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To link to this article DOI: http://dx.doi.org/10.1016/j.buildenv.2012.08.011

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

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Please cite this article as: Blanusa T, Madalena Vaz Monteiro M, Fantozzi F, Vysini E, Li Y, Cameron RWF, Alternatives to *Sedum* on green roofs: Can broad leaf perennial plants offer better 'cooling service'?, *Building and Environment* (2012), doi: 10.1016/j.buildenv.2012.08.011.

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.

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 ^{o}C cooler compared with *Sedum*), substrate cooling beneath its canopy (up to 12 ^{o}C) and

32 even - during short intervals over hottest still periods - the air above the canopy (up to 1 ^{o}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.

3

37

Additional key words:

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

40

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

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

6

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 *Stachy*s

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 <u>2.1. Plant material</u>

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 *Stachy*s 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 <u>2.2. Experiment 1. The effect of species and water availability on leaf stomatal conductance,</u>

155 <u>leaf surface temperature and air temperature above the canopy (glasshouse conditions)</u>

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

8

166   glasshouse; where minimal / night temperatures never fell below 15 ^{o}C and maximal /

167   daytime temperatures were in the range 22 – 37 ^{o}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 m^3 m^{-3} ('well-watered' treatment,

177   three containers per species/substrate) or <0.15 m^3 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 and10:00 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 mmol $m^{-2} s^{-1}$.

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 ≤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 CO_2 concentration at 385 ± 5 mm^3 dm^{-3}. During measurements, photosynthetic

227   photon flux density was supplemented to a minimum of 1000 µmol m^{-2} 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

11

241 substrate was kept weed-free. Plots were rain-fed, but throughout the experiment the SMC

242 remained above 0.15 $m^3 m^{-3}$. 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 (0.48m^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 and10:00 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 Datataker logger (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   <u>2.5. Experiment 4. The role of leaf hairs in *Stachys byzantina* in regulating leaf temperature</u>

277   <u>(controlled environment cabinet)</u>

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 $^{\circ}$C, 50% RH, light supplemented at 550 μmol m^{-2} 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 m^3 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 mmol m^{-2} s^{-1} for *Stachys*, 220.1 mmol m^{-2}

311   s^{-1} for *Hedera* and 217.0 mmol m^{-2} s^{-1} for *Bergenia*. Conversely, in the 'dry' treatment the

312   overall averages were 147. mmol m^{-2} $s^{-1}$for *Stachys*; 98.8 mmol m^{-2} s^{-1} for *Hedera* and 66.4

313   mmol m^{-2} s^{-1} for *Bergenia*.

14

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 $^{\circ}$C vs

321 27.2 $^{\circ}$C, respectively, LSD = 1.25 $^{\circ}$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 $^{\circ}$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 $^{\circ}$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 m^3

334 m^{-3}, and *Sedum* at 0.2 m^3 m^{-3} (Fig 2). In the 'dry' treatment, *Stachys* was maintained at

335 around 0.15 m^3 m^{-3} and *Sedum* and bare substrate below 0.10 m^3 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

15

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 $^{\circ}$C) were similar in 'well- watered' and 'under-watered' plants (27.8 vs 28.3

343 $^{\circ}$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 $^{\circ}$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 $^{\circ}$C daytime, 10-15 $^{\circ}$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 $^{\circ}$C), temperatures were highest in the

363 bare substrate, followed by *Sedum* and lowest in *Stachys*; this was confirmed by both thermal

16

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 $^{\circ}$C cooler than soil under *Sedum*, which was also almost 3 $^{\circ}$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 $^{\circ}$C on average, respectively), but both

369   were significantly lower than over bare substrate (25.9 $^{\circ}$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 $^{\circ}$C vs 25.0 $^{\circ}$C for *Stachys* and *Sedum*

372   respectively, between 12:30 and 13:30 on 3 June, LSD = 0.57 $^{\circ}$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 $^{\circ}$C warmer underneath *Stachys*

375   compared with *Sedum* and bare soil (14.6, 14.0 and 13.7 $^{\circ}$C, respectively, LSD = 0.47 $^{\circ}$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 $^{\circ}$C

388   control vs 23.9 $^{\circ}$C in shaved leaves, LSD = 0.21 $^{\circ}$C). These temperature differences,

17

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 mmol m^{-2} s^{-1} control vs 0.192 mmol m^{-2} s^{-1} shaved leaves, LSD = 0.0479 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 ^{o}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 ^{o}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

18

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 $^{\circ}$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,

21

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 ^{o}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 ^{o}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 CO_2, O_3, 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 adaptions 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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555

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663

664   Figure legends

665

666   Figure 1. Mean surface temperature (^{o}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 ^{o}C, d.f. = 258). Measurements were made between 13 and 14 h.

670

671   Figure 2. Substrate moisture content ($m^{3} m^{-3}$) 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 (^{o}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 ^{o}C, d.f. = 809). Measurements were made between 13 and 14

686   h.

687 List of tables

688

689 Table 1. Average air temperature (^{o}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 ^{o}C, d.f. = 159). The means followed by a different

693 letter are statistically significantly different.

694

695 Table 2. Average air temperature (^{o}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 ^{o}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 (^{o}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)
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

711

712

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)

713

714

Species/surface	Soil temperature (^{o}C)	Air temperature (^{o}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