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Drought versus heat: What's the major constraint on Mediterranean green roof plants?

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HIGHLIGHTS

- The use of hardy shrub species for roof greening should be increased.
- We monitored water status of 11 shrub species growing on shallow green roofs.
- Species heat and drought tolerance, growth, and survival were studied.
- High substrate temperature significantly affected plant survival.
- Root resistance to heat could be used as trait for species selection for green roofs.

GRAPHICAL ABSTRACT

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ABSTRACT

Green roofs are gaining momentum in the arid and semi-arid regions due to their multiple benefits as compared with conventional roofs. One of the most critical steps in green roof installation is the selection of drought and heat tolerant species that can thrive under extreme microclimate conditions. We monitored the water status, growth and survival of 11 drought-adapted shrub species grown on shallow green roof modules (10 and 13 cm deep substrate) and analyzed traits enabling plants to cope with drought (symplastic and apoplastic resistance) and heat stress (root membrane stability). The physiological traits conferring efficiency/safety to the water transport system under severe drought influenced plant water status and represent good predictors of both plant water use and growth rates over green roofs. Moreover, our data suggest that high substrate temperature represents a stress factor affecting plant survival to a larger extent than drought per se. In fact, the major cause influencing seedling survival on shallow substrates was the species-specific root resistance to heat, a single and easy measurable trait that should be integrated into the methodological framework for screening and selection of suitable shrub species for roof greening in the Mediterranean.

1. Introduction

Green roofs are engineered ecosystems representing an effective strategy to address some of the most challenging environmental issues

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in urban areas (Castleton et al., 2010; Berardi et al., 2014). In particular, green roofs have the potential to mitigate the quantity and quality of storm-water runoff, provide thermal insulation to buildings with related energy savings, extend the roof lifespan, mitigate the 'urban heat island', and provide space and habitats for urban biodiversity (Castleton et al., 2010; Madre et al., 2014; Benvenuti and Bacci, 2010; Cao et al., 2014; Vijayaraghavan and Raja, 2014). Extensive green roofs, characterized by shallow substrate, reduced weight and low maintenance costs, represent an innovative, energy-saving solution (Van Mechelen et al., 2014; Price et al., 2011). Over the last decades, the urban areas covered by green roofs has substantially increased in North and Central Europe and in temperate and sub-tropical regions worldwide (Castleton et al., 2010; Madre et al., 2014; Berardi et al., 2014; Thuring and Grant, 2015). More recently, research has focused on the implementation of green roofs in Mediterranean regions, where high temperatures and prolonged drought significantly challenge plant survival in these artificial habitats (Olivieri et al., 2013; Benvenuti and Bacci, 2010; Raimondo et al., 2015; Rayner et al., 2015).

A fundamental question addressed by Mediterranean green roof research is how to increase water retention capacity while keeping the substrate depth at a minimum. In fact, reducing substrate depth to limit installation costs apparently contrasts with the need to maximize the amount of water available to vegetation, and to minimize temperature extremes. In fact, another important aim of recent studies has been the selection of drought tolerant species that can survive the extreme green roof conditions in these hot and arid regions. There is evidence that targeted substrate amendments with hydrogel, peat, and biochar, or modifications to the layering design (substrate particle size, drainage panels etc.), have the potential to enhance the moisture retention properties of green roofs, thus increasing the volume of water available and improving plant water status and survival (Savi et al., 2013, 2014; Cao et al., 2014; Vijayaraghavan and Raja, 2014; Raimondo et al., 2015). Several criteria have been proposed to optimize species' selection for green roofs, but these are mainly based on ecological or morpho-anatomical approaches (Lundholm, 2006; Caneva et al., 2015; Van Mechelen et al., 2014; Rayner et al., 2015). Moreover, most screening studies have been focused on succulents or herbaceous species (Benvenuti and Bacci, 2010; Price et al., 2011; Van Mechelen et al., 2014; Rayner et al., 2015), while studies on shrubs as potential growth forms for green roof vegetation are still limited. Indeed, shrubs are generally characterized by a higher capacity in stomatal control of transpiration than herbaceous plants (Galmés et al., 2007; Farrell et al., 2013) and should be taken into serious consideration when selecting potential species assemblages for Mediterranean green roofs. Moreover, a selection process based on an ecophysiological approach might be more effective, at least when functional traits enabling plants to cope with stress factors, like drought and high temperature, are properly analyzed and quantified.

Plant tolerance to drought stress is commonly quantified in terms of symplastic and apoplastic vulnerability to dehydration. The former is generally correlated to the water potential inducing loss of cell turgor (Ψ_{tlp}, Bartlett et al., 2012). Low Ψ_{tlp} values allow drought-adapted plants to maintain cell turgor, stomatal aperture, and positive carbon gain even under low soil water availability and/or high atmospheric evaporative demand. On the other hand, apoplastic vulnerability to water stress is generally quantified in terms of xylem vulnerability to embolism formation. In fact, intense or prolonged drought can affect the root-to-leaf water transport by causing the breakage of water columns in xylem conduits (Tyree and Sperry, 1989), potentially leading to plant desiccation and death (Nardini et al., 2014b). Xylem hydraulic vulnerability is generally quantified in terms of P50 i.e., the xylem water potential inducing 50% loss of hydraulic conductivity (Choat et al., 2012), with species displaying lower P50 generally performing better under drought stress (Nardini et al., 2013) than species with relatively higher P50 values.

Water availability aside, high temperatures can also pose serious limitations to plant performance on green roofs. Heat stress can alter both membrane stability and enzymatic function and thus affects photosynthesis and respiration, altering carbon gain, growth, and secondary metabolism at the root and shoot levels (Wahid et al., 2007; Huang et al., 2012; Vile et al., 2012). Most importantly, shallow green roof substrates potentially expose root systems to temperature extremes that largely surpass those experienced by plants in natural soils. In fact, the root system is generally more vulnerable to heat stress compared to the shoot (Kuroyanagi and Paulsen, 1988). The co-occurrence of both drought and heat stress over green roofs poses important challenges to plant life, frequently leading to foliage desiccation, plant die-back, and ultimately death (Allen et al., 2010; Price et al., 2011; Nardini et al., 2013; Rayner et al., 2015), and also complicates the identification of key physiological traits allowing to predict plant performance on green roofs installed in arid regions.

To the best of our knowledge, a comparative study of physiological traits conferring resistance to drought and heat stress has never been coupled to the monitoring of plant performance on extensive green roofs. In this study, we contribute to this literature gap, by analyzing the performance in terms of growth and survival of 11 Mediterranean shrub species, established on shallow green roof experimental modules, as related to several indicators of their physiological vulnerability to water stress and high temperatures. We monitored plant water status, leaf symplastic resistance to drought and stem vulnerability to xylem embolism, as well as root resistance to heat stress. We aimed at understanding which functional traits underlie plant performance and survival on Mediterranean green roofs. Our main hypothesis was that plant physiological traits conferring efficiency/safety to the water transport system under severe drought, as well as root resistance to heat stress, significantly influence the overall plant performance and survival. Moreover, on the basis of the results, we propose a methodological framework for screening and selection of suitable shrub species for roof greening in the Mediterranean.

2. Materials and methods

2.1. Study area and experimental set-up

The study was carried out between 2013 and 2015 on the experimental green roof installed on the rooftop of the Dept. of Life Sciences, University of Trieste (NE Italy; 45°39′40″N, 13°47′40″E). Trieste lies on the upper Adriatic coast and it is characterized by a sub-Mediterranean climate, with mild winters and relatively warm, dry summers. Mean annual temperatures in the period 1994–2015 (www.osmer.fvg.it) averaged 15.7 °C (highest 25.1 °C in July, lowest 7.0 °C in January). Maximum daily temperatures frequently exceed 30 °C in summer, while in winter the minimum values drop under 0 °C only occasionally. Mean annual rainfall is 869 mm, with relatively dry periods in July and January–February. Snow events are rare. The prevalent wind (Bora) blows from E-NE.

The experimental extensive green roof was composed of 10 modules, each covering an area of 2.5 m^2. Modules were built with a six-layer system by SEIC (Harpo Spa, Trieste, Italy), consisting of: a waterproof/root resistant membrane, a moisture retention layer, a drainage layer, a filter membrane, and substrate (dry bulk density = 848 kg m^{-3}, organic matter = 2.9%, pH = 6.8, water content at saturation = 0.44 g g^{-1}). The experimental modules were filled with 10 (D-10) or 13 (D-13) cm deep substrate (5 modules per depth). Each module had an independent discharge for excess water runoff, and was equipped with a temperature sensor (TT-500, Tecno.el srl, Roma, Italy) installed at the maximum substrate depth and a soil moisture content sensor (WC, EC-5, Decagon Devices, Pullman, WA, USA), both recording values at 1 h time intervals. In April 2013, the modules were vegetated with 11 woody species belonging to the Mediterranean and sub-Mediterranean flora (Pignatti, 2002). In particular, both evergreen (*Cistus salvifolius* L., *Ligustrum vulgare* L., *Phillyrea angustifolia* L., *Pistacia lentiscus* L., *Salvia officinalis* L.) and deciduous species (*Cotinus coggygria*