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Alternatives to *Sedum* on green roofs: Can broad leaf perennial plants offer better 'cooling service'?

Tijana Blanusa [a,b,*], M. Madalena Vaz Monteiro [b], Federica Fantozzi [c], Eleni Vysini [b], Yu Li [b], Ross W.F. Cameron [d]

[a] *Plant Sciences Department, Royal Horticultural Society, Garden Wisley, Woking GU23 6QB, UK*
[b] *School of Biological Sciences, University of Reading, Whiteknights, Reading RG6 6AS, UK*
[c] *Department of Environmental Sciences 'G. Sarfatti', University of Siena, Via P.A. Mattioli 4, 53100 Siena, Italy*
[d] *Department of Landscape, University of Sheffield, Sheffield S10 2TN, UK*

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ABSTRACT

Green roof plants alter the microclimate of building roofs and may improve roof insulation. They act by providing cooling by shading, but also through transpiration of water through their stomata. However, leaf surfaces can become warmer when plants close the stomata and decrease water loss in response to drying substrate (typically associated with green roofs during summers), also reducing transpirational cooling. By using a range of contrasting plant types (*Sedum* mix – an industry green roof 'standard', *Stachys byzantina*, *Bergenia cordifolia* and *Hedera hibernica*) we tested the hypothesis that plants differ in their 'cooling potential'. We firstly examined how leaf morphology influenced leaf temperature and how drying substrate altered that response. Secondly, we investigated the relationship between leaf surface temperatures and the air temperatures immediately above the canopies (i.e. potential to provide aerial cooling). Finally we measured how the plant type influenced the substrate temperature below the canopy (i.e. potential for building cooling). In our experiments *Stachys* outperformed the other species in terms of leaf surface cooling (even in drying substrate, e.g. 5 °C cooler compared with *Sedum*), substrate cooling beneath its canopy (up to 12 °C) and even – during short intervals over hottest still periods – the air above the canopy (up to 1 °C, when soil moisture was not limited). We suggest that the choice of plant species on green roofs should *not* be entirely dictated by what survives on the shallow substrates of extensive systems, but consideration should be given to supporting those species providing the greatest eco-system service potential.

1. Introduction

Enhancing a city's green infrastructure is frequently thought of as a means to help address a number of environmental problems associated with the built environment [1,2]. The ability of urban vegetation to help mitigate urban heat island effects [3] and to reduce the energy load on buildings [4] are two important ecosystem services that plants can provide. Globally, urbanisation is still increasing and there is more pressure within the urban matrix for land to be used for housing, business development and the associated infrastructure. Consequently, the use of green roofs has been advocated, partially in an attempt to provide some urban green space, without adding to the pressures on land at ground level. Even in countries which traditionally have not suffered from extreme anti-cyclonic conditions ('heat-waves') such as those in Northern Europe, there are concerns that a changing climate combined with urban expansion will result in more frequent incidents of severely elevated temperatures [5]. The use of urban greening is therefore advocated to help mitigate such events, and helps in part to compensate for the lack of alternative cooling mechanisms more typical of warmer Mediterranean climates e.g. lightly coloured buildings with high albedo, thick insulating walls, shuttered windows, greater exploitation of prevailing cooling winds etc. [6].

In Northern Europe and indeed many other regions, vegetation is now considered to be a vital component in reducing air temperatures at the city-wide scale [7,8] as well as locally (e.g. [6,9]). Plants provide a cooling influence by transpiration of water through their stomata [10], but also through direct shading [11]. It has been claimed that green roofs harbour genuine potential for

* Corresponding author. Plant Sciences Department, Royal Horticultural Society, Garden Wisley, Woking GU23 6QB, UK. Tel.: +44 (0) 118 378 6467.
E-mail addresses: tijanablanusa@rhs.org.uk, t.blanusa@reading.ac.uk (T. Blanusa).

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urban temperature reduction [12], but the extent to which they contribute to urban cooling compared to other vegetation types or landforms (e.g. street trees, urban forest, parkland etc.) is unclear. Indeed, there is still some debate as to how micro-climates associated with different types of urban vegetation actually influence climate at the larger urban scale [13]. At a more local level, it is acknowledged that low-growing terrestrial vegetation (lawn grass particularly) can enhance aerial cooling, at least in comparison to harder, more typical urban surfaces (asphalt, concrete, paving etc.) [14,15]. However, the evidence for green roofs providing significant air cooling remains limited [16]. Furthermore, the ability of green roof plants to extract and transpire water may be considerably compromised in the shallow, lithosol-like substrates used on green roofs compared to a deeper profile, natural soil. Also, leaf surfaces are likely to become warmer when plants close their stomata and decrease water loss in response to drying substrate [17].

Green roofs can help insulate buildings against thermal gain from solar radiation [18], although it is often acknowledged that it is the depth of the substrate that determines the extent of insulation more than the amount of vegetation [19]. However, the depth of green roof substrate is often dictated in practice by the weight load placed on the roof (i.e. thinner substrates are preferred from an engineering perspective). The extent to which the vegetation can then provide additional cooling to the substrate, becomes an important practical and research question.

Due to the drought prone and exposed nature of extensive and semi-extensive green roofs, *Sedum* sp. (e.g. *Sedum album*, *S. acre*, etc.) with typical xerophytic characteristics are the most widely used plant group [20]. *Sedum* sp. establish rapidly, provide good surface coverage and are effective in decreasing storm water runoff while requiring low maintenance [21]. A number of studies worldwide have investigated species alternative to *Sedum*, including bulbs and grasses (e.g. in Germany [22]), small shrubs, grasses and ornamental perennials (e.g. in Japan [23]), as well as species mixes that included succulents (e.g. in Canada [24]), but only two tested alternatives to *Sedum* in the UK climatic conditions [25,26]. The focus of these studies has been on ecological function, particularly species survival and growth rates. The results showed that there were alternatives to *Sedum* in terms of good surface coverage and providing protection from water runoff, but there was little emphasis on other ecosystem services, including cooling potential.

Since the priority for plant selection on extensive and semi-extensive green roofs has been stress tolerance (with perhaps aesthetic quality being second), only limited attention has been paid to a species' ability to provide cooling. Indeed, it had been suggested that *Sedum* and other species currently used (and ones with similar morphological adaptations such as small/narrow/succulent/hairy leaves with thick cuticle) are unlikely to offer substantial evapo-transpirational (ETp) cooling, especially when the weather is hot and dry [27]. Furthermore, reduced substrate moisture availability, frequently associated with green roofs, causes leaf stomatal closure and a consequent warming of the leaf surface [28], but the extent of this response is likely to differ between species. Depending on performance, some less stress tolerant species may justify further investment required to support their establishment and growth on roofs, by providing better cooling than 'traditional' green roof species. The philosophy around plant selection should therefore change from solely 'what survives' to 'what provides the greatest ecosystem service' (i.e. cooling). This leads to three questions:

i. Are there species more effective than *Sedum* in regulating their own leaf temperatures in hot weather?
ii. How does this relate to their ability to regulate air and surface (i.e. substrate) temperatures adjacent to the plant?
iii. How would such species perform when conditions become sub-optimal, i.e. reduced water availability?

The aim of our research was to address these questions. By using a range of contrasting plant types we wished to examine how leaf morphology influenced leaf temperature and how decreasing substrate water availability (typically associated with green roofs in hot weather) alters that response. Secondly, we wished to investigate the relationship between leaf surface temperature and the temperature of the air immediately above the canopy (i.e. potential to provide aerial cooling). The choice of height for measurements of air temperatures in our experiment was driven by the hypothesis that differences in leaf temperatures could translate in differences in air temperatures in the immediate vicinity of the plants; these could then be utilised to influence positioning of air conditioning units within vegetation on a building surface (e.g. lowering their energy consumption in a 'cooler' environment). Finally, a third objective was to observe how plant type influenced the temperature of the substrate below the canopy (i.e. potential for building cooling).

Due to its prevalence in practice we used a commercial *Sedum* mix matting in our experiments to act as an industry standard (control) system. In comparison, monocultures of three broad-leaved perennial plants: *Bergenia cordifolia*, *Hedera hibernica* and *Stachys byzantina* were used to compare their thermodynamics to that of the *Sedum* mix. We specifically chose broad-leaved species to test the hypothesis that these would have lower leaf temperatures and perhaps lower surrounding air or substrate temperatures; earlier studies have indicated that traits such as succulence, presence of leaf hairs etc. are involved in regulating leaf temperature [29]. We also selected candidate species to reflect different ecological backgrounds, on the basis that some e.g. *Stachys* (from a Mediterranean climate) may possess a degree of drought tolerance and hence perhaps be the most amenable to green roof culture, but at the same time are suitable for the UK climatic conditions [30].

2. Methods

2.1. Plant material

Three broad-leaved, perennial species: *Bergenia cordifolia* (large, waxy leaves), *Hedera hibernica* (leaves with thick epidermis, providing good cover) and *Stachys byzantina* (leaves with light-coloured hairs) were compared to *Sedum* sp. mix (small, succulent leaves) in Experiment 1, with *Stachys* and or *Sedum* sp. mix used in subsequent experiments.

Sedum was purchased as a commercially used 'Enviromat' matting system (Q Lawns, Hockwold, Norfolk, UK) and represented a random mix of *Sedum album*, *Sedum spurium*, *Sedum acre* and *Sedum sexangulare*. Other plant species were purchased from a commercial nursery as 1-year old plants in 250 ml containers.

2.2. Experiment 1. The effect of species and water availability on leaf stomatal conductance, leaf surface temperature and air temperature above the canopy (glasshouse conditions)

2.2.1. Experimental set-up

On 3 June 2009, plants were planted into custom-made large containers (1.2 m (l) × 0.4 m (w) × 0.4 m (h)) filled to a depth of 0.2 m with commercial intensive green roof substrate (Shire Green Roof Substrates Ltd., Southwater, West Sussex, UK), to mimic a standard semi-intensive green roof. The substrate had the following properties (as specified by the manufacturers): pH = 8.5,