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Accepted Version

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Vaz Monteiro, M., Blanusa, T., Verhoef, A., Richardson, M., Hadley, P. and Cameron, R. W. F. (2017) Functional green roofs: importance of plant choice in maximising summertime environmental cooling and substrate insulation potential. *Energy and Buildings*, 141. pp. 56-68. ISSN 0378-7788 doi: <https://doi.org/10.1016/j.enbuild.2017.02.011> Available at <http://centaur.reading.ac.uk/69025/>

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To link to this article DOI: <http://dx.doi.org/10.1016/j.enbuild.2017.02.011>

Publisher: Elsevier

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**Functional green roofs: Importance of plant choice in maximising  
summertime environmental cooling  
and substrate insulation potential**

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19 **Abstract**

20 Green roof plants can reduce local air temperatures and heat load to a building in the summer,  
21 improving thermal comfort of residents. Little is known, however, about how different plants compare  
22 in their potential to provide these two ecosystem services. Consequently, this study investigated  
23 whether some plants can offer more potential summertime environmental cooling and substrate  
24 insulation than others. Over two summers (2012/2013), canopies of two succulent and four broad-  
25 leaved plant genotypes, with contrasting plant traits, were monitored alongside bare substrate in  
26 Reading, UK. Plants were studied outdoors within small plots (1.5 x 1.5 x 0.1 m). Continuous  
27 monitoring took place during warm days and nights and included variables (leaf surface temperatures)  
28 and fluxes (long-wave radiation, sensible heat flux and transpiration) that are indicative of cooling  
29 potential. The strength of substrate insulation was estimated by comparing the ground heat flux below  
30 the canopies to that of the bare substrate. Plant traits (leaf colour or thickness), structural parameters  
31 (height and leaf area index, LAI), radiative properties (albedo and emissivity), and stomatal  
32 conductance were also measured to help explain the differences in cooling potential among the  
33 species. Non-succulent canopies, in particular light-coloured ones, with high leaf stomatal  
34 conductance and high LAI provided maximum potential for substrate insulation and environmental  
35 cooling in hot periods, particularly compared to bare substrate and thick-leaved succulents. These  
36 results suggest that succulent plants are not best suited to provide significant summertime  
37 environmental cooling and substrate insulation and that others (e.g. *Salvia* and *Stachys*) might be  
38 preferable where the delivery of these benefits is a priority. Our findings highlight that, in addition to  
39 survival, aesthetics and cost, the plants' ability to deliver a range of ecosystem services should be  
40 considered in the plant selection/green roof planning process.

41

42 **Keywords**

43 Green roofs; Plant traits; *Salvia*; *Sedum*; Surface energy balance

44 **Highlights**

- 45 • Plant canopy traits strongly affect cooling and insulation by roof substrates.
- 46 • *Salvia* and *Stachys* potentially provide superior summer cooling/substrate insulation.
- 47 • Thick-leaved succulents do not offer more summer cooling/insulation than bare soil.
- 48 • Dark-leaved plants offered good substrate insulation, but not aerial cooling potential.

## 50 **1. Introduction**

51 Urban landscapes are typically warmer than adjacent rural areas [1]. This phenomenon, (the urban  
52 heat island, UHI), is partly due to anthropogenic activities which generate heat that becomes trapped  
53 within the urban fabric. It is also due to a widespread use of impervious materials, which alter the  
54 thermal and radiative properties of the land surface, significantly influencing the surface energy  
55 balance [2,3]. In urbanised areas, latent heat flux (i.e. evapotranspiration) is thus reduced compared to  
56 more rural, vegetated areas, while heat storage and the resulting re-emission of heat as long-wave  
57 radiation or sensible heat are increased. The heat absorbed, stored and re-released as long-wave  
58 radiation by the urban fabric to the atmosphere can also be intercepted by air pollutants and redirected  
59 back to the urban environment, contributing to further warming [3].

60 The UHI generally has a negative impact on human thermal comfort and health, and this impact is  
61 predicted to increase due to a warming climate. For example, by the 2080s, mean summertime  
62 maximum air temperatures in southern England are estimated to rise by an average of 5.4°C,  
63 compared to 1961-1990 [4]. Heat wave events, which amplify human mortality rates, are also  
64 expected to increase in intensity, duration and frequency [5]. Residents in urban areas will be  
65 particularly susceptible to such events, owing to the already enhanced temperatures associated with  
66 the UHI effect.

67 Plants in cities have an important role in reducing local summertime air temperatures and can mitigate  
68 local UHI [6–9]. However, the area available in highly urbanised cities for green infrastructure  
69 expansion is scarce. Roofs can occupy around 30% of the horizontal surface within a city [10],  
70 making them prime spaces to be vegetated. In addition to being able to reduce local air temperatures  
71 [11], plants on roofs (i.e. green roofs) can further reduce the energy load to the buildings during the  
72 day in summer, thereby leading to a reduced reliance on artificial air conditioning, thus saving energy  
73 [12,13].

74 Such ecosystem services (i.e. both in terms of summertime air temperature regulation and the plants'  
75 ability to reduce the summertime conductive heat load, thus increasing the insulation of the rooftop)  
76 can be provided by a variety of mechanisms. Plants hold, and can subsequently release, relatively  
77 large volumes of water. The vapourisation of liquid water consumes about 2450 J per g of water [14].  
78 This latent energy is retained in the water molecules that exit through the leaf stomata [15], allowing  
79 radiation absorbed by well-watered plants to dissipate without an increase in air temperature within  
80 the immediate environment. Plants on roofs may also absorb less heat than bare roof surfaces [12],  
81 due to higher reflectance, at least compared to dark surface materials such as bitumen or slate.  
82 Additionally, plants in urban areas partially absorb the long-wave energy re-emitted by the adjacent  
83 built surfaces [16] as well as shade a built surface [17]. Thus, when placed on roofs they can reduce  
84 the radiation received by the roof surface. A model simulating the thermal behaviour of green roofs  
85 when several parameters, including LAI, were manipulated, found that an increase in LAI from 2 to 5  
86 led to a decrease of almost 250 W m<sup>-2</sup> in solar radiation transmitted to the roof surface [18]. When  
87 combined, these features lead to green roofs (consisting of the canopy and the below-canopy rooftop)  
88 being considerably cooler in the summer than their non-green counterparts. This will result in a  
89 decrease in the heat conducted to the inner parts of the building, but also reduces the release of  
90 sensible heat and long-wave radiation by the roof, thereby decreasing the extent of warming to the  
91 wider urban environment.

92 While plants differ in their surface temperature when compared to inert roof materials, variations in  
93 leaf characteristics and canopy structure, substrate factors and physiological traits can vary the  
94 thermal properties of canopies associated with different species. Leaf temperature is strongly  
95 influenced by substrate moisture content and leaf stomatal conductance [19,20]. Morphological traits  
96 such as leaf colour, thickness and pubescence also influence leaf temperature [20,21].

97 Many green roofs are planted with succulents such as *Sedum*, as they tolerate the dry conditions  
98 common on extensive green roofs [22,23]. However if sustainable irrigation was possible, other low-  
99 growing plants with higher water requirements could survive too [24]. More water-demanding plants,  
100 if possessing the 'right' traits, could potentially generate greater environmental cooling and substrate

101 insulation in the summer than succulents. A previous study within a Mediterranean climate, however,  
102 could not justify the use of green roofs (with succulent, grass, perennial or small shrub covering)  
103 solely on the basis of beneficial cooling effects, particularly taking into account the water use and  
104 associated costs [25]. In contrast though, in climates where natural precipitation is higher and evenly  
105 distributed over the seasons, the economic benefits of using more water-demanding plants (in terms of  
106 reduced air conditioning, for example) may outweigh costs linked to supplementary irrigation.  
107 Despite preliminary evaluations on how different roof plant communities affect the surrounding  
108 environment and the thermal performance of a roof [26–29], there is still a lack of knowledge on how  
109 key plant traits influence the energy balance of the combined substrate/vegetation layer and the  
110 implications for using different plants to provide direct cooling or insulation services.

111 The main aim of this research was to determine the extent to which plant genotype affects the  
112 thermodynamic properties of the substrate-vegetation system during summer. A range of plants  
113 potential useful for green roof situations, were evaluated within the context of the UK's temperate  
114 maritime climate. This study deliberately does not account for any factors (e.g. roof/building material,  
115 roof orientation, building energy efficiency etc.) that may influence the cooling attributes of green  
116 roofs *per se*. Such an experimental set-up would struggle to be comprehensive and would be too  
117 complicated from an in-depth monitoring point of view, thereby limiting the amount, and potentially  
118 compromising the quality, of the micrometeorological and plant physiological data. To achieve our  
119 aim, six genotypes (two succulent and four broad-leaved) with contrasting leaf stomatal conductance  
120 rates and variations in leaf colour, pubescence or thickness were selected. Canopies were compared  
121 over two summers with regards to their surface temperatures, outgoing long-wave radiation, and their  
122 surface energy balance (net radiation and turbulent heat fluxes, as well as substrate heat flux).  
123 Additional comparisons were made with bare substrate (i.e. non-vegetated plots), which acted as an  
124 experimental control.

125 Improved understanding of the combined effect of these traits will allow urban planners, architects  
126 and green roof professionals to base their future choice of plants not only on genotypes' survival and  
127 aesthetical value, but also on their ability to maximise important ecosystem services.

128 [Insert Nomenclature list]

## 129 **2. Materials and Methods**

### 130 *2.1. Plant material*

131 All plants in the experiment were herbaceous/sub-shrub forms (Figure 1) with potential to be  
132 integrated in green roofs, particularly if additional irrigation is provided during times of prolonged  
133 water deficit. These were (with key leaf characteristics in parenthesis):

- 134 • *Heuchera* ‘Obsidian’ (non-pubescent, purple)
- 135 • *Heuchera* ‘Electra’ (non-pubescent, yellow)
- 136 • *Salvia officinalis* ‘Berggarten’ (pubescent with grey-green hue)
- 137 • *Stachys byzantina* (pubescent with pale grey hue)
- 138 • *Sempervivum* ‘Reinhard’ (non-pubescent, succulent, light to dark green hue)
- 139 • *Sedum* mix (a mat of *Sedum* species used as an industry standard; non-pubescent, succulent  
140 leaves, light-green hue).

141 Individual plants were either propagated in-house or acquired from UK nurseries, as plugs or 9 cm  
142 potted plants. *Sedum* mix was acquired as a green roof mat from a commercial supplier (Q lawns,  
143 Hockwold-cum-Wilton, UK). Non-succulent plants were replanted into 2 L containers to aid further  
144 establishment, at least one month before being planted into the experimental plots.

145 [Insert Figure 1]

### 146 *2.2. Experimental setup*

147 Experiments were carried out in the summers of 2012 (24 July to 21 September) and 2013 (15 July to  
148 31 August), on the outdoor experimental grounds at the University of Reading (UK). In 2012,  
149 fourteen timber frames were constructed (1.5 x 1.5 x 0.1 m) and positioned 1.1 m apart. These were  
150 placed in an open space at ground level rather than on top of building roofs to minimise any ancillary  
151 thermal effects due to building function and infrastructure (parapets, air cooling vents, chimney flues,  
152 etc.) and for ease of access. All frames were lined with polyethylene pond liner and filled with a 0.1 m

153 layer of John Innes compost No. 2. Field capacity and permanent wilting point of a similar substrate  
154 were respectively measured at 0.32 and 0.07 g g<sup>-1</sup> [30]; equivalent to 0.42 and 0.09 m<sup>3</sup> m<sup>-3</sup> when  
155 assuming a substrate bulk density of 1.3 g cm<sup>-3</sup>, an average of values presented for soils and composts  
156 with comparable compositions [31,32]. Each treatment was replicated twice, i.e. two ‘mono-culture’  
157 plots of each genotype. Plant genotypes were randomly allocated to the plots and planted at least 10  
158 days before measurements started, to achieve 100% of coverage (or in the case of *Sempervivum* 80%,  
159 due to the small size of the plants). The *Sedum* mix mat was cut to fit the plot with the underneath  
160 membrane removed, to ensure direct contact with the substrate.

161 Two of the frames were left with just bare substrate so that plant canopies could be compared to an  
162 unplanted ‘control’ surface. A layer of bare substrate was used instead of a rigid inert surface, as it has  
163 similar hydraulic (i.e. in relation to water retention and transfer) and thermal properties to the  
164 substrate layers located below the plant canopies.

165 In 2013, two additional timber frames were constructed and a new treatment was added. These vacant  
166 plots were planted with shorter specimens of *Salvia*, where shoot tips were pinched out to promote a  
167 bushier, lower habit. Consequently, in 2013, *Salvias* planted in that year were approximately half the  
168 height of *Salvias* planted in 2012; these treatments were used to assess the effect of canopy height on  
169 the variables studied.

170 Plots and surrounding areas were kept weed free, and any emerging flower heads removed from the  
171 plants to ensure that only the leaf canopy effect was accounted for (flower heads only accounted for a  
172 very small area).

173 Environmental and temperature measurements, described in Table 1, represent mean values over a 10  
174 minute period (averaged from measurements made every 10 seconds). Sensors (full list in Table 1)  
175 were attached to DL2e loggers (Delta-T Devices Ltd., Cambridge, UK) and a DataHog2 logger (Skye  
176 Instruments Ltd., Llandrindod Wells, UK), which were covered by well-ventilated white plastic boxes  
177 to protect from intense radiation. In addition, incoming long-wave radiation ( $L_i$ ) and wind speed ( $U_z$ )  
178 at 2 m from the ground were monitored at the University’s meteorological station, located 600 m from  
179 the experimental plots.

180 Leaf temperature,  $T_s$ , was measured using thermocouples (Table 1, Figure 2) attached to the underside  
181 of individual leaves mostly with a plastic paper clip [33] thus ensuring the thermocouple was located  
182 within the leaf boundary layer (i.e. the air layer in contact with the leaf surface). For succulent and  
183 *Stachys* leaves, which are small or easily broken, thermocouples were attached by threading [34]. In  
184 all cases, selected leaves were young, exposed and fully expanded, and located in the upper layer of  
185 the canopy. In 2013, plant coverage of yellow *Heuchera* was reduced to < 50% due to winter losses,  
186 thus one of the thermocouples within each plot with yellow *Heuchera* was used to measure leaf  
187 temperature whilst the other was used to measure substrate temperature.

188 Thermocouples and thermistors were calibrated at the start of each experimental season in a hot water  
189 bath and were measuring within 0.30°C of each other.

190 The instantaneous measurements of plant and substrate parameters/variables carried out over the  
191 course of the experiment (i.e. substrate moisture, SMC; leaf stomatal conductance,  $g_s$ ; albedo,  $\alpha$ ;  
192 spectral reflectance; leaf area index, LAI and canopy height,  $h$ ) are described in Table 2 (also see  
193 Figure 2). In addition to the discrete measurements (Table 2), SMC was also continuously recorded  
194 hourly on four randomly selected plots, with SM200 sensors (Delta-T Devices Ltd., Cambridge, UK).  
195 Both the discrete and continuous SMC measurements were used to estimate continuous SMC  
196 variations in each treatment, information needed to estimate substrate heat flux and to guide irrigation  
197 requirements.

198 Leaf emissivity,  $\varepsilon$ , which plays an important role in net radiation calculation *via* the outgoing long-  
199 wave radiation term, was determined in a laboratory test in 2012. Four leaves from each genotype  
200 were evaluated, except for *Sempervivum* where the shape of its leaves prohibited the measurement.  
201 For each leaf,  $\varepsilon$  was calculated based on the temperatures extracted from a thermal image, recorded  
202 with an infrared imaging camera FLIR i5 (FLIR Systems UK, West Malling, UK) whilst the leaf was  
203 floating in a well-stirred water bath [35]. In all cases,  $\varepsilon$  was around 0.97. The fact that all leaf  
204 emissivities were similar suggests that any differences in  $T_s$  between genotypes which we  
205 subsequently determined were caused by differences in  $\alpha$ ,  $g$ , and/or leaf traits that affect aerodynamic  
206 transfer.

207 [Insert Table 1, Table 2 and Figure 2]

### 208 2.3. *Watering requirements*

209 In both summers, all plots, including the bare ones, were manually irrigated whenever a plot's mean  
210 SMC fell below  $0.15 \text{ m}^3 \text{ m}^{-3}$ . Water applied was adjusted so that mean SMC after irrigation was  
211 around  $0.32 \text{ m}^3 \text{ m}^{-3}$ . *Salvia* received the highest irrigation water quantity in both years and  
212 *Sempervivum* the lowest. The total water received by the canopies in 2013 (quantities given are a  
213 combination of both precipitation and supplementary watering) was approximately:  $134 \text{ L/m}^2$  for  
214 *Salvia* planted in 2012,  $127 \text{ L/m}^2$  for *Salvia* planted in 2013,  $126 \text{ L/m}^2$  for purple *Heuchera*,  $105 \text{ L/m}^2$   
215 for *Stachys*,  $99 \text{ L/m}^2$  for *Sedum*,  $93 \text{ L/m}^2$  for yellow *Heuchera* (in plots partially covered) and  $77 \text{ L/m}^2$   
216 for *Sempervivum*.

217 When plots were irrigated, the soil around their frame was also irrigated to reduce micro-scale  
218 advection typical of small-sized plot design experiments surrounded by soil with different moisture  
219 concentrations [36].

### 220 2.4. *Calculation of the outgoing long-wave radiation and surface energy balance*

221 Net radiation, outgoing long-wave radiation and heat fluxes were calculated for every 10 minutes and  
222 averaged hourly. Net radiation,  $R_n$ , was calculated as:

$$223 R_n = S_i + L_i - S_o - L_o, \quad (1)$$

224 where  $S_i$  and  $L_i$  are the short-wave and long-wave radiation received by the surface, and  $S_o$  and  $L_o$  are  
225 the short-wave and long-wave radiation reflected and emitted by the surface.

226 At night,  $S_o$  was assumed to be  $0 \text{ W m}^{-2}$ .

227 Continuous daytime  $S_o$  values were not available, but representative estimates of albedo,  $\alpha$ , were  
228 obtained (see Table 2) to derive  $S_o$ . Using these data, between 10:00-16:00 h,  $S_o$  was calculated as:

$$229 S_o = \alpha S_i \quad (2)$$

230 Between 06:00-10:00 h and 16:00-20:00 h,  $\alpha$  was either assumed to be equal to the mean  $\alpha$  values  
231 between 10:00-16:00 h (when mean  $S_i < 200 \text{ W m}^2$ ), or assumed to increase linearly with a decreasing  
232 sun angle (when mean  $S_i > 200 \text{ W m}^2$ ) [37]. Based on values presented by Monteith and Szeicz [37],

233 during sunny periods, maximum  $\alpha$  (at 06:00 or 20:00 h) was set to a value that was 0.05 higher than  
 234 the mean  $\alpha$  for the period between 10:00-16:00 h for canopies, or to 0.03 for bare substrate.

235  $L_o$  was calculated according to Stefan-Boltzmann's law:

$$236 \quad L_o = \varepsilon \sigma (T_s)^4 + (1 - \varepsilon) L_i, \quad (3)$$

237 where  $\sigma$  is the Stefan-Boltzmann constant.  $T_s$ , the mean leaf/surface temperature of each plot, was  
 238 calculated as the mean of temperatures measured by the thermocouples and  $\varepsilon$  was assumed to be on  
 239 average 0.95 for the bare substrate (based on the ranges presented for bare soils by Rubio et al. [38]),  
 240 0.97 for canopies with LAI > 1, as measured, and 0.96 for canopies with LAI < 1.

241 Sensible heat flux,  $H$ , was calculated as:

$$242 \quad H = \rho_a C_p \frac{(T_s - T_a)}{r_a}, \quad (4)$$

243 where  $T_a$  is the air temperature recorded at 2 m from the ground,  $\rho_a$  is the air density,  $C_p$  is the air  
 244 specific heat and  $r_a$  is the aerodynamic resistance, calculated as:

$$245 \quad r_a = \frac{\ln\left(\frac{z-d}{z_{om}}\right) \ln\left(\frac{z-d}{z_{oh}}\right)}{k^2 U_z}, \quad (5)$$

246 where  $z$  is the height of wind and temperature measurements,  $d$  is the zero plane displacement height,  
 247  $z_{om}$  is the surface roughness length for momentum transfer,  $z_{oh}$  is the surface roughness length for heat  
 248 and vapour transfer,  $k$  is the von Karman's constant (0.41) and  $U_z$  is the wind speed. In this equation  
 249 the effect of atmospheric stability has been neglected as this effect is relatively small.

250 Roughness parameters  $d$ ,  $z_{om}$  and  $z_{oh}$  were calculated as a function of surface cover height:

$$251 \quad d = 2/3 h \quad (6)$$

$$252 \quad z_{om} = 0.123 h \quad (7)$$

$$253 \quad z_{oh} = 0.1 z_{om} \quad (8)$$

254 The height of bare substrate was set to 0.01 m, leading to a  $z_{om}$  for bare substrate of 0.001 m [39].

255 Substrate heat flux,  $G$ , was estimated by Fourier's law:

$$256 \quad G = -\lambda \frac{\Delta T}{\Delta z}, \quad (9)$$

257 here  $\Delta T$  is the substrate temperature difference between two depths (at 0.01 m and 0.06 m) and  $\Delta z$  is  
258 the distance between those two depths. The substrate thermal conductivity,  $\lambda$ , was calculated based on  
259 the assumed value of substrate bulk density, the quartz content and the estimated continuous SMC, as  
260 per Lu et al. [32]. Using Eq. 9 with substrate temperatures measured at 0.01 m and 0.06 m means that  
261 the heat stored in the first 0.01 m of substrate was not accounted for. Calculating this storage would  
262 require an estimate of heat capacity,  $C_h$ , but SMC (required to calculate  $C_h$ ) in such a thin layer cannot  
263 be easily determined. Alternatively one could use substrate temperature at 0 m (i.e. the substrate  
264 surface temperature) to calculate the temperature difference in Eq. 9, but this variable was only  
265 measured in uncovered (bare) plots. However, this storage term was assumed to be relatively small, in  
266 particular below vegetation. Furthermore, the plots, albeit lined with polyethylene membranes, were  
267 not thermally insulated from the ground below them. Thermistors were placed at 0.06 m from the  
268 substrate surface (and 0.04 m from the membranes) to reduce the influence that the heat flux from the  
269 ground below may have had on the calculated  $G$ . We use  $G$  to assess substrate insulation potential of  
270 the green roof plant species. We define substrate insulation potential as the reduction in (surface)  
271 ground heat flux by vegetation cover compared to bare substrate.

272 Latent heat flux,  $LE$ , was calculated as the residual of the energy balance:

$$273 \quad LE = R_n - H - G \quad (10)$$

274 With these calculations, any advection and storage of heat in the canopy biomass and within the  
275 canopy air that might have occurred were embedded in the  $LE$  and  $H$  heat fluxes terms.

## 276 2.5. Statistical analysis

277 Statistical analysis was performed with GenStat 16<sup>th</sup> Edition (VSN International Ltd., Hemel  
278 Hempstead, UK). Differences in  $g_s$  within a season were assessed with analysis of variance  
279 (ANOVA), on the basis of the least significant difference (LSD; 5% level). Two contrasting groups of  
280 data (i.e. day and night) were selected for the analysis of differences in calculated  $T_s$ ,  $L_o$ ,  $R_n$  and heat  
281 fluxes: i). ten (2012)/nine (2013) rain-free days with  $T_{max} > 24^\circ\text{C}$  and ii). ten rain-free nights with  $T_{min}$   
282  $> 12^\circ\text{C}$ . For daytime data, the statistical analysis was only performed over intervals of four hours,  
283 when differences between treatments reached their maximum: i.e. between 12:00-16:00 h for  $T_s$  and  $L_o$

284 or 11:00-15:00 h for  $R_n$  and heat fluxes. For the night periods, differences were statistically analysed  
285 between 20:00-24:00 h, when the effect of the UHI is highest [1].

286 Data from each selected group/period were analysed using residual maximum likelihood (REML)  
287 analysis. All p-values presented in this paper were extracted from each REML analysis and an  
288 estimated LSD, as per Andrist-Rangel et al. [40], was used to assess treatment differences. As means  
289 considered were based on a number of days (and hours within a day), this should have mostly reduced  
290 errors associated with the measurements/calculations.

### 291 **3. Results**

#### 292 *3.1. Environmental and substrate moisture content (SMC) conditions*

293 For the period in which data collection coincided in both seasons (24 July to 31 August) mean daily  
294  $T_{\max}/T_{\min}$  in 2012 and 2013 were 22.5°C/12.6°C and 23.1°C/13.2°C, respectively. Temperatures for the  
295 first thirteen days of the experimental season in 2013 were, however, part of heatwave-like weather  
296 experienced in the UK in July 2013 (mean daily  $T_{\max}/T_{\min}$  for that period were 27.6°C/15.2°C).

297 Despite *Sempervivum*'s plots receiving the lowest amount of water, their SMC was generally the  
298 highest (as a result of their low transpiration), particularly in 2013, where *Sempervivum*'s SMC was  
299 mostly  $\geq 0.30 \text{ m}^3 \text{ m}^{-3}$ . For the remaining treatments, mean SMC varied between 0.15-0.32  $\text{m}^3 \text{ m}^{-3}$ , in  
300 both years (data not shown).

#### 301 *3.2. Plant structure*

302 Of the genotypes tested, *Salvia* planted in 2012 was the tallest (Table 3) with a high LAI recorded in  
303 both years. The specimens of this species planted in 2013 were shorter, but also had relatively high  
304 LAI values. *Sempervivum* and *Sedum* had the shortest stature with relatively low LAI, although the  
305 LAI of *Sempervivum* increased between the two years (Table 3). In contrast, both *Stachys* and yellow  
306 *Heuchera* plots had lower LAI in the second year compared to the first. In plots with yellow  
307 *Heuchera*, the LAI reduction between 2012 and 2013 was particularly dramatic; this was due to many  
308 plants perishing during winter. By 2013, the yellow *Heuchera* plots had the lowest LAI (Table 3).

309 3.3. Short-wave reflectance (albedo,  $\alpha$ , and spectral reflectance)

310 The  $\alpha$  of most plant plots remained unaltered throughout the two-year period (Table 3). There was,  
311 however, a marked reduction in  $\alpha$  of yellow *Heuchera* plots, with its 2012 value of 0.27 falling to 0.14  
312 in 2013. Again, this is the result of the severe reduction in plant cover, which left bare substrate, with  
313 its lower  $\alpha$ , in particular when wet, exposed. The  $\alpha$  of *Sempervivum* plots was also slightly altered  
314 from 2012 to 2013, increasing from 0.14 to 0.17 (Table 3), as in 2013 *Sempervivum* plants were  
315 covering the substrate fully. In uncovered plots, the average  $\alpha$  was lower in 2012 than in 2013 (Table  
316 3), probably due to small SMC differences during the days when  $\alpha$  was measured.

317 An evaluation of spectral reflectance (in the short-wave spectrum) in 2012 showed that the yellow  
318 *Heuchera* plants reflected more radiation than other canopies in the visible wavelengths whilst the  
319 purple *Heuchera* plants reflected less (400-700 nm; Figure 3). At longer wavelengths (700 to 1250  
320 nm; the near infrared region), reflectance was generally greater; differences between genotypes were  
321 more spread in these wavelengths than in the visible spectrum, where only *Heucheras* plants had  
322 different reflectance (Figure 3). Bare substrate on average reflected less radiation than the plants  
323 throughout most of the short-wave spectrum; however, in the visible part of the spectrum, bare  
324 substrate reflected more than purple *Heuchera* plants.

325 [Insert Table 3 and Figure 3]

326 3.4. Leaf stomatal conductance ( $g_s$ )

327 *Salvia* had the highest mean  $g_s$  values, with the new *Salvia* treatment planted in 2013 having a similar  
328 mean  $g_s$  to that of *Salvia* planted in 2012. *Sedum* had the lowest  $g_s$  ( $p < 0.001$ ), with mean values  
329 differing by 249 mmol m<sup>-2</sup> s<sup>-1</sup> in 2012 and 185 mmol m<sup>-2</sup> s<sup>-1</sup> in 2013 from those of *Salvia* planted in  
330 2012 (Figure 4). Due to time restrictions, the number of  $g_s$  measurements executed in 2013 was  
331 substantially lower than in 2012, this might have contributed (along with differences in the stages of  
332 plant maturity or differences in the environmental conditions at the time of measuring) to most  
333 treatments having slightly lower mean  $g_s$  values in 2013 than in 2012. Despite this, the order of  
334 magnitude of the mean  $g_s$  for the five species has not changed between the two years (Figure 4).

335 [Insert Figure 4]

336 3.5. Surface temperature ( $T_s$ ) and outgoing long-wave radiation ( $L_o$ )

337  $T_s$  and related  $L_o$  in 2012 and 2013 are presented in Figure 5 (showing days with  $T_{max} > 24^\circ\text{C}$ , when  
338 the differences in  $T_s$  and  $L_o$  were greatest). During the day, particularly between 12:00-16:00 h, plots  
339 with *Salvia* or *Stachys* had the lowest  $T_s$ , and  $L_o$ , whereas plots with *Sempervivum* or bare substrate  
340 had the highest ( $p > 0.001$ ); differences between mean values during that period reached up to  $10^\circ\text{C}$   
341 and 12% (or  $\sim 65 \text{ W m}^{-2}$ ) for  $T_s$  and  $L_o$ , respectively. Values for  $T_s$ , and related values for  $L_o$ , of purple  
342 *Heuchera* and *Sedum* were generally in-between the values of the other four treatments. The  
343 differences between mean  $T_s$  and  $L_o$  for purple *Heuchera* or *Sedum* plots and those with *Salvia*  
344 reached up to  $5^\circ\text{C}$  and 6% (or  $\sim 30 \text{ W m}^{-2}$ ), respectively. In 2012,  $T_s$  and  $L_o$  values for yellow  
345 *Heuchera* plots were similar to those obtained for *Salvia* and *Stachys* plots (Figures 5a and c). In  
346 contrast, in 2013 after the loss of many of the yellow *Heuchera* plants, mean  $T_s$  and  $L_o$  in yellow  
347 *Heuchera* plots between 12:00-16:00 h were up by  $4^\circ\text{C}$  and 5% (or  $\sim 25 \text{ W m}^{-2}$ ), respectively,  
348 compared to plots with *Salvia* and *Stachys* (Figures 5b and d).  
349 Between 20:00-24:00 h, differences in  $T_s$  and  $L_o$  among treatments, while statistically significant in  
350 2013 ( $p < 0.001$ , data not shown), were within  $2^\circ\text{C}$  or  $\sim 10 \text{ W m}^{-2}$ . As expected, as a result of a lack of  
351 short-wave radiation and transpiration during night-time,  $T_s$  and  $L_o$  differences between the species  
352 were much smaller than during the day. Similar behaviour should be observed for these plants if they  
353 were installed on green roofs.

354 3.6. Energy balance

355 3.6.1. Net radiation ( $R_n$ )

356 Differences in  $R_n$  between treatments were generally less pronounced than the  $L_o$  differences. This  
357 was due to the small  $\alpha$  differences between most plant treatments (Table 3), which resulted in small  
358 differences in  $S_o$  (data not shown), that counterbalanced the  $L_o$  differences. In 2012,  $R_n$  differences  
359 between treatments were not significant ( $p = 0.137$ , Figure 6a). In contrast, in 2013,  $R_n$  differences  
360 were larger between 11:00-15:00 h, with *Sempervivum* plots having significantly lower mean  $R_n$   
361 (11%) than plots with *Stachys* and *Sedum* ( $p < 0.001$ , Figure 6b).

362 3.6.2. *Sensible heat flux (H)*

363 Despite clear differences between most curves being visible in Figs 6c and 6d, treatments had no  
364 overall significant effect on  $H$  between 11:00-15:00 h in 2012 ( $p=0.308$ , Figure 6c). However,  $H$   
365 differences were statistically significant in 2013 ( $p<0.001$ , Figure 6d). *Stachys* and *Salvia* had lowest  
366  $H$  values during daylight hours, whereas *Sempervivum* and purple *Heuchera* had the highest.

367 3.6.3. *Substrate heat flux (G) and substrate insulation potential*

368 Between 11:00-15:00 h,  $G$  was significantly different between treatments for both years ( $p<0.001$ ,  
369 Figures 6e and f). Greatest  $G$  values were associated with the bare substrate. During 2013 (Figure 6f),  
370 the plots with yellow *Heuchera*, *Sempervivum* and *Sedum* had high daytime  $G$ , in comparison to plots  
371 covered by other canopies. Therefore, in terms of substrate insulation potential, which we defined as  
372 the reduction in (surface) ground heat flux by vegetation cover compared to bare substrate, *Heuchera*,  
373 *Sempervivum* and *Sedum* had the lowest potential and the other (non-succulent) species the highest.

374 3.6.4. *Latent heat flux (LE)*

375 Despite noticeable differences in  $LE$  being apparent for a number of treatments between 11:00-15:00  
376 h in 2012 ( $p=0.071$ , Figure 6g), they were only statistically significant in 2013 ( $p<0.001$ , Figure 6h).  
377 This is largely caused by the fact that these curves are based on hourly averages for 10 (year 2012)  
378 and 9 (year 2013) days, respectively, so that there will be a relatively large standard deviation (not  
379 shown in plots, but influencing the  $p$ -values) for each hour, for each treatment. In 2013 in particular,  
380 the overall differences in  $H$  and  $G$  between treatments led to *Salvia* and *Stachys* plots having a  
381 significantly greater  $LE$  (as derived from Eq. 10) than plots with *Sempervivum*, bare substrate and  
382 both *Heucheras*.

383 [Insert Figure 5]

384 3.6.5. *Overall ranking in daytime energy fluxes*

385 For the most part, differences between treatments tended to be more significant in 2013, reflecting  
386 increased canopy maturity and hence increased substrate coverage. The exception was yellow

387 *Heuchera*, where the winter deaths of plants increased the proportion of bare substrate in the plots,  
388 with subsequent effects on the plots' thermodynamic behaviour.

389 Overall, *Salvia* and *Stachys* had proportionally low values of  $H$  and  $G$ ; and conversely, high values of  
390  $LE$ . The opposite was true for bare substrate and *Sempervivum*. As a consequence, the partitioning of  
391  $R_n$  into the different heat fluxes differed between treatments. In 2013, for example, the amount of  $R_n$   
392 used for  $H$ ,  $G$  and  $LE$  between 11:00-15:00 h in *Salvia* plots planted in 2012 was respectively on  
393 average 0%, 3% and 96% whilst for *Sempervivum* plots, those percentages were respectively 25%,  
394 18% and 57% (Table 4). The percentage of  $R_n$  allocated to each of the heat fluxes was intermediate in  
395 *Sedum* and *Heuchera* plots. Although plots with purple *Heuchera* had similar  $H$  values to those with  
396 *Sempervivum*, purple *Heuchera* plots had one of the lowest diurnal  $G$  in 2013. In the second year,  
397 purple *Heuchera* plots had on average a  $\sim 65 \text{ W m}^{-2}$  reduction in  $G$ , compared to *Sempervivum* plots  
398 (Figure 6f). Consequently, in 2013, the amount of  $R_n$  used for  $G$  in plots with purple *Heuchera* was on  
399 average 15% lower than in those with *Sempervivum*, and so in purple *Heuchera* plots, this extra  
400 amount of energy received was instead mainly released as  $LE$  (Table 4).

401 In 2012, yellow *Heuchera* plots showed some of the lowest  $H$  and  $G$  and highest  $LE$  between 11:00-  
402 15:00 h, data similar to *Salvia* and *Stachys* (Figures 6c, e, g and Table 4). However, in 2013, due to  
403 plant death, yellow *Heuchera* plots had on average  $\sim 65 \text{ W m}^{-2}$  greater  $H$  and  $G$  and  $\sim 130 \text{ W m}^{-2}$  lower  
404  $LE$  than plots with *Salvia* planted in 2012 (Figures 6d,f,h). Therefore, in 2013 the percentage of  $R_n$   
405 used for  $H$ ,  $G$  and  $LE$  in yellow *Heuchera* plots differed on average by +14%, +15% and -29%,  
406 respectively, from the percentages allocated for  $H$ ,  $G$  and  $LE$  in plots with *Salvia* (Table 4).

407 *Sedum* plots, on the other hand, had in both years  $H$  and  $LE$  values that were in-between those  
408 calculated for *Salvia* and *Stachys* and for *Sempervivum* and purple *Heuchera*. However,  $G$  values in  
409 *Sedum* plots were closer to those derived for *Sempervivum* plots than for *Salvia* and *Stachys* plots  
410 (Figures 6e and f). For example, in 2013,  $G$  between 11:00-15:00 h was on average up to  $\sim 45 \text{ W m}^{-2}$   
411 greater in *Sedum* plots than in *Salvia* plots. This contributed to a 9% increase in the amount of  $R_n$  used  
412 for  $G$  in plots with *Sedum*, compared to those with *Salvia* planted in 2012. Accordingly, the energy

413 used by *Sedum* plots for *LE* was reduced on average by 20%, compared to *Salvia* plots in that year  
414 (Table 4).

#### 415 3.6.6. Overall ranking in night-time energy fluxes

416 At night, (20:00-24:00 h), there were no significant treatment differences in *LE* ( $p>0.152$ , data not  
417 shown), and the absolute differences in  $R_n$ ,  $H$  and  $G$ , although significant ( $p<0.001$ , data not shown)  
418 were lower than those shown during the day. For nights with  $T_{\min} > 12^{\circ}\text{C}$ , most vegetated plots, except  
419 those with *Sempervivum* and yellow *Heuchera* (in 2013), were gaining more  $H$  than plots with bare  
420 substrate. Furthermore, as expected, at night the upward  $G$  (i.e. heat loss) for bare substrate was  
421 significantly higher than the  $G$  calculated for plots that were completely covered by canopies (hence  
422 excluding yellow *Heuchera* in 2013). Average differences in  $H$  and  $G$  between vegetated plots and  
423 bare substrate plots from 20:00-24:00 h reached  $\sim 25 \text{ W m}^{-2}$  and  $\sim 45 \text{ W m}^{-2}$ , respectively. Average  
424 differences in  $H$  and  $G$  between vegetated plots alone within the same period were smaller:  $\sim 20 \text{ W m}^{-2}$   
425 and  $\sim 30 \text{ W m}^{-2}$ , respectively.

426 [Insert Figure 6 and Table 4]

## 427 4. Discussion

428 Previous studies suggest that by extending the area covered by irrigated green roofs within a city,  
429 local daytime *LE* in the summer can be increased. Consequently, there is a reduction in both the heat  
430 that is absorbed/stored within buildings and the heat that is returned to the atmosphere (as sensible  
431 heat and long-wave radiation) [41,42] and hence, local air temperatures are lower. Thus, the presence  
432 of rooftop vegetation provides important air temperature reduction and building insulation during  
433 summer. Despite this study not being conducted at roof top level and having plots sizes smaller than  
434 typical extensive green roofs, the findings are notable in that they demonstrate that certain plants have  
435 the potential to offer more environmental cooling and substrate insulation than others. This challenges  
436 conventional thinking on the way most green roofs are currently designed, as plants (on extensive and  
437 semi-extensive roofs, with shallow occasionally irrigated substrates) are mostly selected for their  
438 survival potential and not for their ability to provide valuable ecosystem services. In essence, many

439 existing green roofs could be underperforming with regards to insulating against incoming solar  
440 radiation, and reducing air temperatures around buildings.

441 *4.1. Differences in summertime environmental cooling and substrate insulation potential between*  
442 *treatments during the warmest period of the day*

443 Canopies formed by non-succulent, light-coloured plants with high  $g_s$  (Figure 3) and high LAI (*e.g.*  
444 *Salvia*, regardless of its canopy height, and *Stachys*) showed the greatest potential for daytime  
445 environmental cooling. This was evident in the lowest surface temperatures, and related lowest  $L_o$  and  
446  $H$  (Figure 5 and 6) and in the highest  $LE$  values for plots with these species (Figure 6). These canopies  
447 also showed the greatest potential to offer more substrate insulation in hot periods, by having the  
448 lowest  $G$  (Figure 6). In contrast, succulent plants with low  $g_s$  and extremely thick leaves (*e.g.*  
449 *Sempervivum*) showed the lowest substrate insulation potential, and offered no environmental cooling  
450 service compared to bare substrate. A thin layer of substrate can in itself offer more thermal insulation  
451 to roofs than common standard roof materials [43] and has significantly lower daytime surface  
452 temperatures than materials such as concrete, gravel or black membrane [11]. As such, the use of  
453 plants which offer greater reduction in substrate heat flux, heat-deflecting and evapotranspiration  
454 potential than bare substrate is likely to considerably improve the cooling performance of a roof  
455 surface compared to conventional roof systems during the summer months. Consequently, if  
456 occasional irrigation (even in climates such as that of the UK/northern Europe where summer rainfall  
457 is fairly regular) is supplied such that *Salvia*, *Stachys* and species with similar traits can thrive on a  
458 roof environment, then their (and similar) canopies could be ideal candidates in helping reduce the  
459 heat load to buildings and perhaps the negative effects of the UHI at a local scale. Due to the small  
460 size of the plots used in this study and a number of other confounding factors, including typical air  
461 movement characteristics around the building envelope, the implications of these differences cannot  
462 yet be assessed at the building and urban scales. However, this could be a subject for follow-on  
463 empirical evaluations, where these data could be used to provide more accurate plant-based  
464 parameters within existing urban heat models (see Conclusions).

465 The cooling and insulating properties of other canopies (*Heuchera* and *Sedum*) were intermediate.  
466 The potential of the yellow-leaved *Heuchera* to offer the same summertime substrate insulation and  
467 environmental cooling as *Salvia* and *Stachys* was evident in 2012. This was due to this genotype  
468 possessing a high  $\alpha$  and moderate LAI and  $g_s$ . This *Heuchera* cultivar, however, was not as resilient as  
469 *Salvia* and *Stachys*, suffering tissue damage and die-back during the winter of 2012/2013, so by the  
470 summer of 2013 plots were only partially covered. During 2013, plots with yellow *Heuchera* had  
471 therefore higher  $L_o$ ,  $H$  and  $G$  and lower  $LE$  than those plots covered by *Salvia* and *Stachys*, with  
472 values actually approaching those of bare substrate. Plants that are poorly adapted to harsh conditions  
473 should, therefore, be avoided in unprotected spaces such as rooftops, despite having traits that would  
474 in theory lead to maximum environmental cooling and substrate insulation in the summer.

475 In contrast, purple *Heuchera* survived well in all weather conditions in our experiment. Data here  
476 suggests that purple-leaved, non-succulent plants could insulate the substrate from external heat to the  
477 same extent as *Salvia* and *Stachys*.  $G$  in purple *Heuchera* plots was similar to that in *Salvia* and  
478 *Stachys* plots once plants reached a certain height (Figure 6). This was possibly because an air gap  
479 was created between the lower leaves of the canopy and the substrate in 2013 [27], thereby reducing  
480 the temperature gradient between leaves, substrate surface and within the substrate, i.e. the driving  
481 force for  $G$ . However, plants with dark-coloured leaves are best avoided as they do not offer  
482 additional environmental cooling. Although the  $\alpha$  of purple and green leaves was within the same  
483 range in this case, the spectral reflectance showed that purple leaves absorbed more visible radiation  
484 than others. There is a large amount of energy per quantum in the visible wavelengths [44], hence  
485 purple *Heuchera* leaves were consistently absorbing more energy than green or yellow ones. This  
486 contributes to greater warming of purple leaves than other non-succulent leaf types [20]. In highly  
487 urbanised regions, the effect that green roofs may have on temperatures of the surrounding  
488 environment (air and urban fabric) can become important. Accordingly, cultivars that offer both  
489 maximum environmental cooling and minimum substrate warming in the summer should be preferred.  
490 *Sedum*, the most commonly used plants on extensive green roofs, was shown to be less effective than  
491 other plants in its environmental cooling and substrate insulation potential, with the other succulent,

492 *Sempervivum*, performing even worse. These plants are popular due to their xerophytic traits and an  
493 ability to survive on very shallow substrate on green roofs without supplementary irrigation. Not  
494 surprisingly, however, their characteristic small leaves, designed to minimise water loss, compromise  
495 their suitability where cooling and shading are important. Although often marketed for their  
496 ecosystem service potential, the results presented here indicate that, while *Sedum* offers a small  
497 cooling/insulation benefit over bare substrate (and most likely a modestly larger benefit compared to  
498 roofing material), they do not perform as well as some other plants. Particularly in terms of substrate  
499 insulation potential, *Salvia* outperformed *Sedum*, as  $G$  was reduced by up to  $\sim 45 \text{ W m}^{-2}$  in plots with  
500 *Salvia* compared to plots with *Sedum*. Although these findings need to be confirmed at the building  
501 scale, they indicate that plants such as *Salvia* would be better suited than *Sedum* carpets to be used in  
502 green roofs where reducing the building heat load in the summer is a priority.

#### 503 4.2. Main plant traits linked to cooling of the surrounding environment and substrate insulation 504 during the day

505  $L_o$ ,  $H$  and  $LE$  are dependent on surface temperatures but also influence the surface temperatures  
506 themselves. Consequently, those plant traits that contribute most to lowering leaf temperatures during  
507 hot periods also play the largest role in reducing the  $L_o$  and  $H$  and increasing the  $LE$  release into their  
508 surroundings, hence leading to enhanced environmental cooling. Based on our findings [see also 20],  
509 it can be suggested that there are a number of specific traits that are key for the reduction of heat  
510 release into the environment. They include high values of  $g_s$ , high LAI, light leaf colour and low  
511 values of leaf thickness. Additionally, as shown by this study and by indirect evidence from other  
512 studies [e.g. 29], some of these traits also ensure the largest reduction in  $G$ , and so the highest ability  
513 to potentially provide summertime substrate insulation; (i) in particular high LAI, through increased  
514 shading, and (ii) high  $g_s$ , by reducing the energy available for  $G$ , as a result of large  $LE$ .

#### 515 4.3. Differences in night-time cooling/insulation potential between treatments

516 Although night-time surface temperatures and heat flux differences were less pronounced than during  
517 the day, surface temperatures for *Salvia*, *Purple Heuchera* and *Stachys* between 20:00-24:00 h were

518 still significantly lower than for bare substrate or *Sempervivum*. This indicates that the environmental  
519 cooling potentially offered by canopies such as *Salvia* and *Stachys* during the day may extend to the  
520 early night period.

521 In contrast, at night during the summer, bare substrate allowed more heat to be released (Figure 6e  
522 and f) from the substrate layer than the majority of vegetated plots. This inevitably suggests that if the  
523 canopies studied were covering a rooftop, less heat would escape the building at night under green  
524 roof vegetation, leading to reduced regulation of temperatures inside the building during hot nights.  
525 However, semi-extensive roofs - for which the plants we studied would be suitable - are more likely  
526 to be deployed on commercial buildings, where daytime temperatures are the main issue. We  
527 therefore argue that there is an overall summer insulation benefit to using vegetation.

#### 528 4.4. Research limitations

529 The heat fluxes calculated within this study, particularly  $LE$  which was derived from other  
530 estimations, may be subject to errors linked to the data collection or the assumptions made during the  
531 calculations. A potential shortcoming of the results we reported may be linked with the fact that an  
532 explicit advective term (i.e. characterized by the horizontal divergence of  $H$ , when  $H$  is negative and  
533 large enough that a downward  $H$  is produced at the ground during the daytime [36,45]) was not  
534 included in the energy balance calculations. Instead, advection is implicitly embedded in the  $LE$   
535 estimation. To test whether the relative differences among the latent fluxes for the different plant  
536 species would remain once an advective term was taken into consideration, further calculations were  
537 carried out based on the (micro) advection theory and equations provided in [36] (data not shown).  
538 Comparisons between both  $LE$  estimations revealed some differences in the absolute flux values but  
539 not in the ranking of *Salvia*, *Stachys* and *Sedum* (*Sempervivum* and bare substrate were excluded as  
540 we did not have surface resistances required to calculate the advective  $LE$  term).

541 Another point to consider is the fact that air will gradually change its properties to achieve a new  
542 equilibrium when flowing over a (vegetated) surface, and so non-equilibrium conditions were likely  
543 for our small experimental surfaces. Furthermore, small plots such as the ones used here are prone to  
544 edge effects [46]. If the air arriving at the edge of the plot is drier and warmer than the air that would

545 be in equilibrium with a similarly vegetated plot of sufficient size, then the horizontal transport of heat  
546 may overwhelm any local effects of evaporative cooling. Energy exchanges identified in small plots  
547 may not therefore be entirely representative of those observed in real life situations [36].

548 Other potential sources of error lay with the measurements themselves. One example is seen in the  
549 wind speed measurements, used in the estimation of  $H$  via  $r_a$ . Here wind speed values from the  
550 University of Reading's registered meteorological station (approx. 600 m away from the experimental  
551 plots) were used, rather than the data from the somewhat less sophisticated weather station at the  
552 experimental plots. The University meteorological station is located in a more exposed area than the  
553 experimental plots, so although wind speeds at both sites were broadly in agreement, wind speeds at  
554 the meteorological station were slightly higher. Any errors due to an overestimation of wind speed  
555 were, however, equally applied to all treatments. In addition, any inaccuracies in other measurements  
556 due to limited instrument precision may also have resulted in other slight under/overestimations.  
557 Errors in the calculations, due to an error in the measurement of variables such as  $T_a$ ,  $L_i$  and  $S_i$  should  
558 also be similar for all treatments. The errors linked to temperature measurements made with different  
559 individual thermocouples attached to leaves or substrate surface and thermistors placed within the  
560 substrate layer could indeed have influenced the relative differences in fluxes found, as the  
561 temperatures measured by the sensors could have differed by up to 0.3°C (based on the identified  
562 precision error). However, we suggest that the overall differences in surface temperatures and fluxes  
563 between treatments were large enough to indicate that different canopies will have different substrate  
564 insulation and environmental cooling ability.

565 We therefore argue that although most limitations we outlined will have had some influence on the  
566 absolute flux values, they did not change the relative differences between treatments on which our  
567 conclusions are based.

## 568 **5. Conclusions**

569 Climate change predictions suggest that heat waves will increase in frequency and intensity in the  
570 future, so the summertime temperature regulation provided by plants on green roofs, and indeed  
571 elsewhere, green walls, street trees etc. [47], will become increasingly valuable. This study indicates

572 that different types of plants significantly differ in their cooling and insulation benefits during hot  
573 periods, when it is most needed. Our results suggest that plants such as *Salvia* and *Stachys*, which  
574 possess key traits required for a reduction in  $L_o$ ,  $H$  and  $G$  and an increase in  $LE$  (i.e. have typically  
575 high  $g_s$  when sufficiently watered, high LAI, leaves with light leaf colour and reflective, and thin  
576 leaves) may have an important role to play a role in cooling the surrounding environment and  
577 improving the daytime thermal insulation of buildings in the summer, and thus should be given more  
578 consideration when planning green roof plant communities.

579 Looking ahead, the implications for the energy consumption of buildings and for the overall  
580 temperatures in the urban environment of using the studied plant species on green roofs still need to  
581 be assessed. It is well known that typical green roof interventions have the potential to reduce heat  
582 entering buildings and reduce the energy used to regulate internal building temperatures in the  
583 summer, although recently the unequivocal thermal benefits of green roofs have been challenged, for  
584 example by [13]. Notwithstanding, on the basis of our study we hypothesise that plants such as *Salvia*  
585 and *Stachys*, which offer added substrate insulation potential during the day in the summer compared  
586 to typical green roof cover, could lead to a considerable decrease in the heat gained by a building  
587 during that period, when covering its roof. An extrapolation of these preliminary findings to total  
588 savings in the energy consumed by a building would need to account also for the winter effects, the  
589 local climate and the building construction, among other aspects. This hypothesis needs therefore to  
590 be confirmed by a broader-scale evaluation. Models such as EnergyPlus have been developed to  
591 predict energy consumptions in buildings. These models have been used to test the performance of  
592 green roofs based on the parameterisation of substrate and plant characteristics, such as substrate  
593 thermal properties, substrate depth,  $g_s$ ,  $h$ , LAI and  $\alpha$  [13,48]. Now that we have collected a detailed set  
594 of plant parameters for a range of contrasting canopies, we propose that future research could use  
595 available models to investigate the level of such savings for buildings under a range of climate  
596 conditions. Furthermore, a number of models are available to study the impact of greening on the  
597 microclimate within the urban environment (e.g. ENVI-met, [49]) and, using our data, these could be

598 used next to assess the green roof area necessary to make a significant impact on air temperatures at a  
599 city scale, initially in a temperate climate.

600 Based on the evidence we collected, we argue that new urban planning policies should take much  
601 greater consideration of plant choice, when attempting to maximise ecosystem services provision. Not  
602 all components of green infrastructure provide the same benefits, and plant genotype choice within  
603 this infrastructure, can strongly determine the type and level of benefits provided. This paper deals  
604 with green roof scenarios, but we are aware of parallel work on trees which suggests that some  
605 species have four times the cooling potential of others [50]. This paper challenges the notion that  
606 *Sedum* and other succulents commonly used on green roofs are able to provide a viable summer  
607 cooling and insulating benefit, and suggests that alternative species, with greater functionality, are  
608 preferable. This involves providing these new genotypes with adequate ‘support’ systems (e.g.  
609 supplementary irrigation) if that is what is required to ensure effective environmental cooling and  
610 substrate insulation in the summer. Our ongoing research is looking into sustainable ways to provide  
611 the water required by these more water-demanding plants and the added costs of such installation.  
612 Indeed, through more appropriate choice of plants and by extending the scale of plantings, positive  
613 impacts at a city scale may be feasible.

#### 614 **Acknowledgements**

615 This study was financially supported by Fundação para a Ciência e a Tecnologia - Portugal (FCT) and  
616 Programa Operacional Potencial Humano/Fundo Social Europeu (POPH-QREN/FSE) through the  
617 doctoral grant SFRH/BD/69921/2010 to Madalena Vaz Monteiro. During the period of experimental  
618 campaigns and related analyses, Anne Verhoef was in receipt of NERC funding on the SWELTER-21  
619 project (NE/I006729/1), "Soil Water - Climate Feedbacks in Europe in the 21<sup>st</sup> Century (SWELTER-  
620 21)". We thank Val Jasper, Dr Mike Dennett, Prof David Midmore, Dr Curtis Wood, Dr Bruce Main,  
621 Trevor Pitman, Michael Stroud, Helen Dominick, Julia Wesley, Suvarna Punalekar and Rebeka Šiling  
622 for their contributions to this study.

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739 **Legends of figures**

740

741 **Figure 1. Photographs of plant canopies used in the experiment, taken in the early summer of 2012. A.**  
742 ***Heuchera* ‘Obsidian’, B. *Heuchera* ‘Electra’, C. *Salvia officinalis* ‘Berggarten’, D. *Stachys byzantina*, E.**  
743 ***Sempervivum* ‘Reinhard’ and F. *Sedum* mix.**

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745 **Figure 2. Schematic representation exemplifying where measurements were made within a plot.**

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747 **Figure 3. Mean spectral reflectance within the short-wave spectrum for all treatments analysed in 2012,**  
748 **measured during a day in August with  $T_{\max} = 18^{\circ}\text{C}$ .**

749

750 **Figure 4. Mean leaf stomatal conductance ( $g_s$ ) for all treatments measured;  $g_s$  is the average of thirty**  
751 **mean  $g_s$  values per treatment in 2012 (degrees of freedom (d.f.) = 149) and twelve  $g_s$  values per treatment**  
752 **(or eight for *Heuchera* yellow) in 2013 (d.f. = 67). LSDs are shown at the top of the figure.**

753

754 **Figure 5. Mean diurnal cycle of estimated surface temperature ( $T_s$ ) and outgoing long-wave radiation ( $L_o$ )**  
755 **for treatments evaluated in 2012 and 2013. Data presented are a mean of 10 days with  $T_{\max} > 24^{\circ}\text{C}$ . LSDs**  
756 **associated with the REML analysis for the periods delimited by the vertical lines were: a. 4.19 and b.**  
757 **2.81 $^{\circ}\text{C}$ , c. 25.84 and d. 17.07 W m $^{-2}$ .**

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759 **Figure 6. Mean diurnal cycle of estimated net radiation ( $R_n$ ) sensible heat flux ( $H$ ), substrate heat flux ( $G$ )**  
760 **and latent heat flux ( $LE$ ) for treatments evaluated in 2012 and 2013. Data presented are a mean of 10**  
761 **days (2012) and 9 days (2013) with  $T_{\max} > 24^{\circ}\text{C}$ . LSDs associated with the REML analysis for the periods**  
762 **delimited by the vertical lines were: a. 32.34, b. 18.20, c. 80.28, d. 45.40, e. 55.42, f. 53.64, g. 124.66 and h.**  
763 **77.24 W m $^{-2}$ .**

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773 **Nomenclature list and Tables**

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**Nomenclature**

ANOVA analysis of variance

$C_p$  air specific heat ( $1010 \text{ J kg}^{-1}\text{K}^{-1}$ )

$d$  zero plane displacement height (m)

$G$  substrate heat flux ( $\text{W m}^{-2}$ )

$g_s$  leaf stomatal conductance to water  
vapour ( $\text{mmol m}^{-2} \text{ s}^{-1}$ )

$H$  sensible heat flux ( $\text{W m}^{-2}$ )

$h$  surface height (m)

$k$  von Karman's constant (0.41)

LAI leaf area index

$LE$  latent heat flux ( $\text{W m}^{-2}$ )

$L_i$  incoming long-wave radiation ( $\text{W m}^{-2}$ )

$L_o$  outgoing long-wave radiation ( $\text{W m}^{-2}$ )

LSD least significant difference

$r_a$  aerodynamic resistance ( $\text{s m}^{-1}$ )

REML residual maximum likelihood

$R_n$  net radiation ( $\text{W m}^{-2}$ )

$S_i$  incoming short-wave radiation ( $\text{W m}^{-2}$ )

$S_o$  outgoing short-wave radiation ( $\text{W m}^{-2}$ )

SMC substrate moisture content ( $\text{m}^3 \text{ m}^{-3}$ )

$T$  substrate temperature ( $^{\circ}\text{C}$ )

$T_a$  air temperature at 2 m ( $^{\circ}\text{C}$ )

$T_{\max}$	maximum air temperature ( $^{\circ}\text{C}$ )
$T_{\min}$	minimum air temperature ( $^{\circ}\text{C}$ )
$T_s$	leaf/substrate surface temperature ( $^{\circ}\text{C}$ )
$U_z$	wind speed at 2 m ( $\text{m s}^{-1}$ )
$z$	height/depth of sensors
$z_{\text{oh}}$	surface roughness length for heat and vapour transfer (m)
$z_{\text{om}}$	surface roughness length for momentum transfer (m)

*Greek symbols*

$\alpha$	albedo
$\varepsilon$	surface emissivity
$\lambda$	substrate thermal conductivity ( $\text{W m}^{-1} \text{K}^{-1}$ )
$\sigma$	Stefan-Boltzmann constant ( $5.67 \times 10^{-8} \text{W m}^{-2} \text{K}^{-4}$ )
$\rho_a$	air density ( $1.2 \text{kg m}^{-3}$ )

**Table 1. Detail of the methodology used while monitoring environmental conditions and surface and substrate temperatures.**

Type of measurement	Position	Equipment	Number of sensors
Ambient air temperature ( $T_a$ ) and humidity	2 m from ground	Screened RHT2n sensor (Delta-T Devices Ltd., Cambridge, UK)	1
Incoming short-wave radiation ( $S_i$ )	0.5 m from ground	Pyranometer SKS 1110 (Skye Instruments Ltd., Llandrindod Wells, UK)	1
Surface temperature ( $T_s$ )	Leaf temperature: on the underside of the leaf. Bare substrate temperature: 0.005 m below the surface	Copper-constantan thermocouples (T fine PTFE insulated twin twisted wires, in house construction)	2 per plot
Substrate temperature ( $T$ )	At 0.01 m and 0.06 m below the substrate surface	Thermistors (Fenwal UUA32J2, in house construction)	2 per plot

**Table 2. Information on the methodology used to occasionally measure various plant and substrate parameters/variables.**

Type of measurement	Equipment	Frequency	Method applied
Substrate moisture content (SMC)	SM200 probe attached to a HH2 Moisture Meter (Delta-T Devices, Cambridge, UK)	Daily, once (or twice when plots were irrigated)	4 measurements per plot
Leaf stomatal conductance to water vapour ( $g_s$ ) of non-succulent leaves and leaves of <i>Sedum spurium</i> (with flat leaves)	LCi infra-red gas analyser with a broad leaf chamber (ADC Bioscientific Ltd., Hoddesdon, UK). Ambient CO <sub>2</sub> concentration was $375 \pm 10 \text{ mm}^3 \text{ dm}^{-3}$	30 times in 2012 and 12 times in 2013 (or 8 for yellow <i>Heuchera</i> , due to a reduction of leaves compared to 2012)	10 leaves per treatment, on each sampling occasion. Between 10:00-17:00 h
Albedo ( $\alpha$ )	Kipp & Zonen CNR4 radiometer (Campbell Scientific Ltd., Shephed, UK), positioned 0.1 m above the surface (field of view of 180°)	Three cloudless days in each summer	Measurements recorded every minute, for approx. 20 minutes, for each treatment. Between 10:00-16:00 h
Spectral reflectance (400 and 1250 nm)	GER 3700 spectroradiometer with fibre optic lens, with field of view 10° (Geophysical and Environmental Research Corp., Millbrook, USA), positioned 0.5 m above the ground	Once in 2012	10 measurements per treatment, around noon
Leaf area index (LAI)	Leaf area meter (Delta-T Devices, Cambridge, UK)	Beginning and end of experiment, each summer	Leaves collected within a square frame (0.15 x 0.15 m) in each plot
Canopy height ( $h$ )	Tape measure	Once half-way of both experiments	In the centre of each plot, from substrate to the tip of the highest leaf

**Table 3. Mean values of albedo ( $\alpha$ ), leaf area index (LAI) and height ( $h$ ) for all the treatments evaluated in 2012 and 2013. The standard errors associated with  $\alpha$  and LAI means are also presented.**

Treatments	$\alpha$		LAI		$h$ (m)	
	2012	2013	2012	2013	2012	2013
Bare substrate	0.09 $\pm$ 0.003	0.13 $\pm$ 0.001				
<i>Salvia</i> (planted 2012)	0.21 $\pm$ 0.001	0.23 $\pm$ 0.001	5.5 $\pm$ 0.21	5.6 $\pm$ 0.33	0.35	0.60
<i>Salvia</i> (planted 2013)		0.22 $\pm$ 0.002		5.1 $\pm$ 0.31		0.25
<i>Stachys</i>	0.20 $\pm$ 0.001	0.19 $\pm$ 0.001	5.5 $\pm$ 0.12	3.0 $\pm$ 0.27	0.25	0.50
<i>Heuchera</i> yellow	0.27 $\pm$ 0.001	0.14 $\pm$ 0.003	4.5 $\pm$ 0.45	0.7 $\pm$ 0.21	0.18	0.12
<i>Heuchera</i> purple	0.20 $\pm$ 0.002	0.20 $\pm$ 0.002	5.5 $\pm$ 0.25	5.1 $\pm$ 0.19	0.20	0.30
<i>Sedum</i>	0.19 $\pm$ 0.001	0.17 $\pm$ 0.001	3.0 $\pm$ 0.32	2.6 $\pm$ 0.23	0.10	0.15
<i>Sempervivum</i>	0.14 $\pm$ 0.001	0.17 $\pm$ 0.001	2.6 $\pm$ 0.17	3.9 $\pm$ 0.03	0.05	0.05

**Table 4. Mean percentage of net radiation ( $R_n$ ) received by each treatment allocated to the sensible ( $H$ ), substrate ( $G$ ) and latent ( $LE$ ) heat fluxes. Mean percentages were calculated based on estimated mean absolute  $R_n$ ,  $H$ ,  $G$  and  $LE$  values for the period between 11:00-15:00 h for 10 days in 2012 and 9 days in 2013, all with  $T_{\max} > 24^\circ\text{C}$ .**

Treatments	2012 - % $R_n$ converted into			2013 - % $R_n$ converted into		
	$H$	$G$	$LE$	$H$	$G$	$LE$
Bare substrate	15	33	51	13	26	62
<i>Salvia</i> (planted 2012)	7	3	90	0	3	96
<i>Salvia</i> (planted 2013)				6	3	91
<i>Stachys</i>	12	2	86	1	6	93
<i>Heuchera</i> yellow	9	3	88	14	18	68
<i>Heuchera</i> purple	28	10	62	25	2	73
<i>Sedum</i>	17	11	72	11	13	76
<i>Sempervivum</i>	27	11	63	25	18	57