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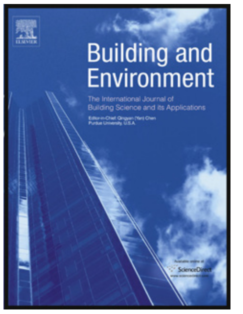

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Highlights:

- Of all the species tested, leaf surface temperature was lowest in *Stachys*, even when water was limited.
- On warm days, both *Stachys* and *Sedum* cooled the air above the substrate compared to bare soil.
- On several hot afternoons in the glasshouse *Stachys* provided more aerial cooling than other species.
- In outdoor conditions we recorded one incidence where *Stachys* provided additional localised aerial cooling.
- On a warm day, temperatures below *Stachys* and *Sedum* canopies were 11 ^{o}C and 4 ^{o}C lower than of bare soil.

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

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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 ^{o}C cooler compared with *Sedum*), substrate cooling beneath its canopy (up to 12 ^{o}C) and even - during short intervals over hottest still periods - the air above the canopy (up to 1 ^{o}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.

Additional key words:

Air cooling; building insulation; drought; leaf temperature; *Stachys byzantina*

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 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. *S. 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 *Stachy*s *byzantina* (leaves with light-coloured hairs) were compared to *Sedum sp.* mix (small, succulent leaves) in Experiment 1, with *Stachy*s 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, S. spurium, S. acre* and *S. 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) x 0.4 m (w) x 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, total pore volume 49-60%, soil organic matter 9.2% and maximum water holding capacity 33.5%.

There were six containers per species and an additional six with unplanted (bare) substrate. Containers were organized in a randomised block design and located in a ventilated glasshouse; where minimal / night temperatures never fell below 15 ^{o}C and maximal / daytime temperatures were in the range 22 – 37 ^{o}C, the RH in the compartment was around 30% during daytime and 70% during the night. Twenty eight plants per container of *Stachys* and *Bergenia* and eight plants of *Hedera* per container were planted to achieve 90% of initial ground coverage. *Sedum* mat, with the root barrier layer removed, was laid on top of the 0.2 m deep substrate.

2.2.2. Watering treatments

At planting and daily until 9 June all containers were watered to container capacity; from 10 June 2009 until the end of the experiment 30 days later (10 July 2009) containers were either watered to achieve soil moisture content (SMC) >0.25 $m^3 m^{-3}$ ('well-watered' treatment, three containers per species/substrate) or <0.15 $m^3 m^{-3}$ ('under-watered'/'dry' treatment). Preliminary experiments suggested that this SMC lead to stomatal closure and growth reduction, without affecting plant survival. Hand-watering was performed in late afternoon, daily or weekly, for 'well-watered' and 'dry' treatments, respectively.

2.2.3. Plant and substrate measurements

Substrate moisture content was measured twice weekly using SM200 probe (Delta-T Devices Ltd., Cambridge, UK) in five locations across the middle of the longer axis of each of the containers, close to a plant. Measurements were made between 09:00 and10:00 h (British Summer Time, BST).

Leaf stomatal conductance to water vapour (g_s) was measured in all species apart from *Sedum* (where the leaves were too small and thick for the instrument's chamber), twice weekly between 10:00 and 15:00 h (BST) to follow SMC measurements, using AP4 porometer (Delta-T Devices Ltd., Cambridge, UK) on seven randomly selected plants (two leaves per plant) in each of the containers. Leaf stomatal conductance is measured as the rate of passage of water vapour leaving a stomatal pore and is expressed in mmol m^{-2} s^{-1}.

Surface temperatures (plants and bare substrate) were measured by analysing Infra-Red thermal images; the images were taken between 13:00 and 14:00 h (BST) at regular intervals during the experiment to capture multiple days with similar and varying weather, using Thermo Tracer TH7800 camera (NEC San-ei Instruments Ltd., Japan). Thermal images were taken from the 30^o angle with respect to the vertical and 1 m distance from the container edge and from 1.2 m height in all cases; nine areas of 50 x 50 mm in the middle of each container were analysed for their average temperature using the NS9200 Report Generator software (NEC San-ei Instruments Ltd., Japan). Air temperature was measured at 30 min intervals at fixed height 300 mm above the middle of the substrate surface for the duration of the experiment using screened RHT2n sensors attached to a DL2e logger (Delta-T Devices Ltd., Cambridge, UK). The height of the sensor was dictated by the experimental design in experiment 1, where the sensor was placed directly above the centre of the plant canopy and 100 mm above the height of the lip of the container the plants were grown in. This was implemented to enable us to measure temperature at a fixed height above the ground, so that we can compare absolute impact of the absence of vegetation / various types of vegetation which inherently differs in canopy height. Preliminary evaluations indicated there was less temporary fluctuation in temperatures at the 300 mm height when glasshouse doors or vents were opened compared to higher positions; and lowering the sensors further, could result in direct shading of a large proportion of the canopy. Prior to the start of measurements, in all experiments, temperature sensors were compared by running them for 24 h in a controlled environment room and found to be within ≤1% error of each other.

2.3. Experiment 2. Comparisons between *Sedum* mix and *Stachys byzantina*: leaf surface temperature and air temperature above the canopy (glasshouse conditions)

On 1 June 2010, *Stachys byzantina* was planted and *Sedum* matting was laid into containers and two watering regimes were imposed, as described for Experiment 1 (Section 2.2.2.). There were 10 containers for each of the plant covers and an additional 10 containers with unplanted substrate. The experiment ran for approx. 3 weeks from 3-23 June 2010 and measurements of SMC, surface and air temperature were made as described for Experiment 1 (Section 2.2.3). Additionally, measurements of g_s were performed in both species with an LCi portable open gas exchange system (ADC BioScientific Ltd., Hoddesdon, UK) with ambient CO_2 concentration at 385 ± 5 $mm^3\ dm^{-3}$. During measurements, photosynthetic photon flux density was supplemented to a minimum of 1000 $\mu mol\ m^{-2}\ s^{-1}$ by an external (50 W, 12 V) halogen source. Measurements on seven plants per container (two leaves per plant) were carried out between 10:00 and 15:00 h (BST).

2.4. Experiment 3. Comparisons between *Sedum* mix and *Stachys byzantina*: leaf surface temperature, air temperature above the canopy and ground surface cooling (outdoor conditions)

An outdoor experiment was set up at the University of Reading, UK. Six plots, each measuring 2.2 m (l) x 2.2 m (w) x 0.1 m (d), were constructed at ground level using timber, lined with polyethylene pond liner (0.75 mm thickness) and filled with John Innes No 2 substrate to 0.1 m depth. There were two plots for each of the surfaces: bare substrate, *Stachys byzantina* and *Sedum sp.* matting. Vegetation was planted in September 2010 and by the onset of the experiment (27 May 2011), plants covered 100% of the plot surfaces; bare substrate was kept weed-free. Plots were rain-fed, but throughout the experiment the SMC remained above 0.15 $m^3 m^{-3}$. The experiment commenced on 27 May 2011 and terminated on 3 July 2011.

To increase the likelihood of detecting local air temperature differences outdoors, where there is greater air mixing, screened temperature sensors RHT2n were placed at two heights on the edge and in the centre of the plots. One sensor was placed in line with the plant canopy (20-30mm above the soil surface) surface and another 100 mm above the canopy The larger planted area in this experiment (4.84 m^2) compared to Experiment 1 (0.48m^2) enabled sensors to be placed closer to the canopy than before, without affecting a proportionally large area of the canopy through shade. Furthermore, in this experiment we were interested in using top of the plant canopy, rather than the soil surface, as a 'reference point', to provide us with the relative comparisons between plant species. Additionally, soil surface temperature beneath the plants was measured by placing thermocouples (type Fenwal UUA32J2, in house construction) 5 mm below the soil surface in the centre of all plots. Temperature was measured at 5 s intervals and averaged every 10 min. Measurements of leaf surface temperature were by thermal imaging as described for Experiment 1 (section 2.2.3). Additionally, anemometer (A 100R, Skye Instruments Ltd., Llandrindod Wells, UK) was placed in the centre of the experimental area to monitor wind velocity at the same time as temperature readings were recorded.

Substrate moisture content was measured twice weekly using SM200 probe (Delta-T Devices Ltd., Cambridge, UK) between 09:00 and10:00 h (BST) in 12 locations evenly distributed across every plot. Net total radiation (i.e. difference between incoming and outgoing/reflected radiation) was measured on 3 June using net pyrradiometer CN1/919 (Middleton Solar, Melbourne, Australia) attached to DT 500 Datataker logger (Omni Instruments, Dundee, UK). The measurements were made between 11:30 and 12:30 h (BST), logging every 30 s for

15 minutes, 300 mm above one plot per each of the surfaces (bare soil, *Sedum* mix and *Stachys*). During the same time period we recorded the surface temperatures of the surfaces where net radiation measurements were made using the methodology described in Section 2.2.3.

Leaf area index (LAI) was measured at the end of the experiment by dividing the leaf area of *Stachys* and *Sedum* (measured with Area Meter, Delta-T Devices Ltd., Cambridge, UK) by the surface area from which the leaves were sampled (three samples per plot). For the proportion of non-flat *Sedum* leaves (*S. album* and *S. sexangulare*) LAI was adjusted by multiplying by k = 0.5, as suggested by Chen and Black [31].

2.5. Experiment 4. The role of leaf hairs in *Stachys byzantina* in regulating leaf temperature (controlled environment cabinet)

Leaf hairs were removed on 21 March 2010 from both ab- and adaxial surfaces on ten young fully expanded *Stachys* leaves from three containerised plants grown in the glasshouse, using an electrical hair trimmer (D.D., Wahl, UK). The effectiveness of hair removal was measured under the light microscope using five additional leaves per treatment; on average unshaved leaf hairs were 2.19 mm long and the shaved ones were significantly shorter at 0.47 mm (LSD = 0.138 mm). Three days after shaving, ten 'shaved' leaves along with ten unshaved ('control') leaves were excised under water and placed immediately and into 25 ml conical flasks with 10 ml water [32]. Vials with individual leaves were weighed and thermal images of the leaves were taken; vials were then placed in the controlled environment cabinets for 24 h (temperature 22 ^{o}C, 50% RH, light supplemented at 550 μmol m^{-2} s^{-1}) and weighing and imaging procedure repeated 2, 4, 6, 8 and 24 h after the start of the experiment. Leaf stomatal conductance (five leaves per treatment @ 2, 4, 6, 8 and 24 h after the start of the experiment) and individual leaf areas (at the end of the experiment) were measured as described for Experiments 2 (Section 2.3) and 3 (Section 2.4), respectively.

2.6. Statistical analysis

Data were analysed using GenStat (11th Edition, Lawes Agricultural Trust, Rothamsted Experimental Station, UK). Analysis of variance (ANOVA) was used to assess the effects of different watering regimes and the plant species/surface on measured parameters; variance levels were checked for homogeneity and values were presented as means with associated least significant differences (LSD, P = 0.05).

3. Results

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

From day 4 of the experiment, significant differences in SMC were apparent between the 'well- watered' and 'dry' treatment plants and from day 10 the SMC was consistently at, or below, 0.15 m^3 m^{-3} in the 'dry' treatment (data not shown). Within both 'well- watered' and 'dry' plants, SMC was similar between *Stachys*, *Hedera* and *Bergenia* and always higher in those three species than in *Sedum* (data not shown).

Leaf stomatal conductance (g_s) was consistently lower in the 'dry' treatment from day 14. In 'well-watered' plants average g_s values were 233.1 mmol m^{-2} s^{-1} for *Stachys*, 220.1 mmol m^{-2} s^{-1} for *Hedera* and 217.0 mmol m^{-2} s^{-1} for *Bergenia*. Conversely, in the 'dry' treatment the overall averages were 147. mmol m^{-2} $s^{-1}$for *Stachys*; 98.8 mmol m^{-2} s^{-1} for *Hedera* and 66.4 mmol m^{-2} s^{-1} for *Bergenia*.

When measured on the hottest days, *Stachys* consistently had the lowest leaf surface temperature amongst all species, both under 'well- watered' and 'dry' regimes (e.g. see data for early afternoon measurement on 3 July 2009, Day 24 of the experiment, Fig. 1). All other species had similar leaf surface temperatures when they were well watered (Fig. 1). In the 'dry' treatment the following order of surface temperatures was recorded on 3 July: bare substrate > *Hedera* = *Sedum* > *Bergenia* > *Stachys* (Fig. 1). There was no significant difference in leaf surface temperature between 'well- watered' and 'dry' *Stachys* (26.5 ^{o}C vs 27.2 ^{o}C, respectively, LSD = 1.25 ^{o}C). All other surfaces associated with the 'dry' regime were warmer than those 'well-watered' (Fig. 1). Air temperature in the glasshouse compartment at the time when leaf temperatures were measured on 3 July was 30.7 ^{o}C.

In terms of air temperatures above various surfaces we were only able to establish treatment / species differences on hottest days (air T_{max} > 32 ^{o}C) and only during early afternoons (12:00 – 16:00 h). Air temperatures were lowest above *Stachys* grown in 'well-watered' treatment and above *Sedum* in the 'dry' regime (Table 1).

<u>3.2. Experiment 2. Comparisons between *Sedum* mix and *Stachys byzantina*; leaf surface temperature and air temperature above the canopy (glasshouse conditions)</u>

In this experiment, there was a difference in SMC between 'well- watered' and 'dry' treatments in both plant species and on bare substrate from Day 4 of the experiment (Fig. 2). Well-watered *Stachys* and bare substrate SMC was maintained, on average, at least at 0.3 $m^3 m^{-3}$, and *Sedum* at 0.2 $m^3 m^{-3}$ (Fig 2). In the 'dry' treatment, *Stachys* was maintained at around 0.15 $m^3 m^{-3}$ and *Sedum* and bare substrate below 0.10 $m^3 m^{-3}$ (Fig. 2).

Leaf stomatal conductance was significantly lower in plants within the 'dry' treatment compared to the 'well-watered' treatment from day 9 in *Stachys* and Day 16 in *Sedum* (Fig. 3). This was accompanied by the decrease in the instantaneous evaporation (E) in these species during the same period (data not shown). Over the course of the experiment reducing irrigation decreased g_s by 40% (*Stachys)* and 50% (*Sedum)* (Fig. 3).

As in Year 1, leaf temperatures in *Stachys* on the hottest days (i.e. maximal daytime temperature > 30 ^oC) were similar in 'well- watered' and 'under-watered' plants (27.8 vs 28.3 ^oC) and lower in *Stachys* than in any other surface/watering combination (Fig. 4). Surface temperatures were also higher in 'dry' substrate and *Sedum* compared to the 'well-watered' equivalents (Fig. 4).

Significant differences in air temperatures above the surfaces were only detected on the hottest day of the experiment (21 June 2010, maximal daytime temperature in the glasshouse compartment was 31.5 ^oC) and only during early afternoon (12-16 h); air temperatures were lowest above 'well-watered' *Stachys* (Table 2).

3.3. Experiment 3. Comparisons between *Sedum* mix and *Stachys byzantina*: leaf surface temperature, air temperature above the canopy and ground surface cooling (outdoor conditions)

During the outdoor experiment in June 2011 there was extensive cloud cover on many of the days over which the experiment was conducted. According to data from sensors on the experimental site and information from University of Reading's weather station , there were only two days (3rd and 4th June) where full sunlight, low wind speeds and warm temperatures (20-25 ^oC daytime, 10-15 ^oC nightie) were consistently recorded (i.e. > 12 hours sunlight). Surface temperatures of plants and substrate outdoors showed identical patterns to that in glasshouse Experiments 1 and 2. For example, during the warmest day of the experiment (4 June 2011, Day 8 of the experiment, air T_{max} = 25.6 ^oC), temperatures were highest in the bare substrate, followed by *Sedum* and lowest in *Stachys*; this was confirmed by both thermal imaging and temperature sensors (data not shown). We found significant differences in soil temperatures during the warmest part of the day (12 – 16 h). Soil underneath *Stachys* was over 11 ^{o}C cooler than soil under *Sedum*, which was also almost 3 ^{o}C cooler than bare substrate in the period 12 – 16 h (Table 3). In the same period, air temperatures 100 mm above *Stachys* and *Sedum* were similar (24.8 and 25.1 ^{o}C on average, respectively), but both were significantly lower than over bare substrate (25.9 ^{o}C) (Table 3). Significant differences in air temperature above the two plant canopies were observed, however, on other warm days, but only during shorter intervals (e.g. 24.1 ^{o}C vs 25.0 ^{o}C for *Stachys* and *Sedum* respectively, between 12:30 and 13:30 on 3 June, LSD = 0.57 ^{o}C, F pr. = 0.002). In terms of the night time air temperatures, there was no difference between the surfaces (data not shown). Night time soil temperatures, however, were about 1 ^{o}C warmer underneath *Stachys* compared with *Sedum* and bare soil (14.6, 14.0 and 13.7 ^{o}C, respectively, LSD = 0.47 ^{o}C, d.f. = 293) between 3 and 4 June, but not during 4 and 5 June (data not shown).

Net radiation was highest above bare soil (665.1 W m^{-2}) followed by that over *Sedum* mix (552.7 W m^{-2}) and lowest over *Stachys* (523.6 W m^{-2}, LSD = 13.55 W m^{-2}), indicating that *Stachys* was reflecting back more of the incoming radiation. Leaf area indices were similar in *Sedum* mix and *Stachys* (2.29 vs 2.30, respectively).

3.4. Experiment 4. The role of leaf hairs in *Stachys byzantina* in regulating leaf temperature (controlled environment cabinet)

Results of the 24 h controlled environment experiment measuring the impact of hair removal on leaf temperature in *Stachys* showed that leaf temperature was consistently significantly higher in shaved leaves, compared with controls (hairs left intact) (e.g. at 24 h, 23.3 ^{o}C control vs 23.9 ^{o}C in shaved leaves, LSD = 0.21 ^{o}C). These temperature differences, however, were not matched by statistically significant differences in volume of water lost over 24 h (3.3 kg m^{-2} control compared to 4.3 kg m^{-2} shaved, LSD 2.68 kg m^{-2}) or g_s (e.g. at 4 h, 0.227 mmol m^{-2} s^{-1} control vs 0.192 mmol m^{-2} s^{-1} shaved leaves, LSD = 0.0479 mmol m^{-2} s^{-1}).

4. Discussion

Differences in leaf temperatures between species were apparently strongly linked to differences in leaf morphology and physiology of the species being tested. *Stachys byzantina* retained the lowest leaf surface temperature when exposed to high air temperatures on clear, sunny days (Figure 1). Furthermore, *Stachys* was the only species where water deficiency did not significantly increase leaf temperature, with temperature differences being <0.7 ^{o}C between 'well- watered' and 'under-watered' plants, despite very large differences in substrate moisture content and leaf stomatal conductance. In contrast, the level of irrigation supplied to other species such as *Sedum* and *Hedera* strongly influenced leaf surface temperature, with leaves of plants exposed to the drier regime being as much as 4.5 ^{o}C warmer than those of 'well-watered' plants.

Temperatures of bare, unplanted, substrate were also significantly affected by moisture content, with 'well-watered' substrates always having lower surface temperature than those where irrigation had been restricted, clearly demonstrating the cooling influence of evaporation alone. The ability for plants to provide additional surface cooling again appeared to be influenced by species choice. Leaf surface temperatures of *Stachys* plants held under 'well-watered' conditions were lower than the surface temperatures of damp bare substrate (Figures 1 and 4). Similarly, 'well-watered' *Sedum* was also cooler than the watered bare substrate in Experiment 3 (Figure 4), but surface temperatures of *Bergenia* and *Hedera* were little different from that of damp bare substrate (Figure 1). Under the 'dry' conditions, however, leaf temperatures were always lower than those of the bare substrate.

The relationship between surface temperatures and the air temperature recorded 300 mm above the substrate within the glasshouse environment was more complex. During particularly warm periods, lowest air temperatures were measured above *Stachys* canopy, but only when the plants were 'well-watered' (Tables 1 and 2). Air temperatures above 'dry' *Stachys* could be relatively high; note the 7 ^{o}C difference between leaf and air temperature with this treatment in Experiment 1 (compare Figure 1 and Table 1 data). Overall, there were poor correlations between leaf / substrate surface temperatures and air temperatures above the plots. The relatively small plot sizes and the close proximity of the different treatments and subsequent air mixing may partially explain the variability that accounted for this. Although we specifically chose the semi-protected character of the glasshouse to reduce air movement and mixing, there may still have been interference due to thermal gradients associated with the structure of the glasshouse, concrete floors, metal framework etc., as well as neighbouring treatments. In this experiment we also specifically chose to measure temperature at set heights above the substrate, not the plant canopies, and the latter were themselves variable even within a monoculture of the one species. Although we raised the height of the sensors to account for this (100mm above the highest plants), this may have predisposed the sensors to other interfering effects (i.e. greater air movement across the top of the containers, rather than within them). Outdoors, at 100 mm above ground and over longer averages (e.g. between 12:00 and 16:00 h over two experimental plots) we only detected significant differences in air temperature between vegetation and bare soil, and not between *Stachys* and *Sedum* (although the difference was only borderline statistically insignificant). This difference between vegetated *vs* non-vegetated (instead of the species difference) was measured consistently during the experiment and in various types of weather. Over shorter intervals on hottest days, however, we found occasional periods when air over *Stachys* was cooler than over *Sedum* and we argue that this difference may become important in the scenarios of prolonged hot weather. Even with larger plots, Kjelgren and Montague [33] failed to show any difference in air temperature above two neighbouring areas of grass and asphalt outdoors, due apparently to their close proximity and air mixing (height of measurement was not reported). Other reports though, have detected differences in air temperature above low growing vegetation and hard surfaced areas when measuring at 1 to 2 m above ground level [15, 16]. Clearly, the contribution of low growing vegetation to wider aerial cooling effects requires further investigation (especially with respect to air mixing and convection, e.g. [34]), with perhaps effects of vegetated *vs* non-vegetated areas being more noteworthy than any subtleties due to plant species choice. Nevertheless, plant selection may be more critical at the smaller scale, especially within a few centimetres of the building envelope (where air mixing may be more limited due to parapets, ridge tiles or other structural features), as well as being used to improve the efficiency of mechanical air conditioning units through localized cooling [35]. Future work needs to account for confounded factors associated with air movement even a very local levels, however, and more systematic use of sensors placed at discrete distances from the transpiring leaves may be required to determine the ‘zone of cooling influence’ before air mixing etc. dilutes any effect.

Of the species we tested, *Stachys* had the greatest capacity for regulating its own temperature and keeping its leaves cool. It retained the lowest surface temperature even when soil moisture became limited and stomata closed. In the controlled environments utilised in Experiment 4 it was evident that retaining hairs on the leaves of *Stachys* reduced the amount of infra-red radiation emitted from the leaf (i.e. the leaves appeared cooler), compared to those leaves where the hairs were trimmed. This cooling conferred by the leaf hairs may be related to light hair colour reflecting or refracting more incoming irradiance [36], and appears to be supported by lower net-radiation values over *Stachys* which we measured in our experiment. The presence of hairs on leaves has been cited as a mechanism to reduce moisture loss from the leaf surface [37] and / or protect tissues from excessive irradiance, particularly UV wavelengths [38, 39]. In our experiment, although shaved leaves of *Stachys* lost more water than unshaved ones, differences in moisture loss were not significant. The fact that surface temperatures were significantly different though, may suggest that the predominant role for *Stachys* hairs is to reduce the intensity of incoming irradiance, provide higher reflectance / albedo and avoid direct heat stress, perhaps with any capacity to trap moisture as only a secondary role. Despite the phenomena of being able to lower its leaf temperature irrespective of the irrigation level applied, the ability for *Stachys* to maximise air cooling was still strongly dependant on moisture being available and water transpiring through its leaves: greatest air cooling corresponding to the presence of the *Stachys* canopy *combined* with the stomata being open.

The final component we were interested in was the impact of vegetation type on the substrate temperature below the leaf canopy. It is widely acknowledged that the presence of vegetation lowers soil temperatures during the day and, in the case of green roofs, reduces the temperatures of the roof membrane (e.g. [40]) and the building interior underneath the roof (e. g. [18]). However, these measurements are usually made in model scenarios and species (*Sedum*, turf) and the understanding of how different plant species impact on surface and building temperatures is limited [16, 23, 41]. Measurements of temperatures underneath plant canopies of six species showed that the presence of closed canopies (as opposed to sparser, more open canopies) [16] and higher leaf area index [10] was associated with lower surface temperatures during the day. In another study, *Petunia* coverage reduced soil temperature more than Hedera [23], but the specifics of the mechanism have not been elucidated. In our study, we again observed the most positive results with *Stachys*, with substrate temperatures below the *Stachys* canopy being >11 ^{o}C lower than under *Sedum* during the warmest periods (Table 3). Extra shading did not appear to account for this, as the LAI of the two species were similar. The presence of leaf hairs which would act to increase energy reflectance from *Stachys'* leaves, in addition to evapotranspiration, appears to be important for the regulation of temperature by this plant species. The night time temperatures of the substrate underneath the *Stachys* were only 1 ^{o}C higher than that of the bare substrate and *Sedum*, while the daytime differences were – as already discussed - much larger. We feel therefore that the overall benefit is in using *Stachys*. Additionally, if the thermal load onto the building during the day is decreased and reflection increased (as it appears to with *Stachys*) the night time thermal discomfort of the building residents underneath this roof, on balance, will be smaller.

Our experiments explore the concepts and general principles that differences in plant structure and function, which affect plants' regulation of own temperature, can impact the air and surface temperatures. These concepts now have to be validated by further, more applied, field studies. Similarly, more research is required to investigate the impacts of localized cooling on the leaf, substrate surface, immediate air volume etc. on large, city scale effects. Many urban climate models tend to represent vegetation very simply (see [42]) or define it in broad terms; 'grass' / 'trees' with little precision based on species, albedo characteristics or indeed the impacts of a range of environmental factors that influence stomatal behaviour either directly (irradiance, atmospheric CO_2, O_3, humidity, leaf temperature, soil moisture availability,[43]) or indirectly (hormonal and hydraulic signalling, [44]). The data presented here demonstrate that variations in plant phenotype and physiological adaptions within a range of low-growing species can influence cooling effects on leaf, substrate and by inference, building surfaces, if not always consistently and categorically on air temperatures.

5. Conclusions

We advocate 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 for supporting those species that provide the greatest eco-system service potential. This includes, perhaps, justifying the additional expense associated with providing a deeper substrate (such as a semi-extensive system) or even supplementary irrigation from a sustainable source. In this study *Stachys* outperformed the other species under test in terms of leaf surface cooling, cooling the substrate beneath its canopy and even - during short intervals over hottest still periods - the air above the canopy, when soil moisture was not limited**.** The fact we measured air temperature differences between the species only during the hottest periods of the experiment may be an important point: it suggests that in many cases either vegetation type is fine, but when temperatures begin to peak (and, potentially, the UHI events start to become significant) there is an advantage with *Stachys*. This is particularly in respect to lowering air temperatures around the building envelope thus potentially reducing cooling demand and decreasing temperatures around air conditioning units, thereby lowering energy consumption. *Stachys* is unlikely to be as resilient as *Sedum* in terms of survival in the most-droughty, extensive, green roofs (e.g. 50-100 mm deep), but is a drought-adapted species in its own right, capable of survival and persistence without additional irrigation in semi-extensive (200 mm depth) systems within Northern Europe [20]. Nevertheless, we are continuing to investigate the sustainable irrigation regimes/systems to support the growth of such species to help support them under more extreme climates and to understand potential economic impacts of choosing them (i.e. cooling cost reduction vs increased irrigation and maintenance costs). We are also focusing on the importance of leaf colour and thickness/morphology in the energy balance of leaves and the surrounding surfaces. Our future work will incorporate biological and modelling approaches to provide answers about which biological traits, and through what mechanisms, provide the greatest benefits in a more applied context.

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Figure legends

Figure 1. Mean surface temperature (^{o}C) of bare substrate and plant leaves on July 3, 2009 (Day 24 of the Experiment 1). Vertical bars are mean of nine temperature measurements per container and three containers per plant species/surface, a line represents associated LSD (1.25 ^{o}C, d.f. = 258). Measurements were made between 13 and 14 h.

Figure 2. Substrate moisture content (m^3 m^{-3}) of 'well- watered'/ 'wet' and 'under-watered'/ 'dry' *Sedum, Stachys byzantina* and bare substrate in Experiment 2 (in 2010). Data are mean of 5 measurements per container and three containers per plant species/surface, a line represents associated LSD. Measurements were made between 9 and 10 h.

Figure 3. Leaf stomatal conductance to water vapour (g_s) 'well- watered'/ 'wet' and 'under-watered'/ 'dry' *Sedum* and *Stachys byzantina* in Experiment 2 (in 2010). Data are mean of 14 measurements per container and three containers per plant species/surface; thick and thin lines represent LSDs associated with *Stachys* and *Sedum*, respectively. Measurements were made between 10 and 15 h.

Figure 4. Mean surface temperature (^{o}C) of bare substrate and plant leaves on June 16, 17 and 21 2010 (Days 14, 15, and 19 of the Experiment 2). Vertical bars are mean of nine temperature measurements per container and five containers per plant species/surface, a line represents associated LSD (1.35 ^{o}C, d.f. = 809). Measurements were made between 13 and 14 h.

List of tables

Table 1. Average air temperature (^{o}C) at fixed height, 300 mm above the substrate level, on two hottest days of the Experiment 1 (27 and 30 June 2009, Days 16 and 19 of the experiment) between 12 and 16 h. Data are mean of sixteen measurements per species/surface and ranked lowest to highest (LSD = 1.61 ^{o}C, d.f. = 159). The means followed by a different letter are statistically significantly different.

Table 2. Average air temperature (^{o}C) at fixed height, 300 mm above the substrate level, on the hottest day of the Experiment 2 (21 June 2010, Day 19 of the experiment) between 12 and 16 h. Data are mean of sixteen measurements per species/surface and ranked lowest to highest (LSD = 0.758 ^{o}C, d.f. = 95). The means followed by a different letter are statistically significantly different.

Table 3. Average soil and air (100 mm above the substrate level, sensor in the centre of the plot) temperatures (^{o}C) associated with different surfaces on the hottest day of the Experiment 3 (4 June 2011, Day 8 of the experiment) between 12 and 16 h. Data are mean of fifty measurements per species/surface and ranked lowest to highest (LSDs are given in the table separately for soil and air temperatures, d.f. = 149). The means followed by a different letter are statistically significantly different.

708

Species/Treatment	Air temperature (^{o}C)
Stachys wet	32.2 a
Sedum dry	32.5 ab
Substrate wet	32.8 abc
Hedera wet	33.4 abc
Substrate dry	33.9 bc
Sedum wet	34.0 bc
Bergenia wet	34.1 bc
Bergenia dry	34.2 c
Stachys dry	34.4 c
Hedera dry	34.4 c
LSD (d.f.)	1.61 (159)

709

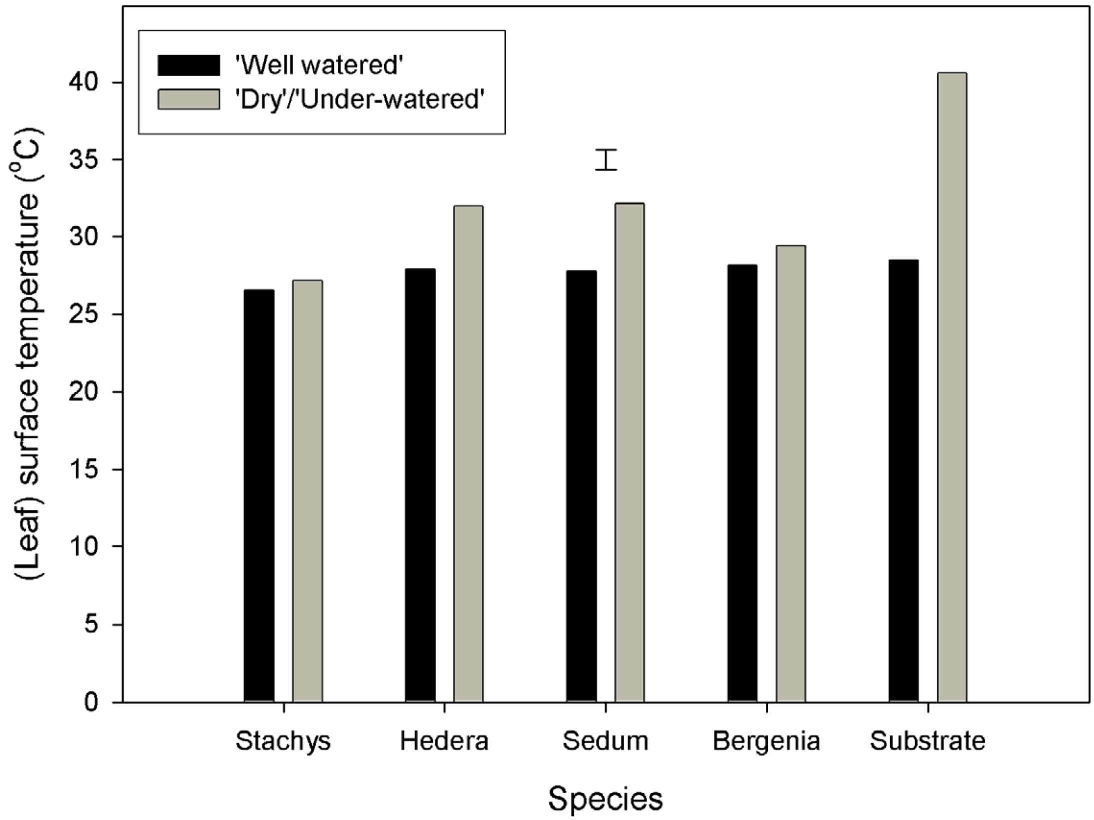
710

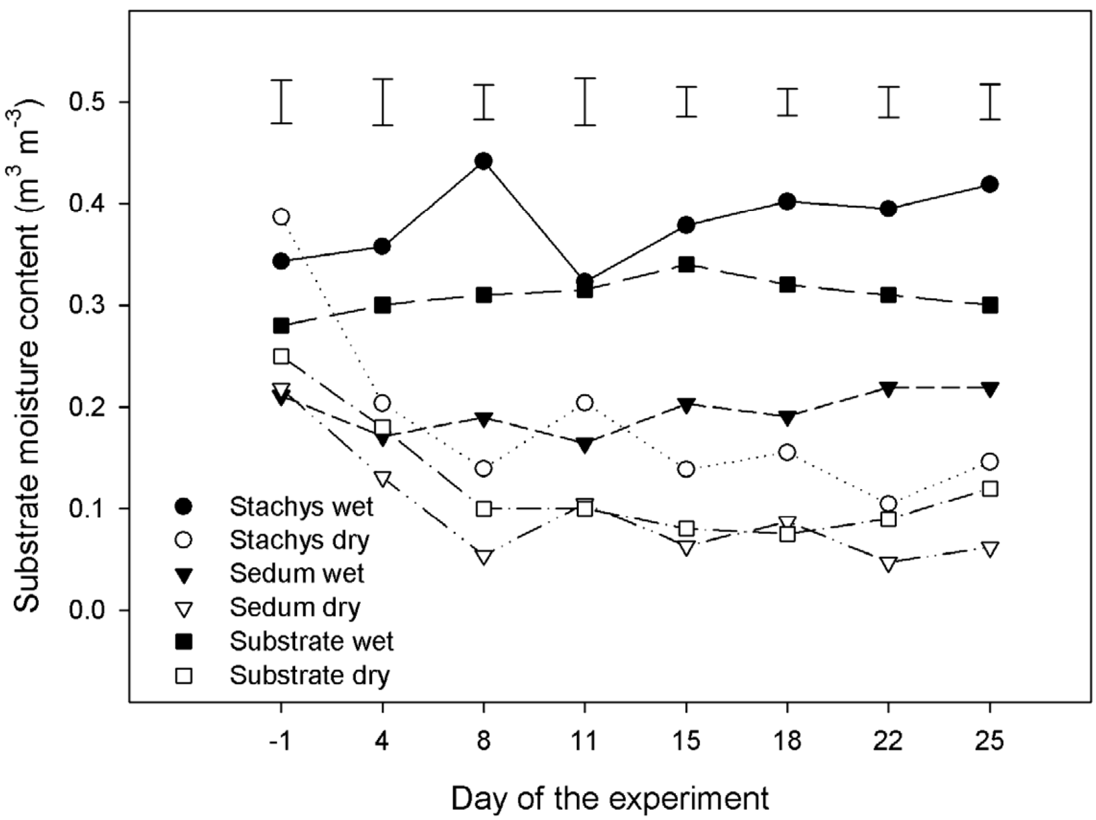
Species/Treatment	Air temperature (^{o}C)
Stachys wet	33.4 a
Substrate wet	33.7 ab
Sedum wet	34.0 ab
Stachys dry	34.1 ab
Sedum dry	34.3 bc
Substrate dry	35.0 c
LSD (d.f.)	0.76 (95)

714

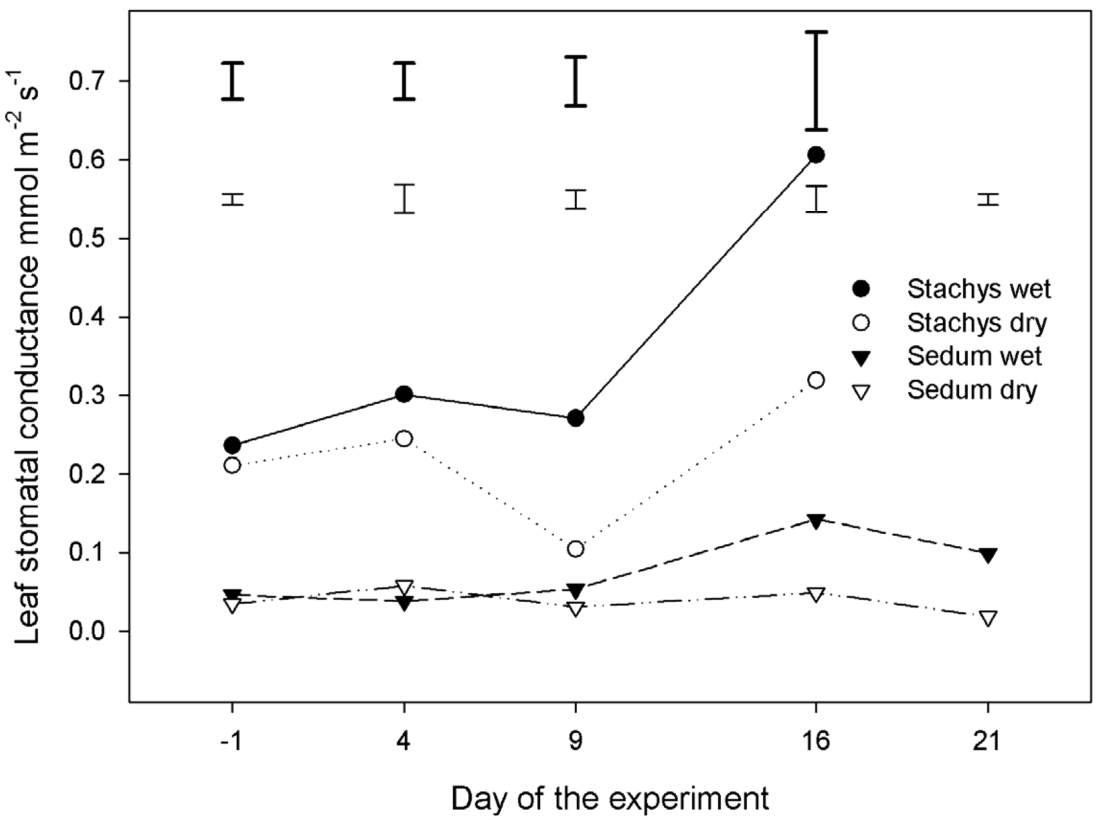
Species/surface	Soil temperature (°C)	Air temperature (°C) @ 100 mm
Stachys byzantine	22.2a	24.8a
Sedum mix	34.2b	25.1a
Bare substrate	37.1c	25.9b
LSD (d.f.)	1.09 (149)	0.32 (149)

715

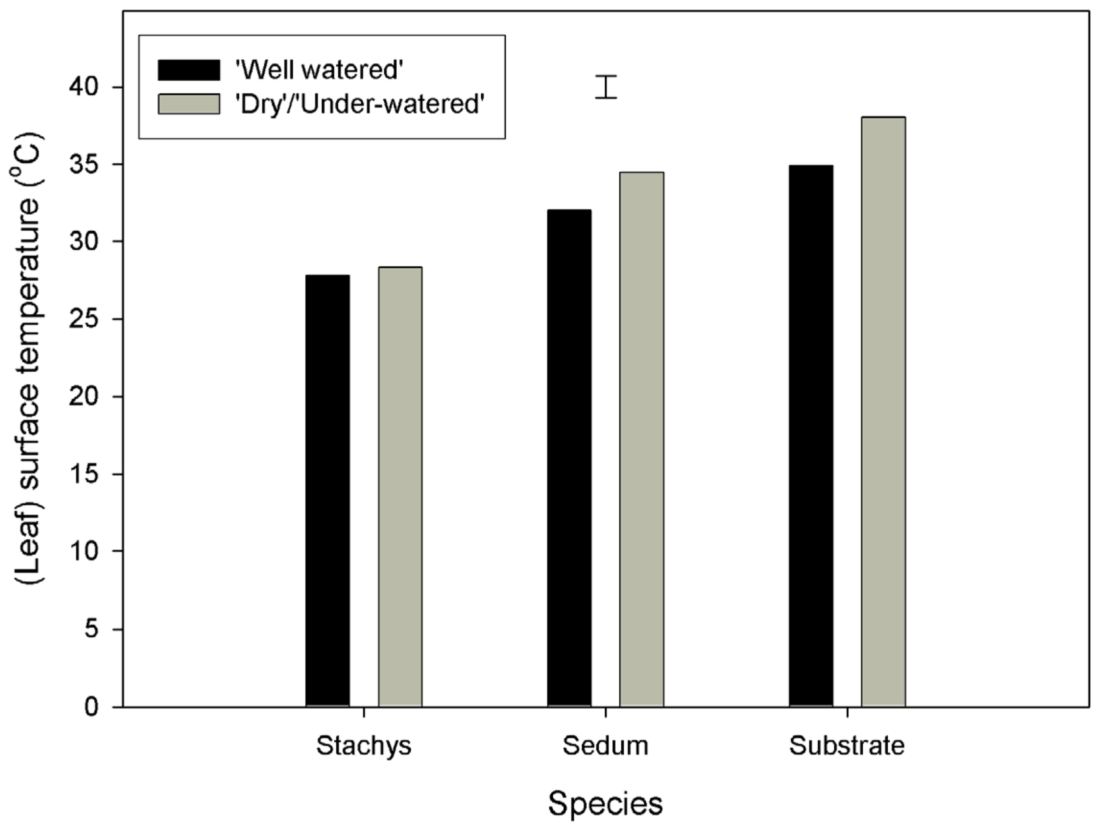

'Well watered'
'Dry'/'Under-watered'
(Leaf) surface temperature (°C)
0
5
10
15
20
25
30
35
40
Stachys
Hedera
Sedum
Bergenia
Substrate
Species



Substrate moisture content (m^3 m^{-3})
0.0
0.1
0.2
0.3
0.4
0.5
Stachys wet
Stachys dry
Sedum wet
Sedum dry
Substrate wet
Substrate dry
-1
4
8
11
15
18
22
25
Day of the experiment



Leaf stomatal conductance mmol m-2 s-1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Stachys wet
Stachys dry
Sedum wet
Sedum dry
-1
4
9
16
21
Day of the experiment



'Well watered'
'Dry'/'Under-watered'
(Leaf) surface temperature (°C)
0
5
10
15
20
25
30
35
40
Stachys
Sedum
Substrate
Species