high density plastic root barrier sheet (Zinco Root Barrier WSF 40); moisture retention and protection layer (Zinco SSM 45); a high-density polyethylene 40 mm drainage layer (Zinco Floradrain® FD40-E); a geotextile filter sheet layer (Zinco Filter Sheet SF), and a mineral-based substrate. The 125 mm deep mineral-based substrate consisted of (by volume): 50% scoria 10 mm minus, 20% scoria 7 mm aggregate; 20% coarse washed sand 1–2 mm and 10% horticultural grade coir. Controlled release fertiliser (Scotts Osmocote plus, Low P, 8–9 months N16: P1.3: K9.1) was added at a rate of 1.5 kg m^{-3}. The physical and chemical properties of the substrate were tested using Australian Standards procedures (Australian Standard, 2003a,b) as described in Farrell et al. (2012) for air-filled porosity (14.1%), volumetric water content at field capacity (34%), bulk density (wet: 1.21 kg m^{-3}; dry: 0.85 kg m^{-3}); pH (7.1) and soluble salts (463 $\mu S\, cm^{-1}$ EC). The total saturated weight loading of the substrate at 125 mm depth was 170.9 kg m^{-2}. Thermocouples recorded temperature at multiple locations; including on and through the green roof profile, on the surface of the adjoining bitumen roof and in two control rooms located beneath the roof (Fig. 3).

The green roof was subdivided into four rectangular quadrants, each 4.2 m^2 in area with two intersecting pathways through the middle (Fig. 1). The 32 herbaceous plant taxa used in the experiment (Table 1) were selected on the basis of leaf succulence (succulent species only), appropriate green roof habitat templates (Australia) or evidence of green roofs use internationally. For Australian species, plains grasslands, coastal dunes and salt lake communities provided the habitat template for plant selection. Consideration was also given to select species that were perennial, low growing/spreading, moderate to high in vigour, tolerant of water deficits (where known) and readily available from commercial suppliers. Plants were then categorised into four life-form groups: forbs (9 species), monocots (8 species), upright succulents (6 species) and prostrate succulents (9 species). Each group was planted in one of the four quadrants, with ten replicates planted randomly on a 20 × 20 cm grid spacing (Fig. 1). Plants were obtained as tube stock in 100 mm deep pots (200 ml volume) and were planted on 16 July, except for *Kleinia mandraliscae*, *Carpobrotus rossii* and *Tetragonia implexicoma* which were planted on 22 August. Plants were irrigated as required (minimum of 25 mm of supplementary water supplied by hand twice per week) for six weeks post-planting to assist establishment.

2.3. Assessment of plant performance

Plant survival was monitored weekly for 30 weeks after planting (16 July to 13 February when most plants were dead), then monthly for the remaining 12 weeks until the end of the experiment (8 May). Plants were considered alive if any green shoots or tissue were observed at the base of the plant. All plants that died during the experiment were left in-situ to allow for the possibility of regeneration through re-seeding or re-sprouting.

Plant health and vigour for all species were also rated visually each month throughout the experiment on a scale of 0 to 4 for (i)