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Green roofs for a drier world: Effects of hydrogel amendment on substrate and plant water status

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HIGHLIGHTS

- Green roof technology is still under-represented in arid climates.
- We assessed the potential advantages of polymer hydrogel amendment.
- Hydrogel amendment significantly improved substrate and plant water status.
- Reduced substrate depth sustained lower plant biomass independent of the amendment.
- Hydrogel allowed to reduce substrate depth improving small sized plant water status.

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ABSTRACT

Climate features of the Mediterranean area make plant survival over green roofs challenging, thus calling for research work to improve water holding capacities of green roof systems. We assessed the effects of polymer hydrogel amendment on the water holding capacity of a green roof substrate, as well as on water status and growth of *Salvia officinalis*. Plants were grown in green roof experimental modules containing 8 cm or 12 cm deep substrate (control) or substrate mixed with hydrogel at two different concentrations: 0.3 or 0.6%. Hydrogel significantly increased the substrate's water content at saturation, as well as water available to vegetation. Plants grown in 8 cm deep substrate mixed with 0.6% of hydrogel showed the best performance in terms of water status and membrane integrity under drought stress, associated to the lowest above-ground biomass. Our results provide experimental evidence that polymer hydrogel amendments enhance water supply to vegetation at the establishment phase of a green roof. In particular, the water status of plants is most effectively improved when reduced substrate depths are used to limit the biomass accumulation during early growth stages. A significant loss of water holding capacity of substrate-hydrogel blends was observed after 5 months from establishment of the experimental modules. We suggest that cross-optimization of physical–chemical characteristics of hydrogels and green roof substrates is needed to improve long term effectiveness of polymer-hydrogel blends.

1. Introduction

Green roofs are an example of ecological engineering technology addressed at partially replacing vegetation that was removed to construct buildings. This green technology is largely accepted as a useful measure to address environmental impacts of urban areas while allowing sustainable development (Getter and Rowe, 2006). Recent studies have demonstrated that implementation of green roofs in urban areas can reduce the urban heat island effect (Kolokotsa et al., 2013; Santamouris, 2012), reduce and delay storm-water runoff (Nagase and Dunnett, 2012; Speak et al., 2013), improve air and water quality (Li et al., 2010; Rowe, 2011; Vijayaraghavan et al., 2012), improve noise reduction (Van Renterghem and Botteldooren, 2009), contribute to thermal insulation of buildings with consequent energy savings (Sailor, 2008; D'Orazio et al., 2012), and favor habitat and biodiversity conservation (Baumann, 2006; Brenneisen, 2006; Bates et al., 2013). Green roofs are often quoted to provide additional social (Francis and Lorimer, 2011) and environmental benefits, including the possibility to use or re-use recycled materials in their construction (Bates et al., 2013; Farrell et al., 2013; Mickovski et al., 2013) and to produce bioelectricity exploiting living plants and microbial fuel cells (Helder et al., 2013).

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Modern green roofs generally include a waterproofing and root-resistant membrane which protects the rooftop against root penetration and damage, a water retention layer designed to store water, a drainage layer that allows excess water to flow away from the roof, a filter fabric preventing the loss of fine soil particles, and a lightweight mineral substrate and vegetation. Green roof installations can be categorized as intensive versus extensive. While intensive green roofs have thicker substrate depth (>15–20 cm) and can support shrubs and even small trees, extensive green roofs are characterized by thinner substrates (<15–20 cm), where only small sized vegetation can thrive successfully (Getter and Rowe, 2006; Oberndorfer et al., 2007). Due to their lower costs as well as to widespread building mechanical limitations, extensive green roofs are much more common than intensive ones.

Green roof technology has become increasingly important in the last 20 years, and thousands of installations have been realized worldwide, especially in countries characterized by temperate and subtropical climates (Brenneisen, 2006; Li et al., 2010; Smith and Roebber, 2011; Speak et al., 2013). Germany is considered as one of the leading countries in green roof development, with over 14% of roofs artificially greened (Herman, 2003). Chicago is one of the leading cities, with more than 50 000 m^2 green roof installed only in 2008 (Smith and Roebber, 2011). In the Mediterranean climate, the interest in this technology is increasing, although research and installation efforts are still limited (D'Orazio et al., 2012; Santamouris, 2012; Farrell et al., 2013; Kolokotsa et al., 2013; Olate et al., 2013). This is likely due to the features of Mediterranean climate, characterized by high summer temperatures and prolonged seasonal drought, both making plant survival over green roofs quite challenging (Fioretti et al., 2010; Nardini et al., 2012; Savi et al., 2013).

In order to promote the development of green roof technology in Mediterranean climate, research work should be mainly addressed to selecting native plant species capable to survive under harsh environmental conditions (MacIvor et al., 2011; Olate et al., 2013; Van Mechelen et al., 2014), and to improving substrate water holding capacities to ensure larger amounts of available water while maintaining low substrate thickness, weight and related costs (Farrell et al., 2013; Papafotiou et al., 2013; Savi et al., 2013). Suitable species can be found in local habitats characterized by micro-climatic conditions similar to those prevailing over green roofs. As an example, Van Mechelen et al. (2014) analyzed ten plant traits relevant for heat and water stress resistance of 372 Mediterranean open habitat species, and selected 28 species with estimated good ability to acclimate and survive on green roofs. On the other hand, Savi et al. (2013) have recently shown that slight modification of green roof layering can improve water availability to plants, and Papafotiou et al. (2013) found that the use of grape marc compost amendment ensured higher substrate water holding capacities, allowing reduction of substrate depth without causing restriction of plant growth and survival at the establishment phase and during drought events.

Over the last decade, several studies focusing on agriculture, nursery management and forestry practices have demonstrated the potential of different polymer hydrogel amendments to increase water holding capacity of potting mixtures and natural soils (Arbona et al., 2005; Sojka et al., 2007; Luo et al., 2009). Hydrogels are synthetic superabsorbent polymers generally constituted by water-insoluble highly cross-linked polyacrylamides which can absorb water up to 400 times their own weight when saturated (Bouranis et al., 1995; Oschmann et al., 2009). Luo et al. (2009) recorded a 36% increase in water holding capacity when mixing the growing medium with 0.6% (w/w) of polymer hydrogel, while Akhter et al. (2004) reported a linear relationship between percentage of hydrogel amendment (0.1%, 0.2% and 0.3%) and increase of water content at field capacity for both sandy-loam (17%, 26% and 47%) and loam (23%, 36% and 50%) soils. Application of hydrogel to the rhizosphere of *Pinus sylvestris* seedlings improved the survival rate of plants by 19% during land reclamation (Sarvaš et al., 2007). Apparently, when hydrogels are added to the substrate plant growth is improved, drought effects are delayed and the frequency of irrigations can be reduced (Akhter et al., 2004; Arbona et al., 2005; Shi et al., 2010; Chirino et al., 2011).

Recent studies have suggested that the use of hydrogel polymers can enhance the water holding capacity and plant available water of green roof substrates (Oschmann et al., 2009; Olszewski et al., 2010; Farrell et al., 2013). As a consequence, the timespan before permanent wilting of *Triticum aestivum* and *Lupinus albus* grown in green roof experimental modules, as well as their root and total dry masses, increased in response to hydrogel amendment (Farrell et al., 2013). Oschmann et al. (2009) and Olszewski et al. (2010) found that hydrogels significantly increased coverage and regeneration of grasses and *Sedum* species over green roofs.

The aim of the present study was to specifically test the effectiveness of hydrogels added to green roof substrate in ameliorating plant water status, drought resistance and survival. We specifically tested: a) water relation properties and related variations over a short-time interval of substrate, polymer hydrogel and substrate-hydrogel blends; b) possible differences in water status of plants growing on substrate or substrate-hydrogel blends; and c) minimum substrate thickness and suitable hydrogel concentrations assuring plant survival during intense drought episodes.

2. Materials and methods

2.1. Study area

The study was carried out over the roof of the Dept. of Life Sciences, University of Trieste (Trieste, 45°39′40″ N, 13°47′40″E) between early April and late September 2013. Climate data for the area in the period 1995–2012 (http://www.osmer.fvg.it) report an average annual temperature of 15.7 °C, with a maximum of 25 °C and a minimum of 6.8 °C reached in July and January, respectively. Mean annual rainfall is 843 mm, with most precipitation occurring between September to November (290 mm) and relatively dry periods in January–February (105 mm) and July (55 mm).

2.2. Experimental modules and plant material

Wooden beams were used to construct three test beds (each measuring 2 m^2) over a flat rooftop. Each test bed, lying on a 20 mm thick drainage element, was divided into ten experimental modules 40 cm × 40 cm each (for a total of 30 modules) using wood dividers. The green roof layering was assembled using the following materials provided by Harpo Spa, Trieste, Italy: water retention tissue Idromant4 (thickness 4 mm, weight 400 g/m^2), plastic profiled drainage panel Medidrain MD40 (thickness 4 cm, water retention 4 l/m^2); geotextile filter membrane MediFilter MF1 and SEIC substrate for extensive green roof installation (dry bulk density 848 kg/m^3, Fig. 1a). The holes (2.5 mm) of Medidrain MD40 were widened to a diameter of 6 mm and increased in number (from 300 holes/m^2 to 600 holes/m^2), according to Savi et al. (2013). The substrate is based on a mix of mineral material (lapillus, pomix and zeolite) enriched with 2.9% organic matter. Grain size ranged from 0.05 mm to 20 mm with a total porosity of 67.35%, pH = 6.8, drainage rate of 67.36 mm/min, and a cation exchange capacity and electrical conductivity equaling about 23.8 meq/100 g and 9 mS/m, respectively.

Experimental modules were divided into two main categories on the basis of substrate depth: 8 cm and 12 cm. Within each category, 10 modules were filled with substrate mixed with a water-absorbent polymer hydrogel (cross-linked polyacrilic acid-potassium salt, STOCKSORB 660 medium, Evonik Industries) at two concentrations i.e. 0.3% w/w (5 modules) and 0.6% w/w (5 modules). Five modules per depth were used as controls (substrate only). Hence, six different layering types were assembled, each replicated five times (Fig. 1b).

On April 17th 2013, one individual of *Salvia officinalis* L. (Common sage) was transplanted in each module. Potted plants were provided by a local nursery and were all of similar size at the time of planting.