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Drought stress response of *Sedum sediforme* grown in extensive green roof systems with different substrate types and depths☆,☆☆

Panayiotis A. Nektarios*, Nikolaos Ntoulas, Efthimia Nydrioti, Iro Kokkinou, Eleftheria-Maria Bali, Ioannis Amountzias

Laboratory of Floriculture and Landscape Architecture, Dept. of Crop Science, Agricultural University of Athens, 75, Iera Odos, Athens 118 55, Greece

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ABSTRACT

Sedums are considered among the best plant species for use on extensive green roof types. The present study evaluated the growth capacity of native *Sedum sediforme* (Jacq.) Pau in extensive green roof systems that varied in substrate type and depth as well as in the applied irrigation regime. The two substrate types included either soil-less (Pum_{50}:Per_{20}:C_{20}:Z_{10}) or soil-amended substrate (S_{15}:Pum_{40}:Per_{20}:C_{20}:Z_5) that comprised sandy loam soil [S], pumice [Pum], perlite [Per], compost [C], and zeolite [Z] at volumetric proportions indicated by their subscripts. Each substrate type was used at two depths (7.5 or 15 cm). During the summer drought periods two different irrigation regimes (high and low) were utilised: (a) in 2010, the high irrigation regime replenished 30% of the cumulated daily pan evaporation (E_{pan}) between consecutive irrigation applications, while the low irrigation regime replenished half of it (15% E_{pan}) and (b) in 2011, the high irrigation regime remained the same as in 2010, while the low irrigation regime was not irrigated at all. Measurements included physical and chemical characterisation of the utilised substrates as well as plant growth and physiological measurements that included plant height, dry weight, chlorophyll and carotenoid determination. It was found that during the first study year plant growth was promoted by the soil-less substrate, which was also depicted in the prolific flowering in the following study year, while chlorophyll and carotenoid content increased in the deeper substrates. By contrast, in the second study year plant growth and physiology was mainly enhanced in deeper substrates, while substrate type was indifferent. Despite the observed differences *S. sediforme* was able to survive under minimal or no irrigation even at the shallow depth of 7.5 cm and proved to be a native plant species that could successfully be utilised in extensive green roof systems in the Mediterranean and other semi-arid climatic regions.

1. Introduction

Green roofs are considered an upcoming technology for greening urban landscapes. Their introduction in city centres has multiple and versatile advantages for the urban environment, that include building energy savings (Kotsiris et al., 2012), mitigation of urban heat island effect (Akbari et al., 2001; Dunnett and Kingsbury, 2010; Getter and Rowe, 2006; Wong et al., 2003), noise and dust abatement (Liesecke and Borgwardt, 1997; Rowe, 2011; Van Renterghem and Botteldooren, 2009), and storm water management (Moran et al., 2004; VanWoert et al., 2005).

In addition, green roofs enable the re-introduction of lost native flora within the built city environment, which in turn facilitates fauna rehabilitation (Brenneisen, 2003; Wolf and Lundholm, 2008). On the other hand, it has been emphasised that old and aged buildings, which account for the largest proportion of existing constructions in urbanised city centres, can only withstand minimal additional loads. This can be achieved with the use of extensive green roof types that are characterised by shallow substrate depth, varying from 5 to 15 cm and having a saturated weight of 70–140 kg m^{-2}. Given that maintenance requirements are minimal, extensive green roofs are the cheapest of all planted green roof systems to construct and maintain.

Due to minimal substrate depth and the harsh environmental conditions that prevail on building's roof tops as well as their reduced maintenance requirements, plants with special

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* Corresponding author. Tel.: +30 2105294554; fax: +30 2105294553.
E-mail address: pan@aua.gr (P.A. Nektarios).

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characteristics must be utilised to achieve sustainability on extensive green roofs. To date, the most successful extensive green roof flora consists of succulent plants, particularly those of the *Sedum* genus (Durhman et al., 2007; Snodgrass and Snodgrass, 2006). *Sedums* are succulent plants with the capacity to enable the crassulacean acid metabolism (CAM) pathway when stressed by drought. In contrast to C_3 and C_4 metabolic pathways, CAM plants stomata open and absorb atmospheric CO_2 during the night, thus coinciding with minimal evapotranspiration demands (Ting, 1985). Moreover, CO_2 assimilation to carbohydrates occurs during the daytime with the stomata being closed (Borland and Dodd, 2002).

However, depending on the species and on environmental stresses, plants can be categorised into obligatory or facultative CAM cycle, while the amplitude of the CAM cycle itself can vary according to plant species, its developmental stage, and the environmental conditions (Winter and Smith, 1996). CAM metabolism has contributed to *Sedum* sp. being considered as one of the most promising plant species for extensive green roofing with minimal maintenance and increased tolerance to various rooftop environmental stresses. Aside from their reduced transpiration demands, the *Sedum* species are considered the preferred choice for extensive green roofs due to several other capacities that include a non-aggressive root system and their ability to sustain growth in shallow substrates (Durhman et al., 2007).

The *Sedum* species have been investigated as plant material for extensive green roofs by several researchers. Thuring et al. (2010) compared the survival of two *Sedum* species and three perennial plants when subjected to early or late drought, under two substrate types and three substrate depths (3, 6 and 12 cm). They found that *Sedum* survival was the highest compared to the remaining plant species, especially at the shallowest depths and even under the imposition of drought soon after planting.

Getter and Rowe (2009) evaluated the effects of substrate depth (4, 7 and 10 cm) on plant community development and survival of 12 *Sedum* species over a period of 4 years in Michigan, USA. They found that the *Sedum* species responded differently depending on the depth of the substrate, and also on their survival over the course of the 4-year study since some plants lasted for the entire 4-year period, while some others lasted for 1 or 2 years. *Sedum sediforme* (Jacq.) Pau that was included in the study preferred deeper substrates, but was extinguished after 2 years from all depth treatments. In the shallow substrate depth of 4 cm, *S. sediforme* was extinguished from the experimental plots within the first year, while in substrate depths of 7 and 10 cm, it was extinguished during the second study year.

Monterusso et al. (2005) evaluated 20 native plant species, including two *Sedum* species, for their establishment capacity when placed over three different commercial drainage systems. They also demonstrated that *Sedums* and four other native plant species were able to survive without irrigation when drought stress was applied in the second study year.

Similarly, VanWoert et al. (2005) evaluated the growth of the *Sedum* plant species in different substrate types and depths with and without the placement of a water retaining fabric below the substrate layer under variable irrigation regimes. *Sedums* were capable of surviving and growing on all occasions even without the application of irrigation.

The aim of the current study is manifold: (a) to evaluate the establishment and growth of the native species *S. sediforme* (Jacq.) Pau under two substrate types developed from locally available materials aiming to minimise their CO_2 footprint, (b) to determine the impact of substrate depth on survival and growth of *S. sediforme* under drought stress conditions, and (c) to evaluate the response of *S. sediforme* growth to different irrigation regimes.

2. Materials and methods

2.1. Construction of experimental plots

The study was conducted at the experimental plots of the Laboratory of Floriculture and Landscape Architecture at the Agricultural University of Athens (lat 37° 59′ N, long. 23° 42′ 41″ E) from 20 March 2010 until 20 September 2012. The study comprised of 40 outdoor experimental plots, each of which was 60 cm × 58 cm. The experimental site was covered with perforated plastic liner and was levelled with the use of 200 mm coarse gravel bed. The experimental plots were constructed on top of the gravel shaft with wooden boards 20 mm thick × 200 mm wide. The wooden boards were utilised to separate adjacent plots and to prevent mechanical and hydrological continuity between them. The different substrate depth (either 7.5 or 15 cm) was accomplished by increasing or reducing the height of the gravel within each experimental plot.

In each experimental plot the entire layering structure of an extensive green roof system was simulated. More specifically, a protective synthetic cloth made of recycled polyester fibers was placed on top of the gravel layer. The protective cloth had a thickness of 3 mm, a weight of 0.32 kg m^{-2}, and retained 3 L m^{-2} of water (TSM32, Zinco, Egreen, Athens, Greece). This material is commonly used on green roofs for protecting the waterproofing membranes and for increasing water storage. On top of the protective cloth the drainage geocomposite comprised of an undulated recycled polyethylene core 25 mm in height, 1.5 kg m^{-2} in weight, and 3 L m^{-2} in water storage capacity (FD25, Zinco, Egreen). The geocomposite was covered with a non-woven geotextile (SF, Zinco, Egreen) made of heat-bonded polypropylene, with a thickness of 600 μm, a mass of 100 g m^{-2}, an aperture opening size (AOS) O_{90} of 95 μm, and a permeability of 0.07 m s^{-1}. The geotextile was stapled to the side boards and cut on all sides at a depth of 50–60 mm below the final substrate surface to prevent any wick-like capillary water movement towards the atmosphere. The experimental plots were then filled with the appropriate substrate. Substrates Pum_{50}:Per_{20}:C_{20}:Z_{10} and S_{15}:Pum_{40}:Per_{20}:C_{20}:Z_5 were composed by uniformly mixing pumice (Pum), perlite (Per), compost (C), clinoptinolite zeolite (Z), and sandy loam soil (S) in volumetric proportions indicated by the subscripts. The selected materials were locally available in an effort to reduce transportation costs and CO_2 footprint as well as to support local market products. The first substrate, Pum_{50}:Per_{20}:C_{20}:Z_{10}, was a soil-less mixture, while the second one had a small percentage of sandy loam soil in order to investigate the capacity of soil-less substrates to support sustainable plant growth. Particle size distribution was 0.05–8 mm for pumice (LAVA, Mineral & Quarry A.D., Athens, Greece), 0.8–2.5 mm for zeolite (S & B Industrial Minerals A.D., Athens, Greece) and 1–5 mm for perlite (Perloflor, ISOCON A.D., Athens, Greece). The sandy loam soil had 77.0% sand, 7.8% silt, 15.2% clay, and 0.703% (w/w) organic matter, a pH of 8.63, and an electrical conductivity (E.C.) of 80 μS cm^{-1}. The compost was provided by L. Kambanis S.A. (Spata, Greece); its chemical and nutritional characteristics are listed in Table 1. The substrates were formulated by mixing the ingredients uniformly in a concrete mixer and were sufficiently compressed after their placement into the experimental plots. The filled plots were then left to settle further by natural rainfall for 2 months.

2.2. Plant material handling

S. sediforme is a native perennial succulent plant with flowering stems of 25–60 cm height and shorter non-flowering shoots. Both flowering stems and non-flowering shoots have woody base. The leaves are succulent, oblong, flattened on the upper surface