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

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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 °C and 4 °C lower than of bare soil.

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

3

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15

16 **Abstract**

17

18 Green roof plants alter the microclimate of building roofs and may improve roof insulation.

19 They act by providing cooling by shading, but also through transpiration of water through

20 their stomata. However, leaf surfaces can become warmer when plants close the stomata and

21 decrease water loss in response to drying substrate (typically associated with green roofs

22 during summers), also reducing transpirational cooling. By using a range of contrasting plant

23 types (*Sedum* mix – an industry green roof ‘standard’, *Stachys byzantina*, *Bergenia cordifolia*24 and *Hedera hibernica*) we tested the hypothesis that plants differ in their ‘cooling potential’.

25 We firstly examined how leaf morphology influenced leaf temperature and how drying

26 substrate altered that response. Secondly, we investigated the relationship between leaf

27 surface temperatures and the air temperatures immediately above the canopies (i.e. potential

28 to provide aerial cooling). Finally we measured how the plant type influenced the substrate

29 temperature below the canopy (i.e. potential for building cooling). In our experiments *Stachys*

30 outperformed the other species in terms of leaf surface cooling (even in drying substrate, e.g.

31 5 °C cooler compared with *Sedum*), substrate cooling beneath its canopy (up to 12 °C) and

32 even - during short intervals over hottest still periods - the air above the canopy (up to 1 °C,

33 when soil moisture was not limited). We suggest that the choice of plant species on green

34 roofs should *not* be entirely dictated by what survives on the shallow substrates of extensive

35 systems, but consideration should be given to supporting those species providing the greatest

36 eco-system service potential.

37

38 **Additional key words:**

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

40

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41 **1. Introduction**

42

43 Enhancing a city's green infrastructure is frequently thought of as a means to help address a
44 number of environmental problems associated with the built environment [1, 2]. The ability
45 of urban vegetation to help mitigate urban heat island effects [3] and to reduce the energy
46 load on buildings [4] are two important ecosystem services that plants can provide. Globally,
47 urbanisation is still increasing and there is more pressure within the urban matrix for land to
48 be used for housing, business development and the associated infrastructure. Consequently,
49 the use of green roofs has been advocated, partially in an attempt to provide some urban
50 green space, without adding to the pressures on land at ground level. Even in countries which
51 traditionally have not suffered from extreme anti-cyclonic conditions ('heat-waves') such as
52 those in Northern Europe, there are concerns that a changing climate combined with urban
53 expansion will result in more frequent incidents of severely elevated temperatures [5]. The
54 use of urban greening is therefore advocated to help mitigate such events, and helps in part to
55 compensate for the lack of alternative cooling mechanisms more typical of warmer
56 Mediterranean climates e.g. lightly coloured buildings with high albedo, thick insulating
57 walls, shuttered windows, greater exploitation of prevailing cooling winds etc. [6].
58 In Northern Europe and indeed many other regions, vegetation is now considered to be a vital
59 component in reducing air temperatures at the city-wide scale [7, 8] as well as locally (e.g. [6,
60 9]). Plants provide a cooling influence by transpiration of water through their stomata [10],
61 but also through direct shading [11]. It has been claimed that green roofs harbour genuine
62 potential for urban temperature reduction [12], but the extent to which they contribute to
63 urban cooling compared to other vegetation types or landforms (e.g. street trees, urban forest,
64 parkland etc.) is unclear. Indeed, there is still some debate as to how micro-climates
65 associated with different types of urban vegetation actually influence climate at the larger

66 urban scale [13]. At a more local level, it is acknowledged that low-growing terrestrial
67 vegetation (lawn grass particularly) can enhance aerial cooling, at least in comparison to
68 harder, more typical urban surfaces (asphalt, concrete, paving etc.) [14, 15]. However, the
69 evidence for green roofs providing significant air cooling remains limited [16]. Furthermore,
70 the ability of green roof plants to extract and transpire water may be considerably
71 compromised in the shallow, lithosol-like substrates used on green roofs compared to a
72 deeper profile, natural soil. Also, leaf surfaces are likely to become warmer when plants close
73 their stomata and decrease water loss in response to drying substrate [17].

74

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

82

83 Due to the drought prone and exposed nature of extensive and semi-extensive green roofs,
84 *Sedum sp.* (e.g. *S. album*, *S. acre*, etc.) with typical xerophytic characteristics are the most
85 widely used plant group [20]. *Sedum sp.* establish rapidly, provide good surface coverage and
86 are effective in decreasing storm water runoff while requiring low maintenance [21]. A
87 number of studies worldwide have investigated species alternative to *Sedum*, including bulbs
88 and grasses (e.g. in Germany [22]), small shrubs, grasses and ornamental perennials (e.g. in
89 Japan [23]), as well as species mixes that included succulents (e.g. in Canada, [24]) but only
90 two tested alternatives to *Sedum* in the UK climatic conditions [25, 26]. The focus of these

91 studies has been on ecological function, particularly species survival and growth rates. The
92 results showed that there were alternatives to *Sedum* in terms of good surface coverage and
93 providing protection from water runoff, but there was little emphasis on other ecosystem
94 services, including cooling potential.

95

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

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

115

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

128

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

140

141 **2. Methods**

142

143 2.1. Plant material

144

145 Three broad-leaved, perennial species: *Bergenia cordifolia* (large, waxy leaves), *Hedera*
146 *hibernica* (leaves with thick epidermis, providing good cover) and *Stachys byzantina* (leaves
147 with light-coloured hairs) were compared to *Sedum sp.* mix (small, succulent leaves) in
148 Experiment 1, with *Stachys* and or *Sedum sp.* mix used in subsequent experiments.
149 *Sedum* was purchased as a commercially used 'Enviromat' matting system (Q Lawns,
150 Hockwold, Norfolk, UK) and represented a random mix of *Sedum album*, *S. spurium*, *S. acre*
151 and *S. sexangulare*. Other plant species were purchased from a commercial nursery as 1-year
152 old plants in 250 ml containers.

153

154 2.2. Experiment 1. The effect of species and water availability on leaf stomatal conductance,
155 leaf surface temperature and air temperature above the canopy (glasshouse conditions)

156

157 *2.2.1 Experimental set-up*

158 On 3 June 2009, plants were planted into custom-made large containers (1.2 m (l) x 0.4 m (w)
159 x 0.4 m (h)) filled to a depth of 0.2 m with commercial intensive green roof substrate (Shire
160 Green Roof Substrates Ltd., Southwater, West Sussex, UK), to mimic a standard semi-
161 intensive green roof. The substrate had the following properties (as specified by the
162 manufacturers): pH = 8.5, total pore volume 49-60%, soil organic matter 9.2% and maximum
163 water holding capacity 33.5%.

164 There were six containers per species and an additional six with unplanted (bare) substrate.

165 Containers were organized in a randomised block design and located in a ventilated

166 glasshouse; where minimal / night temperatures never fell below 15 °C and maximal /
167 daytime temperatures were in the range 22 – 37 °C, the RH in the compartment was around
168 30% during daytime and 70% during the night. Twenty eight plants per container of *Stachys*
169 and *Bergenia* and eight plants of *Hedera* per container were planted to achieve 90% of initial
170 ground coverage. *Sedum* mat, with the root barrier layer removed, was laid on top of the 0.2
171 m deep substrate.

172

173 2.2.2. Watering treatments

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

181

182 2.2.3. Plant and substrate measurements

183 Substrate moisture content was measured twice weekly using SM200 probe (Delta-T Devices
184 Ltd., Cambridge, UK) in five locations across the middle of the longer axis of each of the
185 containers, close to a plant. Measurements were made between 09:00 and 10:00 h (British
186 Summer Time, BST).

187 Leaf stomatal conductance to water vapour (g_s) was measured in all species apart from *Sedum*
188 (where the leaves were too small and thick for the instrument's chamber), twice weekly
189 between 10:00 and 15:00 h (BST) to follow SMC measurements, using AP4 porometer
190 (Delta-T Devices Ltd., Cambridge, UK) on seven randomly selected plants (two leaves per

191 plant) in each of the containers. Leaf stomatal conductance is measured as the rate of passage
192 of water vapour leaving a stomatal pore and is expressed in $\text{mmol m}^{-2} \text{s}^{-1}$.

193

194 Surface temperatures (plants and bare substrate) were measured by analysing Infra-Red
195 thermal images; the images were taken between 13:00 and 14:00 h (BST) at regular intervals
196 during the experiment to capture multiple days with similar and varying weather, using
197 Thermo Tracer TH7800 camera (NEC San-ei Instruments Ltd., Japan). Thermal images were
198 taken from the 30° angle with respect to the vertical and 1 m distance from the container edge
199 and from 1.2 m height in all cases; nine areas of 50 x 50 mm in the middle of each container
200 were analysed for their average temperature using the NS9200 Report Generator software
201 (NEC San-ei Instruments Ltd., Japan). Air temperature was measured at 30 min intervals at
202 fixed height 300 mm above the middle of the substrate surface for the duration of the
203 experiment using screened RHT2n sensors attached to a DL2e logger (Delta-T Devices Ltd.,
204 Cambridge, UK). The height of the sensor was dictated by the experimental design in
205 experiment 1, where the sensor was placed directly above the centre of the plant canopy and
206 100 mm above the height of the lip of the container the plants were grown in. This was
207 implemented to enable us to measure temperature at a fixed height above the ground, so that
208 we can compare absolute impact of the absence of vegetation / various types of vegetation
209 which inherently differs in canopy height. Preliminary evaluations indicated there was less
210 temporary fluctuation in temperatures at the 300 mm height when glasshouse doors or vents
211 were opened compared to higher positions; and lowering the sensors further, could result in
212 direct shading of a large proportion of the canopy. Prior to the start of measurements, in all
213 experiments, temperature sensors were compared by running them for 24 h in a controlled
214 environment room and found to be within $\leq 1\%$ error of each other.

215

216 2.3. Experiment 2. Comparisons between *Sedum* mix and *Stachys byzantina*: leaf surface
217 temperature and air temperature above the canopy (glasshouse conditions)

218

219 On 1 June 2010, *Stachys byzantina* was planted and *Sedum* matting was laid into containers
220 and two watering regimes were imposed, as described for Experiment 1 (Section 2.2.2.).
221 There were 10 containers for each of the plant covers and an additional 10 containers with
222 unplanted substrate. The experiment ran for approx. 3 weeks from 3-23 June 2010 and
223 measurements of SMC, surface and air temperature were made as described for Experiment 1
224 (Section 2.2.3). Additionally, measurements of g_s were performed in both species with an
225 LCi portable open gas exchange system (ADC BioScientific Ltd., Hoddesdon, UK) with
226 ambient CO₂ concentration at $385 \pm 5 \text{ mm}^3 \text{ dm}^{-3}$. During measurements, photosynthetic
227 photon flux density was supplemented to a minimum of $1000 \mu\text{mol m}^{-2} \text{ s}^{-1}$ by an external (50
228 W, 12 V) halogen source. Measurements on seven plants per container (two leaves per plant)
229 were carried out between 10:00 and 15:00 h (BST).

230

231 2.4. Experiment 3. Comparisons between *Sedum* mix and *Stachys byzantina*: leaf surface
232 temperature, air temperature above the canopy and ground surface cooling (outdoor
233 conditions)

234

235 An outdoor experiment was set up at the University of Reading, UK. Six plots, each
236 measuring 2.2 m (l) x 2.2 m (w) x 0.1 m (d), were constructed at ground level using timber,
237 lined with polyethylene pond liner (0.75 mm thickness) and filled with John Innes No 2
238 substrate to 0.1 m depth. There were two plots for each of the surfaces: bare substrate,
239 *Stachys byzantina* and *Sedum sp.* matting. Vegetation was planted in September 2010 and by
240 the onset of the experiment (27 May 2011), plants covered 100% of the plot surfaces; bare

241 substrate was kept weed-free. Plots were rain-fed, but throughout the experiment the SMC
242 remained above $0.15 \text{ m}^3 \text{ m}^{-3}$. The experiment commenced on 27 May 2011 and terminated on
243 3 July 2011.

244 To increase the likelihood of detecting local air temperature differences outdoors, where there
245 is greater air mixing, screened temperature sensors RHT2n were placed at two heights on the
246 edge and in the centre of the plots. One sensor was placed in line with the plant canopy (20-
247 30mm above the soil surface) surface and another 100 mm above the canopy. The larger
248 planted area in this experiment (4.84 m^2) compared to Experiment 1 (0.48 m^2) enabled sensors
249 to be placed closer to the canopy than before, without affecting a proportionally large area of
250 the canopy through shade. Furthermore, in this experiment we were interested in using top of
251 the plant canopy, rather than the soil surface, as a 'reference point', to provide us with the
252 relative comparisons between plant species. Additionally, soil surface temperature beneath
253 the plants was measured by placing thermocouples (type Fenwal UUA32J2, in house
254 construction) 5 mm below the soil surface in the centre of all plots. Temperature was
255 measured at 5 s intervals and averaged every 10 min. Measurements of leaf surface
256 temperature were by thermal imaging as described for Experiment 1 (section 2.2.3).
257 Additionally, anemometer (A 100R, Skye Instruments Ltd., Llandrindod Wells, UK) was
258 placed in the centre of the experimental area to monitor wind velocity at the same time as
259 temperature readings were recorded.

260 Substrate moisture content was measured twice weekly using SM200 probe (Delta-T Devices
261 Ltd., Cambridge, UK) between 09:00 and 10:00 h (BST) in 12 locations evenly distributed
262 across every plot. Net total radiation (i.e. difference between incoming and outgoing/reflected
263 radiation) was measured on 3 June using net pyrradiometer CN1/919 (Middleton Solar,
264 Melbourne, Australia) attached to DT 500 Datalogger (Omni Instruments, Dundee,
265 UK). The measurements were made between 11:30 and 12:30 h (BST), logging every 30 s for

266 15 minutes, 300 mm above one plot per each of the surfaces (bare soil, *Sedum* mix and
267 *Stachys*). During the same time period we recorded the surface temperatures of the surfaces
268 where net radiation measurements were made using the methodology described in Section
269 2.2.3.

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

275

276 2.5. Experiment 4. The role of leaf hairs in *Stachys byzantina* in regulating leaf temperature
277 (controlled environment cabinet)

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

290 and individual leaf areas (at the end of the experiment) were measured as described for
291 Experiments 2 (Section 2.3) and 3 (Section 2.4), respectively.

292

293 2.6. Statistical analysis

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

299

300 **3. Results**

301

302 3.1. Experiment 1. The effect of species and water availability on leaf stomatal conductance, 303 leaf surface temperature and air temperature above the canopy (glasshouse conditions)

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

309 Leaf stomatal conductance (g_s) was consistently lower in the ‘dry’ treatment from day 14. In
310 ‘well-watered’ plants average g_s values were $233.1 \text{ mmol m}^{-2} \text{ s}^{-1}$ for *Stachys*, $220.1 \text{ mmol m}^{-2}$
311 s^{-1} for *Hedera* and $217.0 \text{ mmol m}^{-2} \text{ s}^{-1}$ for *Bergenia*. Conversely, in the ‘dry’ treatment the
312 overall averages were $147. \text{ mmol m}^{-2} \text{ s}^{-1}$ for *Stachys*; $98.8 \text{ mmol m}^{-2} \text{ s}^{-1}$ for *Hedera* and 66.4
313 $\text{mmol m}^{-2} \text{ s}^{-1}$ for *Bergenia*.

314 When measured on the hottest days, *Stachys* consistently had the lowest leaf surface
 315 temperature amongst all species, both under ‘well- watered’ and ‘dry’ regimes (e.g. see data
 316 for early afternoon measurement on 3 July 2009, Day 24 of the experiment, Fig. 1). All other
 317 species had similar leaf surface temperatures when they were well watered (Fig. 1). In the
 318 ‘dry’ treatment the following order of surface temperatures was recorded on 3 July: bare
 319 substrate > *Hedera* = *Sedum* > *Bergenia* > *Stachys* (Fig. 1). There was no significant
 320 difference in leaf surface temperature between ‘well- watered’ and ‘dry’ *Stachys* (26.5 °C vs
 321 27.2 °C, respectively, LSD = 1.25 °C). All other surfaces associated with the ‘dry’ regime
 322 were warmer than those ‘well-watered’ (Fig. 1). Air temperature in the glasshouse
 323 compartment at the time when leaf temperatures were measured on 3 July was 30.7 °C.
 324 In terms of air temperatures above various surfaces we were only able to establish treatment /
 325 species differences on hottest days (air $T_{\max} > 32$ °C) and only during early afternoons (12:00
 326 – 16:00 h). Air temperatures were lowest above *Stachys* grown in ‘well-watered’ treatment
 327 and above *Sedum* in the ‘dry’ regime (Table 1).

328

329 3.2. Experiment 2. Comparisons between *Sedum* mix and *Stachys byzantina*; leaf surface
 330 temperature and air temperature above the canopy (glasshouse conditions)

331 In this experiment, there was a difference in SMC between ‘well- watered’ and ‘dry’
 332 treatments in both plant species and on bare substrate from Day 4 of the experiment (Fig. 2).
 333 Well-watered *Stachys* and bare substrate SMC was maintained, on average, at least at 0.3 m³
 334 m⁻³, and *Sedum* at 0.2 m³ m⁻³ (Fig 2). In the ‘dry’ treatment, *Stachys* was maintained at
 335 around 0.15 m³ m⁻³ and *Sedum* and bare substrate below 0.10 m³ m⁻³ (Fig. 2).
 336 Leaf stomatal conductance was significantly lower in plants within the ‘dry’ treatment
 337 compared to the ‘well-watered’ treatment from day 9 in *Stachys* and Day 16 in *Sedum* (Fig.
 338 3). This was accompanied by the decrease in the instantaneous evaporation (E) in these

339 species during the same period (data not shown). Over the course of the experiment reducing
340 irrigation decreased g_s by 40% (*Stachys*) and 50% (*Sedum*) (Fig. 3).

341 As in Year 1, leaf temperatures in *Stachys* on the hottest days (i.e. maximal daytime
342 temperature > 30 °C) were similar in ‘well- watered’ and ‘under-watered’ plants (27.8 vs 28.3
343 °C) and lower in *Stachys* than in any other surface/watering combination (Fig. 4). Surface
344 temperatures were also higher in ‘dry’ substrate and *Sedum* compared to the ‘well-watered’
345 equivalents (Fig. 4).

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

350

351 3.3. Experiment 3. Comparisons between *Sedum* mix and *Stachys byzantina*: leaf surface
352 temperature, air temperature above the canopy and ground surface cooling (outdoor
353 conditions)

354

355 During the outdoor experiment in June 2011 there was extensive cloud cover on many of the
356 days over which the experiment was conducted. According to data from sensors on the
357 experimental site and information from University of Reading’s weather station , there were
358 only two days (3rd and 4th June) where full sunlight, low wind speeds and warm temperatures
359 (20-25 °C daytime, 10-15 °C nightie) were consistently recorded (i.e. > 12 hours sunlight).

360 Surface temperatures of plants and substrate outdoors showed identical patterns to that in
361 glasshouse Experiments 1 and 2. For example, during the warmest day of the experiment (4
362 June 2011, Day 8 of the experiment, air $T_{\max} = 25.6$ °C), temperatures were highest in the
363 bare substrate, followed by *Sedum* and lowest in *Stachys*; this was confirmed by both thermal

364 imaging and temperature sensors (data not shown). We found significant differences in soil
365 temperatures during the warmest part of the day (12 – 16 h). Soil underneath *Stachys* was
366 over 11 °C cooler than soil under *Sedum*, which was also almost 3 °C cooler than bare
367 substrate in the period 12 – 16 h (Table 3). In the same period, air temperatures 100 mm
368 above *Stachys* and *Sedum* were similar (24.8 and 25.1 °C on average, respectively), but both
369 were significantly lower than over bare substrate (25.9 °C) (Table 3). Significant differences
370 in air temperature above the two plant canopies were observed, however, on other warm
371 days, but only during shorter intervals (e.g. 24.1 °C vs 25.0 °C for *Stachys* and *Sedum*
372 respectively, between 12:30 and 13:30 on 3 June, LSD = 0.57 °C, F pr. = 0.002). In terms of
373 the night time air temperatures, there was no difference between the surfaces (data not
374 shown). Night time soil temperatures, however, were about 1 °C warmer underneath *Stachys*
375 compared with *Sedum* and bare soil (14.6, 14.0 and 13.7 °C, respectively, LSD = 0.47 °C, d.f.
376 = 293) between 3 and 4 June, but not during 4 and 5 June (data not shown).
377 Net radiation was highest above bare soil (665.1 W m⁻²) followed by that over *Sedum* mix
378 (552.7 W m⁻²) and lowest over *Stachys* (523.6 W m⁻², LSD = 13.55 W m⁻²), indicating that
379 *Stachys* was reflecting back more of the incoming radiation. Leaf area indices were similar in
380 *Sedum* mix and *Stachys* (2.29 vs 2.30, respectively).

381

382 3.4. Experiment 4. The role of leaf hairs in *Stachys byzantina* in regulating leaf temperature
383 (controlled environment cabinet)

384

385 Results of the 24 h controlled environment experiment measuring the impact of hair removal
386 on leaf temperature in *Stachys* showed that leaf temperature was consistently significantly
387 higher in shaved leaves, compared with controls (hairs left intact) (e.g. at 24 h, 23.3 °C
388 control vs 23.9 °C in shaved leaves, LSD = 0.21 °C). These temperature differences,

389 however, were not matched by statistically significant differences in volume of water lost
390 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
391 h, $0.227 \text{ mmol m}^{-2} \text{ s}^{-1}$ control vs $0.192 \text{ mmol m}^{-2} \text{ s}^{-1}$ shaved leaves, LSD = $0.0479 \text{ mmol m}^{-2}$
392 s^{-1}).

393

394 4. Discussion

395

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

406

407 Temperatures of bare, unplanted, substrate were also significantly affected by moisture
408 content, with ‘well-watered’ substrates always having lower surface temperature than those
409 where irrigation had been restricted, clearly demonstrating the cooling influence of
410 evaporation alone. The ability for plants to provide additional surface cooling again appeared
411 to be influenced by species choice. Leaf surface temperatures of *Stachys* plants held under
412 ‘well-watered’ conditions were lower than the surface temperatures of damp bare substrate
413 (Figures 1 and 4). Similarly, ‘well-watered’ *Sedum* was also cooler than the watered bare

414 substrate in Experiment 3 (Figure 4), but surface temperatures of *Bergenia* and *Hedera* were
415 little different from that of damp bare substrate (Figure 1). Under the ‘dry’ conditions,
416 however, leaf temperatures were always lower than those of the bare substrate.
417
418 The relationship between surface temperatures and the air temperature recorded 300 mm
419 above the substrate within the glasshouse environment was more complex. During
420 particularly warm periods, lowest air temperatures were measured above *Stachys* canopy, but
421 only when the plants were ‘well-watered’ (Tables 1 and 2). Air temperatures above ‘dry’
422 *Stachys* could be relatively high; note the 7 °C difference between leaf and air temperature
423 with this treatment in Experiment 1 (compare Figure 1 and Table 1 data). Overall, there were
424 poor correlations between leaf / substrate surface temperatures and air temperatures above the
425 plots. The relatively small plot sizes and the close proximity of the different treatments and
426 subsequent air mixing may partially explain the variability that accounted for this. Although
427 we specifically chose the semi-protected character of the glasshouse to reduce air movement
428 and mixing, there may still have been interference due to thermal gradients associated with
429 the structure of the glasshouse, concrete floors, metal framework etc., as well as neighbouring
430 treatments. In this experiment we also specifically chose to measure temperature at set
431 heights above the substrate, not the plant canopies, and the latter were themselves variable
432 even within a monoculture of the one species. Although we raised the height of the sensors to
433 account for this (100mm above the highest plants), this may have predisposed the sensors to
434 other interfering effects (i.e. greater air movement across the top of the containers, rather than
435 within them). Outdoors, at 100 mm above ground and over longer averages (e.g. between
436 12:00 and 16:00 h over two experimental plots) we only detected significant differences in air
437 temperature between vegetation and bare soil, and not between *Stachys* and *Sedum* (although
438 the difference was only borderline statistically insignificant). This difference between

439 vegetated vs non-vegetated (instead of the species difference) was measured consistently
440 during the experiment and in various types of weather. Over shorter intervals on hottest days,
441 however, we found occasional periods when air over *Stachys* was cooler than over *Sedum* and
442 we argue that this difference may become important in the scenarios of prolonged hot
443 weather. Even with larger plots, Kjelgren and Montague [33] failed to show any difference in
444 air temperature above two neighbouring areas of grass and asphalt outdoors, due apparently
445 to their close proximity and air mixing (height of measurement was not reported). Other
446 reports though, have detected differences in air temperature above low growing vegetation
447 and hard surfaced areas when measuring at 1 to 2 m above ground level [15, 16]. Clearly, the
448 contribution of low growing vegetation to wider aerial cooling effects requires further
449 investigation (especially with respect to air mixing and convection, e.g. [34]), with perhaps
450 effects of vegetated vs non-vegetated areas being more noteworthy than any subtleties due to
451 plant species choice. Nevertheless, plant selection may be more critical at the smaller scale,
452 especially within a few centimetres of the building envelope (where air mixing may be more
453 limited due to parapets, ridge tiles or other structural features), as well as being used to
454 improve the efficiency of mechanical air conditioning units through localized cooling [35].
455 Future work needs to account for confounded factors associated with air movement even a
456 very local levels, however, and more systematic use of sensors placed at discrete distances
457 from the transpiring leaves may be required to determine the ‘zone of cooling influence’
458 before air mixing etc. dilutes any effect.

459

460 Of the species we tested, *Stachys* had the greatest capacity for regulating its own temperature
461 and keeping its leaves cool. It retained the lowest surface temperature even when soil
462 moisture became limited and stomata closed. In the controlled environments utilised in
463 Experiment 4 it was evident that retaining hairs on the leaves of *Stachys* reduced the amount

464 of infra-red radiation emitted from the leaf (i.e. the leaves appeared cooler), compared to
465 those leaves where the hairs were trimmed. This cooling conferred by the leaf hairs may be
466 related to light hair colour reflecting or refracting more incoming irradiance [36], and appears
467 to be supported by lower net-radiation values over *Stachys* which we measured in our
468 experiment. The presence of hairs on leaves has been cited as a mechanism to reduce
469 moisture loss from the leaf surface [37] and / or protect tissues from excessive irradiance,
470 particularly UV wavelengths [38, 39]. In our experiment, although shaved leaves of *Stachys*
471 lost more water than unshaved ones, differences in moisture loss were not significant. The
472 fact that surface temperatures were significantly different though, may suggest that the
473 predominant role for *Stachys* hairs is to reduce the intensity of incoming irradiance, provide
474 higher reflectance / albedo and avoid direct heat stress, perhaps with any capacity to trap
475 moisture as only a secondary role. Despite the phenomena of being able to lower its leaf
476 temperature irrespective of the irrigation level applied, the ability for *Stachys* to maximise air
477 cooling was still strongly dependant on moisture being available and water transpiring
478 through its leaves: greatest air cooling corresponding to the presence of the *Stachys* canopy
479 *combined* with the stomata being open.

480

481 The final component we were interested in was the impact of vegetation type on the substrate
482 temperature below the leaf canopy. It is widely acknowledged that the presence of vegetation
483 lowers soil temperatures during the day and, in the case of green roofs, reduces the
484 temperatures of the roof membrane (e.g. [40]) and the building interior underneath the roof
485 (e. g. [18]). However, these measurements are usually made in model scenarios and species
486 (*Sedum*, turf) and the understanding of how different plant species impact on surface and
487 building temperatures is limited [16, 23, 41]. Measurements of temperatures underneath plant
488 canopies of six species showed that the presence of closed canopies (as opposed to sparser,

489 more open canopies) [16] and higher leaf area index [10] was associated with lower surface
490 temperatures during the day. In another study, *Petunia* coverage reduced soil temperature
491 more than *Hedera* [23], but the specifics of the mechanism have not been elucidated. In our
492 study, we again observed the most positive results with *Stachys*, with substrate temperatures
493 below the *Stachys* canopy being >11 °C lower than under *Sedum* during the warmest periods
494 (Table 3). Extra shading did not appear to account for this, as the LAI of the two species were
495 similar. The presence of leaf hairs which would act to increase energy reflectance from
496 *Stachys*' leaves, in addition to evapotranspiration, appears to be important for the regulation
497 of temperature by this plant species. The night time temperatures of the substrate underneath
498 the *Stachys* were only 1 °C higher than that of the bare substrate and *Sedum*, while the
499 daytime differences were – as already discussed - much larger. We feel therefore that the
500 overall benefit is in using *Stachys*. Additionally, if the thermal load onto the building during
501 the day is decreased and reflection increased (as it appears to with *Stachys*) the night time
502 thermal discomfort of the building residents underneath this roof, on balance, will be smaller.

503
504 Our experiments explore the concepts and general principles that differences in plant
505 structure and function, which affect plants' regulation of own temperature, can impact the air
506 and surface temperatures. These concepts now have to be validated by further, more applied,
507 field studies. Similarly, more research is required to investigate the impacts of localized
508 cooling on the leaf, substrate surface, immediate air volume etc. on large, city scale effects.
509 Many urban climate models tend to represent vegetation very simply (see [42]) or define it in
510 broad terms; 'grass' / 'trees' with little precision based on species, albedo characteristics or
511 indeed the impacts of a range of environmental factors that influence stomatal behaviour
512 either directly (irradiance, atmospheric CO₂, O₃, humidity, leaf temperature, soil moisture
513 availability,[43]) or indirectly (hormonal and hydraulic signalling, [44]). The data presented

514 here demonstrate that variations in plant phenotype and physiological adaptations within a
515 range of low-growing species can influence cooling effects on leaf, substrate and by
516 inference, building surfaces, if not always consistently and categorically on air temperatures.

517

518 **5. Conclusions**

519

520 We advocate that the choice of plant species on green roofs should *not* be entirely dictated by
521 what survives on the shallow substrates of extensive systems, but consideration should be
522 given for supporting those species that provide the greatest eco-system service potential. This
523 includes, perhaps, justifying the additional expense associated with providing a deeper
524 substrate (such as a semi-extensive system) or even supplementary irrigation from a
525 sustainable source. In this study *Stachys* outperformed the other species under test in terms of
526 leaf surface cooling, cooling the substrate beneath its canopy and even - during short intervals
527 over hottest still periods - the air above the canopy, when soil moisture was not limited. The
528 fact we measured air temperature differences between the species only during the hottest
529 periods of the experiment may be an important point: it suggests that in many cases either
530 vegetation type is fine, but when temperatures begin to peak (and, potentially, the UHI events
531 start to become significant) there is an advantage with *Stachys*. This is particularly in respect
532 to lowering air temperatures around the building envelope thus potentially reducing cooling
533 demand and decreasing temperatures around air conditioning units, thereby lowering energy
534 consumption. *Stachys* is unlikely to be as resilient as *Sedum* in terms of survival in the most-
535 droughty, extensive, green roofs (e.g. 50-100 mm deep), but is a drought-adapted species in
536 its own right, capable of survival and persistence without additional irrigation in semi-
537 extensive (200 mm depth) systems within Northern Europe [20]. Nevertheless, we are
538 continuing to investigate the sustainable irrigation regimes/systems to support the growth of

539 such species to help support them under more extreme climates and to understand potential
540 economic impacts of choosing them (i.e. cooling cost reduction vs increased irrigation and
541 maintenance costs). We are also focusing on the importance of leaf colour and
542 thickness/morphology in the energy balance of leaves and the surrounding surfaces. Our
543 future work will incorporate biological and modelling approaches to provide answers about
544 which biological traits, and through what mechanisms, provide the greatest benefits in a more
545 applied context.

546

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553

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555

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- 663

664 Figure legends

665

666 Figure 1. Mean surface temperature ($^{\circ}\text{C}$) of bare substrate and plant leaves on July 3, 2009
667 (Day 24 of the Experiment 1). Vertical bars are mean of nine temperature measurements per
668 container and three containers per plant species/surface, a line represents associated LSD
669 (1.25°C , d.f. = 258). Measurements were made between 13 and 14 h.

670

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

675

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

681

682 Figure 4. Mean surface temperature ($^{\circ}\text{C}$) of bare substrate and plant leaves on June 16, 17 and
683 21 2010 (Days 14, 15, and 19 of the Experiment 2). Vertical bars are mean of nine
684 temperature measurements per container and five containers per plant species/surface, a line
685 represents associated LSD (1.35°C , d.f. = 809). Measurements were made between 13 and 14
686 h.

687 List of tables

688

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

694

695 Table 2. Average air temperature ($^{\circ}\text{C}$) at fixed height, 300 mm above the substrate level, on
696 the hottest day of the Experiment 2 (21 June 2010, Day 19 of the experiment) between 12 and
697 16 h. Data are mean of sixteen measurements per species/surface and ranked lowest to
698 highest (LSD = 0.758 $^{\circ}\text{C}$, d.f. = 95). The means followed by a different letter are statistically
699 significantly different.

700

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

707

708

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

709

710

711

712

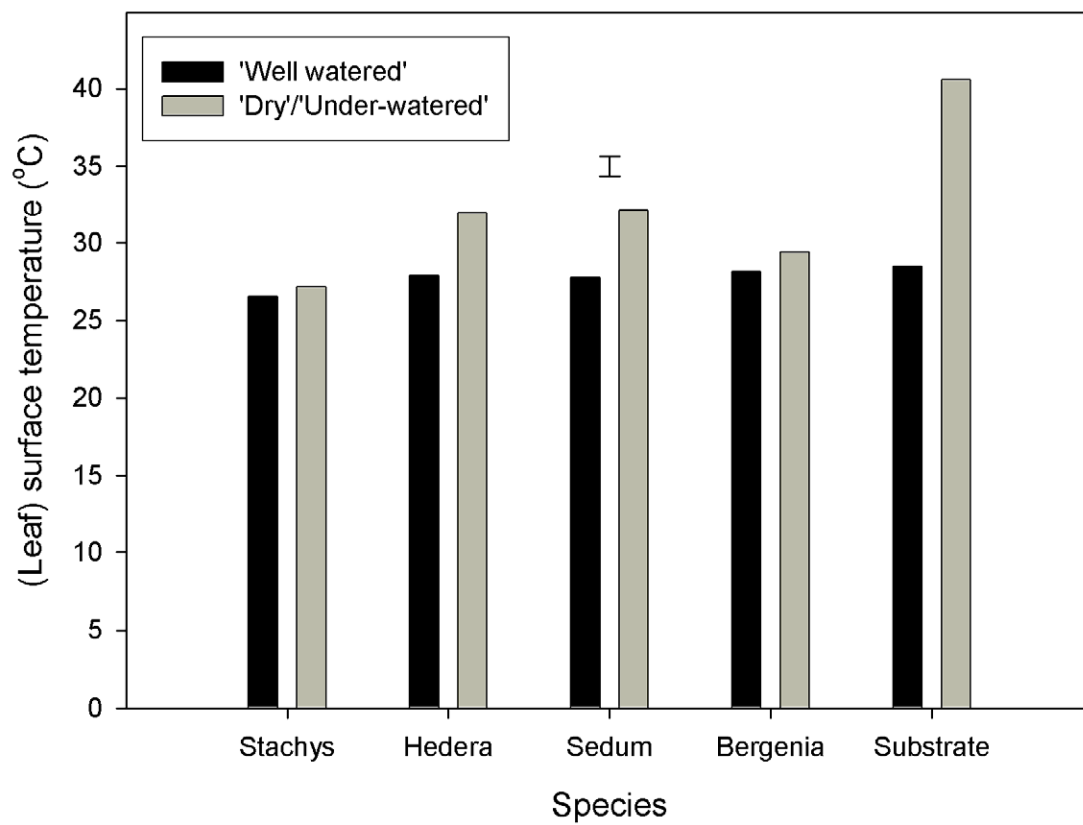
Species/Treatment	Air temperature (°C)
<i>Stachys</i> wet	33.4 a
Substrate wet	33.7 ab
<i>Sedum</i> wet	34.0 ab
<i>Stachys</i> dry	34.1 ab
<i>Sedum</i> dry	34.3 bc
Substrate dry	35.0 c
LSD (d.f.)	0.76 (95)

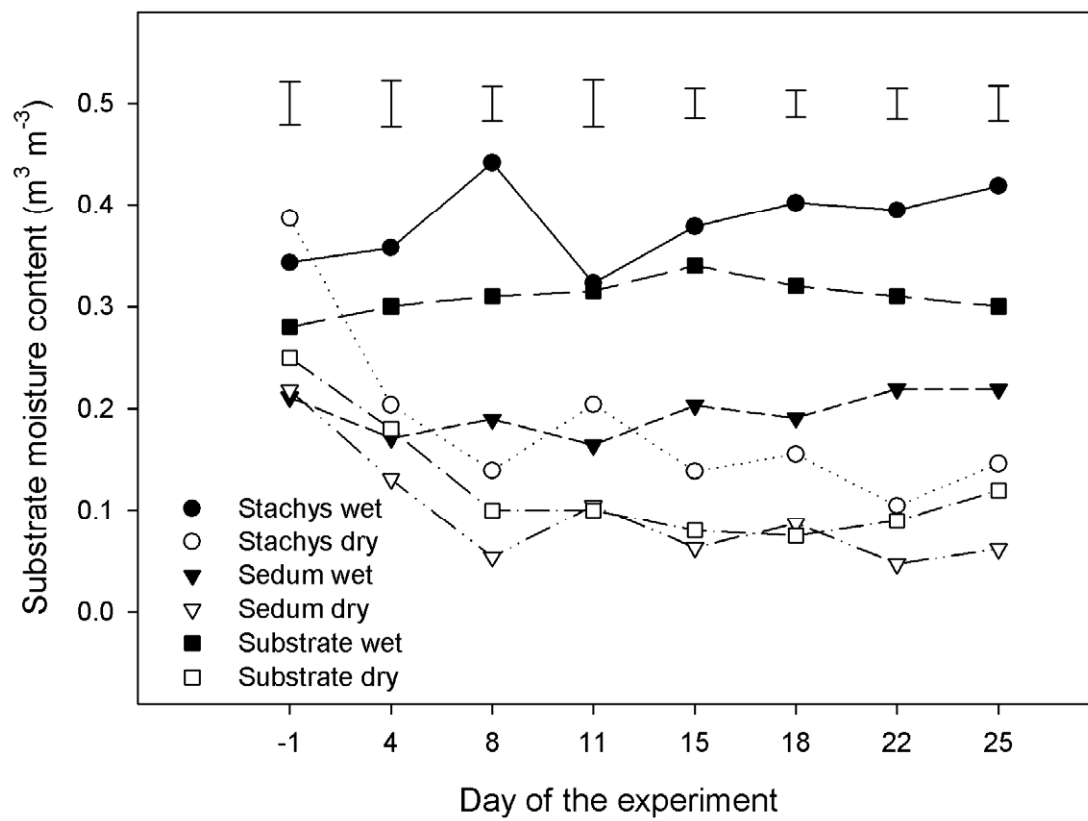
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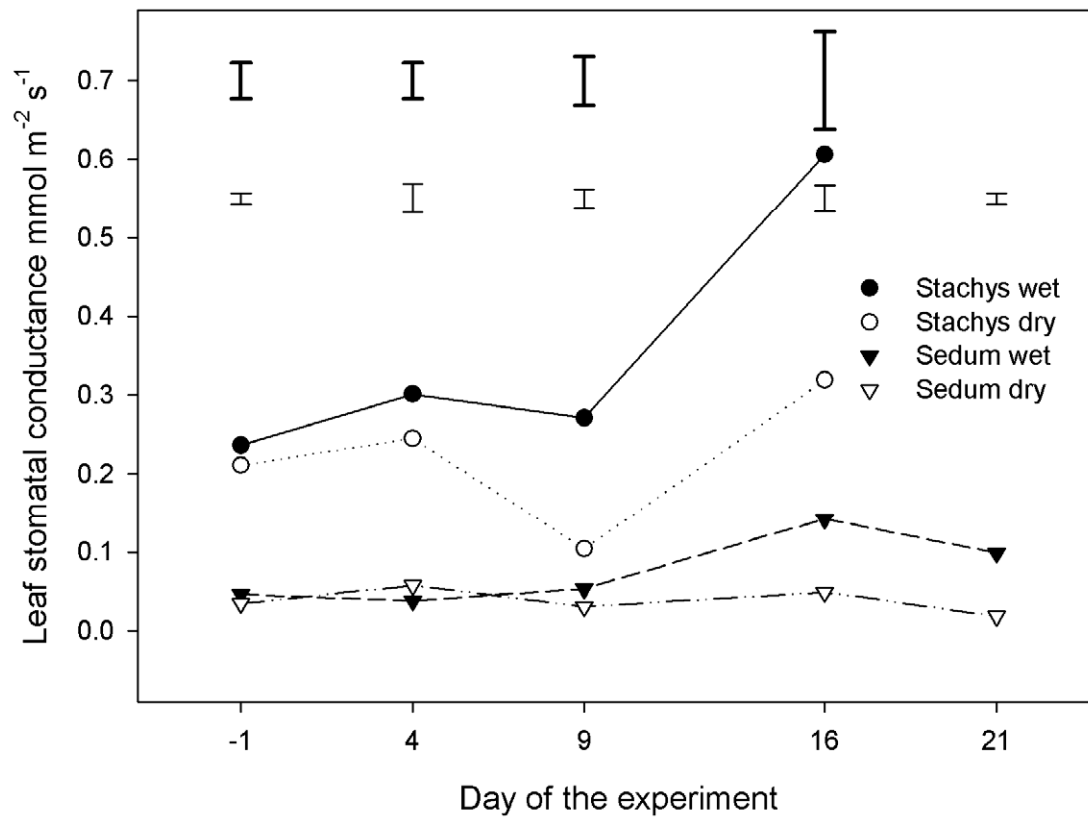
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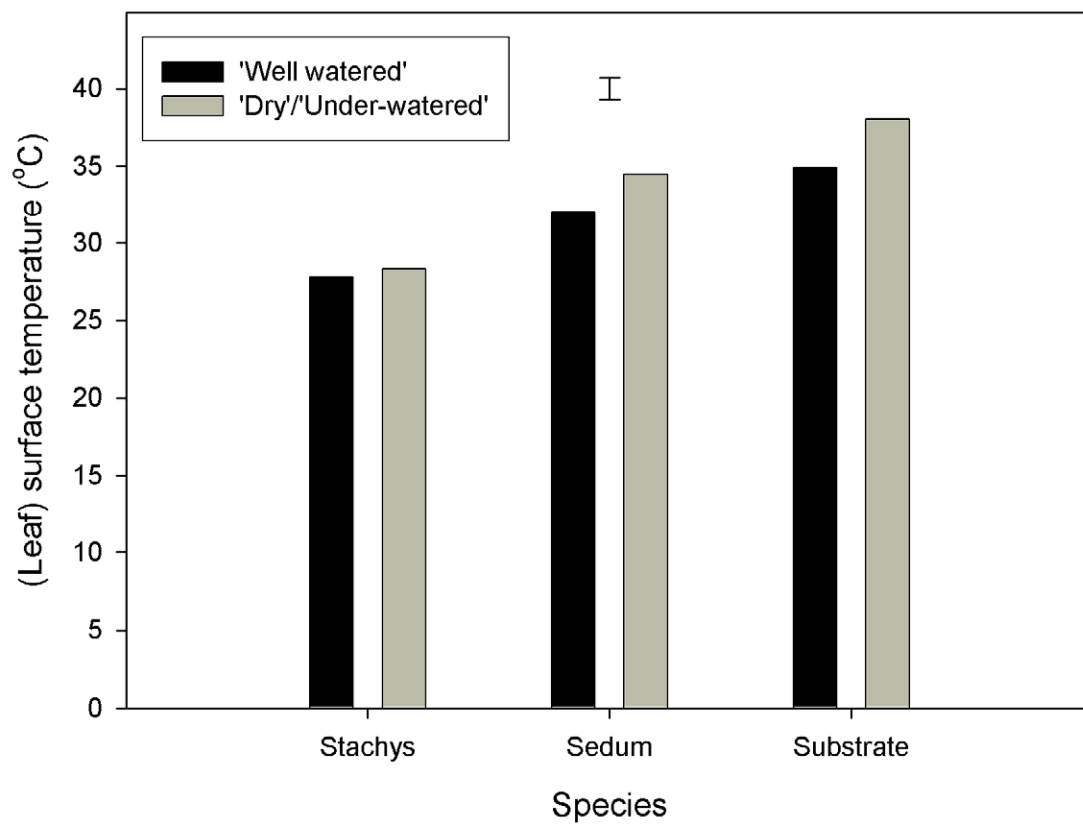
Species/surface	Soil temperature (°C)	Air temperature (°C) @ 100 mm
<i>Stachys byzantine</i>	22.2a	24.8a
<i>Sedum</i> mix	34.2b	25.1a
Bare substrate	37.1c	25.9b
LSD (d.f.)	1.09 (149)	0.32 (149)

715









ACCEPTED