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

M. Vaz Monteiro^{1#}, T. Blanuša^{1,2,*}, A. Verhoef³, M. Richardson¹, P. Hadley¹ and R.W.F. Cameron⁴

¹School of Agriculture, Policy and Development, University of Reading, RG6 6AS, UK

²Royal Horticultural Society, Plant Sciences Department, Garden Wisley, Woking GU23 6QB, UK

³Department of Geography and Environmental Science, School of Archaeology, Geography and Environmental Science; University of Reading, Whiteknights, RG6 6AB, UK

⁴Department of Landscape, University of Sheffield, S10 2TN, UK

*author for correspondence: tijanablanusa@rhs.org.uk

#Current address: Urban Forest Research Group, Centre for Sustainable Forestry and Climate Change, Forest Research, Alice Holt Lodge, Farnham, GU10 4LH, UK

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⁻² 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⁻¹ [30]; equivalent to 0.42 and 0.09 m³ m⁻³ when
155 assuming a substrate bulk density of 1.3 g cm⁻³, 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, α ;
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, ε , 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, ε 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, ε 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 α , 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 L/m^2 for
214 *Salvia* planted in 2012, 127 L/m^2 for *Salvia* planted in 2013, 126 L/m^2 for purple *Heuchera*, 105 L/m^2
215 for *Stachys*, 99 L/m^2 for *Sedum*, 93 L/m^2 for yellow *Heuchera* (in plots partially covered) and 77 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 W m^{-2} .

227 Continuous daytime S_o values were not available, but representative estimates of albedo, α , 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, α was either assumed to be equal to the mean α 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 α (at 06:00 or 20:00 h) was set to a value that was 0.05 higher than
 234 the mean α 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 σ 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 ε 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, ρ_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 ΔT is the substrate temperature difference between two depths (at 0.01 m and 0.06 m) and Δz is
258 the distance between those two depths. The substrate thermal conductivity, λ , 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 16th 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, α , and spectral reflectance)

310 The α of most plant plots remained unaltered throughout the two-year period (Table 3). There was,
311 however, a marked reduction in α 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 α , in particular when wet, exposed. The α 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 α was lower in 2012 than in 2013 (Table
316 3), probably due to small SMC differences during the days when α 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⁻² s⁻¹ in 2012 and 185 mmol m⁻² s⁻¹ 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°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°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°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°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 α 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 α 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 α 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 α [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.

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739 **Legends of figures**

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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.**

746

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} .**

758

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 (W m^{-2})

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

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

h surface height (m)

k von Karman's constant (0.41)

LAI leaf area index

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

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

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

LSD least significant difference

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

REML residual maximum likelihood

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

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

S_o outgoing short-wave radiation (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 (m s^{-1})
z	height/depth of sensors
z_{oh}	surface roughness length for heat and vapour transfer (m)
z_{om}	surface roughness length for momentum transfer (m)

Greek symbols

α	albedo
ε	surface emissivity
λ	substrate thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
σ	Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{W m}^{-2} \text{K}^{-4}$)
ρ_a	air density (1.2kg 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 ₂ 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 (α)	Kipp & Zonen CNR4 radiometer (Campbell Scientific Ltd., Shepshed, 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 (α), leaf area index (LAI) and height (h) for all the treatments evaluated in 2012 and 2013. The standard errors associated with α and LAI means are also presented.

Treatments	α		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