



## 10 ABSTRACT

11 Green roofs are of increasing interest to ecologists, engineers and architects, as cities  
12 grow and aim to become more sustainable. They could be exploited to improve  
13 urban biodiversity and ecosystem services, yet almost nothing is known about them  
14 from a soil community ecology perspective, despite how critical soil food webs are  
15 to ecosystem functioning. This paper provides the first comprehensive study  
16 incorporating the annual cycle of green roof soil microarthropods.

17 Microarthropod communities were monitored over 14 months on two extensive  
18 green roofs. Abiotic factors, including substrate moisture, were recorded, as were  
19 biotic factors such as plant and mycorrhizal colonisation. Microarthropod  
20 interactions with these variables were then examined.

21 Microarthropod diversity was low overall, with a few dominant species peaking  
22 seasonally. On occasion, total abundance was comparable to other early  
23 successional soils. The majority of species present were drought tolerant collembola  
24 and xerophillic mites, suggesting that moisture levels on green roofs are a major  
25 limiting factor for soil microarthropods.

26 Our results suggest that the microarthropod community present in extensive green  
27 roof soils is impoverished, limiting the success of above ground flora and fauna and  
28 ultimately the success of the roof as an urban habitat. We conclude that green roof  
29 building guidelines should incorporate soil communities in their design and should  
30 aim to be heterogeneous at the roof and landscape level, for the purpose of  
31 supporting soil biodiversity and creating sustainable habitats.

32 **Key-words:** collembola; mycorrhizas; oribatid mite; urban biodiversity

### 33 **1. Introduction**

34 Green roofs, i.e. intentionally vegetated roofs, are attracting the attention of ecologists  
35 as a novel urban habitat (Oberndorfer et al., 2007). They were developed to provide a  
36 range of environmental and economic benefits, from improving the energy efficiency of  
37 buildings (Jaffal et al., 2012) to carbon sequestration (Getter et al., 2009). They  
38 encompass a range of designs, from deep ‘intensive’ roofs to shallow (often less than 80  
39 mm) ‘extensive’ roofs. The majority of UK green roofs are extensive, with a crushed  
40 red brick substrate and hardy plants of the genus *Sedum* (Grant, 2006). They are  
41 designed to be cost effective and low maintenance, but are a challenging environment  
42 for non-drought adapted plants (Dunnett and Kingsbury, 2004). Despite their harsh  
43 conditions, green roofs support rare insect communities (Kadas, 2006), birds  
44 (Fernandez-Canero and Gonzalez-Redondo, 2010) and local plant taxa (Molineux,  
45 2010; Monterusso et al., 2005) and associated pollinators (Kadas, 2006). To date, little  
46 work has been done on below-ground communities, despite abundant evidence to  
47 suggest that these are inextricably linked to above-ground processes (Wardle et al.,  
48 2004).

49 Subterranean microarthropods regulate decomposition of organic matter, aid nutrient  
50 cycling and shape soil food webs (Moore et al., 1988). They also significantly affect  
51 plant (Ingham et al., 1985) and fungal (Finlay, 1985) growth and can assist movement  
52 of fungal spores through soil (Lilleskov and Bruns, 2005). Microarthropods are,  
53 therefore, a valuable asset, providing multiple ecosystem services. Despite their  
54 importance, they have received remarkably little attention in green roof research and  
55 design.

56 Mites and collembola are prevalent soil microarthropods in the majority of ground  
57 level soils (Vreeken-Buijs et al., 1998) and are known to occur in green roof substrates.  
58 Two short-term studies, Schrader and Böning (2006) and Schindler et al., (2011) found  
59 collembola on green roofs, the latter finding Coleoptera, Hymenoptera and Chilopoda  
60 additionally, in low abundances. One longer study, that of Davies et al. (2010) reported  
61 that mites and collembola accounted for 80% of their roof emergence trap counts. To  
62 date, only these three studies have examined green roof soil invertebrates.

63 Unquestionably, two of the most important factors affecting plant growth on green  
64 roofs are the availability of soil organic matter and water (Nagase and Dunnett, 2011).  
65 In other field soils, many invertebrates (collembola in particular) are known to be  
66 limited by the availability of moisture (Verhoef and van Selm, 1983). Furthermore,  
67 arthropod species richness on roofs is known to be correlated with vegetation cover  
68 (Schindler et al., 2011). We therefore hypothesised that soil microarthropod abundance  
69 in green roofs would be related to plant cover and moisture availability. It is also well  
70 established that in plant communities there are complex interactions between soil  
71 invertebrates and soil microbes, principally arbuscular mycorrhizal (AM) fungi (Gange  
72 and Brown, 2002). To date, no study has searched for the presence of AM fungi in the  
73 roots of green roof plants. The predominant genus planted, *Sedum*, is known to form  
74 arbuscular mycorrhizal associations (Busch and Lelley, 1997), but as the plants are  
75 generally supplied by the horticultural industry as plugs or modular units, grown either  
76 indoors or outdoors, opportunities for mycorrhizal colonization vary. Thus, our second  
77 hypothesis was that arbuscular mycorrhizal presence in green roof substrates would be  
78 low, due to a lack of inoculum and invertebrates to disperse it (Gormsen et al., 2004).

79 Cook-Patton and Bauerle (2012) suggest that a fuller exploration of animal-plant  
80 interactions needs to be performed on green roofs, combined with studying ways of  
81 enhancing diversity. The overall aim of our work is to do exactly this, but prior to any  
82 manipulative experiment, it is essential to characterise the existing community. Thus,  
83 the overarching aim of this paper is to characterise the green roof soil community and to  
84 understand the reasons for the occurrence (or not) of certain constituents. We present  
85 the first study to examine changes over an annual cycle of microarthropods in extensive  
86 green roof soils and determine what organisms constitute the green roof community and  
87 what challenges they face.

## 88 **2. Materials and methods**

### 89 *2.1 Field sites*

90 Two green roofs in the grounds of Royal Holloway, University of London, were used in  
91 this study (Roof A and Roof B). Both were built in April 2004 (so were 6-7 years old at  
92 the time of sampling) and were plug planted with *Sedum album*, *S. acre*, *S. spurium*, *S.*  
93 *kamtschaticum* and *S. rupestre*, in proportions of approximately 3.5:3.5:1:1:1  
94 respectively. The substrate is 80% crushed brick and 20% organic matter (commercial  
95 compost) and is approximately 75mm deep. These roofs are built to a homogenous  
96 industry standard, with equal depth and mix of substrate and planting at regular  
97 intervals. The roofs are within 40m of one another and are 12m high. Roof A is 1960m<sup>2</sup>  
98 in area and B is approximately 2240m<sup>2</sup>. No fertilization, supplementary watering or  
99 removal of naturally colonising plants has ever occurred.

### 100 *2.2 Sampling*

101 We adopted the method of stratified random sampling for soil invertebrates. Each roof  
102 was divided into 12 6m x 12m strata. On each sampling occasion, in each stratum, a

103 1m<sup>2</sup> sample area was placed at random and two samples were taken from this with an  
104 85mm diameter soil corer, inserted down to the roof lining (75mm). This method was  
105 chosen to overcome problems associated with aggregated soil invertebrate distributions  
106 (Ettema and Wardle, 2002), and resulted in a sample of 38.7cm<sup>3</sup> at each sampling point.  
107 Larger amounts could not be removed for fear of permanently damaging the roof  
108 structure. Samples were taken at monthly intervals from March 2010 to April 2011  
109 inclusive.

110 Samples were weighed to determine wet weight and microarthropods were extracted  
111 with Berlese Tullgren funnels for five days (MacFadyen, 1953) at approximately 18°C.  
112 In March 2011, samples were separated into a moss and substrate layer and extracted  
113 separately to determine if invertebrates showed spatial separation. Dry weight was  
114 obtained from samples after extraction to determine the percentage water content of the  
115 substrate.

116 Invertebrates were stored in 70% ethanol until sorted to species/family level  
117 (collembola, commonest mites) or morphospecies (rarer mites, insect larvae) and  
118 counted using a dissecting microscope at x100. Identification was carried out using a  
119 compound microscope at x400.

120 Collembola were identified using Hopkin (2007). Mites were identified using  
121 Strandtmann (1971), Strandtmann and Davies (1972), Walter and Proctor (2001) and  
122 Krantz and Walter (2009).

### 123 *2.3 Biotic factors*

#### 124 *2.3.1 Arbuscular mycorrhizal fungi*

125 AM fungal counts were obtained alongside invertebrate sampling in October 2010 by  
126 removing one portion of root from one individual of *S. kamtschaticum* in each plot.

127 This plant was chosen because it was present in most plots. The procedure was only  
128 performed once, so as to limit the impact on the fragile roof community.

129 Visualization of mycorrhizas in the roots was performed after clearing in 10% KOH  
130 with a modified ink staining method of Vierheilig et al. (1998), using commercial ink  
131 with 1% HCl. Percent root length colonized was obtained with the cross-hair eyepiece  
132 method of McGonigle et al. (1990). Presence of hyphae, vesicles and arbuscules were  
133 recorded at x200 magnification.

### 134 *2.3.2 Plant cover and diversity*

135 Plant cover and plant diversity estimates were obtained in April, June, July and  
136 November 2010 and April 2011 in the same plots used for invertebrate analysis.  
137 Individuals were counted and identified to species where possible. Additionally,  
138 vegetation cover was estimated by eye with the aid of a quadrat split into 1% fractions.

### 139 *2.4 Abiotic factors*

140 Daily and monthly average temperature readings were obtained from a weather station  
141 within Royal Holloway Earth Sciences department, situated on a roof approximately  
142 300m from our study site. Average rainfall for South-East England was obtained from  
143 Met Office records (Met Office 2011).

### 144 *2.5 Statistical analysis*

145 All statistical tests were performed in SPSS 19.0. Normality tests were performed on  
146 whole data sets and data were transformed if necessary by  $\ln+1$  or square root.  
147 Differences between total microarthropod abundance over time were tested using a two-  
148 factor, repeated measures ANOVA, employing time and roof as main effects, and were  
149 also performed for collembola and mites separately. Months were separated with  
150 Tukey's HSD post-hoc tests.

151 Relationships between organisms and abiotic and biotic factors were examined using  
152 linear and curvilinear regressions. Mites, collembola and total microarthropod  
153 abundance were the dependent factors and plant cover, plant diversity, mycorrhiza,  
154 temperature and substrate water content were the independent factors.

155 Diversity was measured using the Shannon Wiener Index and was calculated in four  
156 variations: all roof organisms, mite morphospecies, collembolan species and all  
157 organisms not belonging to mites or collembola. Data examining differences in mite and  
158 collembolan diversity between the roofs did not meet the assumptions of ANOVA and  
159 so were examined with Mann Whitney-U tests.

160 March 2011 data were examined for spatial separation of mites and collembola  
161 between the moss and substrate layers on each roof using a two-factor ANOVA,  
162 employing roof and layer as main effects.



163 **3 Results**

164 *3.1 Total microarthropods*

165 Overall, soil faunal diversity was low, with only 42 species/morphospecies found over  
 166 the 14 month period (Table 1). The fauna was dominated by collembola (61%) and  
 167 mites (38%) but also included small numbers of Chilopoda, Coleoptera, Hemiptera,  
 168 Aranae and larvae, mostly of Diptera, Lepidoptera and Coleoptera. Of these less  
 169 prevalent groups, larvae were most common but no group represented more than 1%  
 170 relative abundance. No correlations were found between total abundance and any  
 171 abiotic or biotic factors.

172

173 **Table 1.** Orders of microarthropods encountered on two extensive green roofs (Roof A  
 174 and B, pooled).

175		Mean	Relative	No. sp./
176	Order	individuals m <sup>-2</sup>	abundance (%)	morphospecies
177	<i>Collembola (ad &amp; juv)</i>	20637.8 (± 1056.7)	62.13	5
178	<i>Acarina (ad &amp; juv)</i>	12359.7 (± 888.5)	37.21	15 <sup>a</sup>
179	<i>Hemiptera (ad &amp; juv)</i>	54.4 (± 8.7)	0.16	6 <sup>a</sup>
180	<i>Aranae (ad &amp; juv)</i>	9.6 (± 2.3)	0.03	1
181	<i>Chilopoda (ad &amp; juv)</i>	13.1 (± 3.7)	0.04	1 <sup>a</sup>
182	<i>Coleoptera (ad)</i>	6.4 (± 1.4)	0.02	3
183	<i>Diptera (ad)</i>	9.9 (± 1.7)	0.03	1 <sup>a</sup>
184	<i>Unidentified insect larvae</i>	89.2 (± 5.1)	0.3	11 <sup>a</sup>

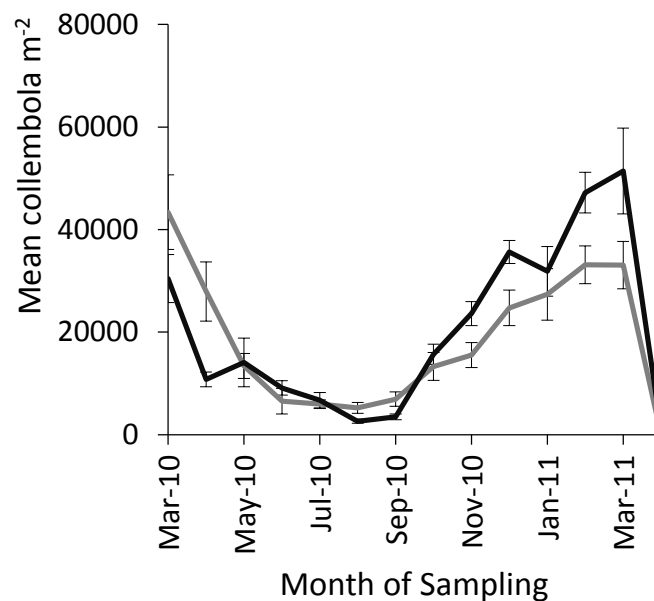
185 <sup>a</sup>morphospecies, as opposed to species

186

## 187 3.2 Collembola

188 Only six collembola species made up the 72 978 individuals counted. 74% were  
 189 *Sminthurinus aureus*, 23% *Deuterosminthurus pallipes*, 1% *Parisotoma notabilis* and  
 190 less than 1% were made up of *Bourletiella hortensis*, *D. bicinctus* and *Isotomurus*  
 191 *palustris*. *Sminthurinus aureus* and *D. pallipes* showed almost identical seasonal trends,  
 192 although *D. pallipes* was always lower in abundance.

193 Collembolan density varied between 0 – 120 000 individuals m<sup>-2</sup> (average  $\approx$  19 000  
 194 ( $\pm$ 1000) m<sup>-2</sup>, median  $\approx$  14 000m<sup>-2</sup>). Total abundance did not vary between roofs but  
 195 varied greatly over time ( $F_{6,4, 128.3} = 47.8, p < 0.001$ ) with peaks in March of each year  
 196 (Fig. 1).

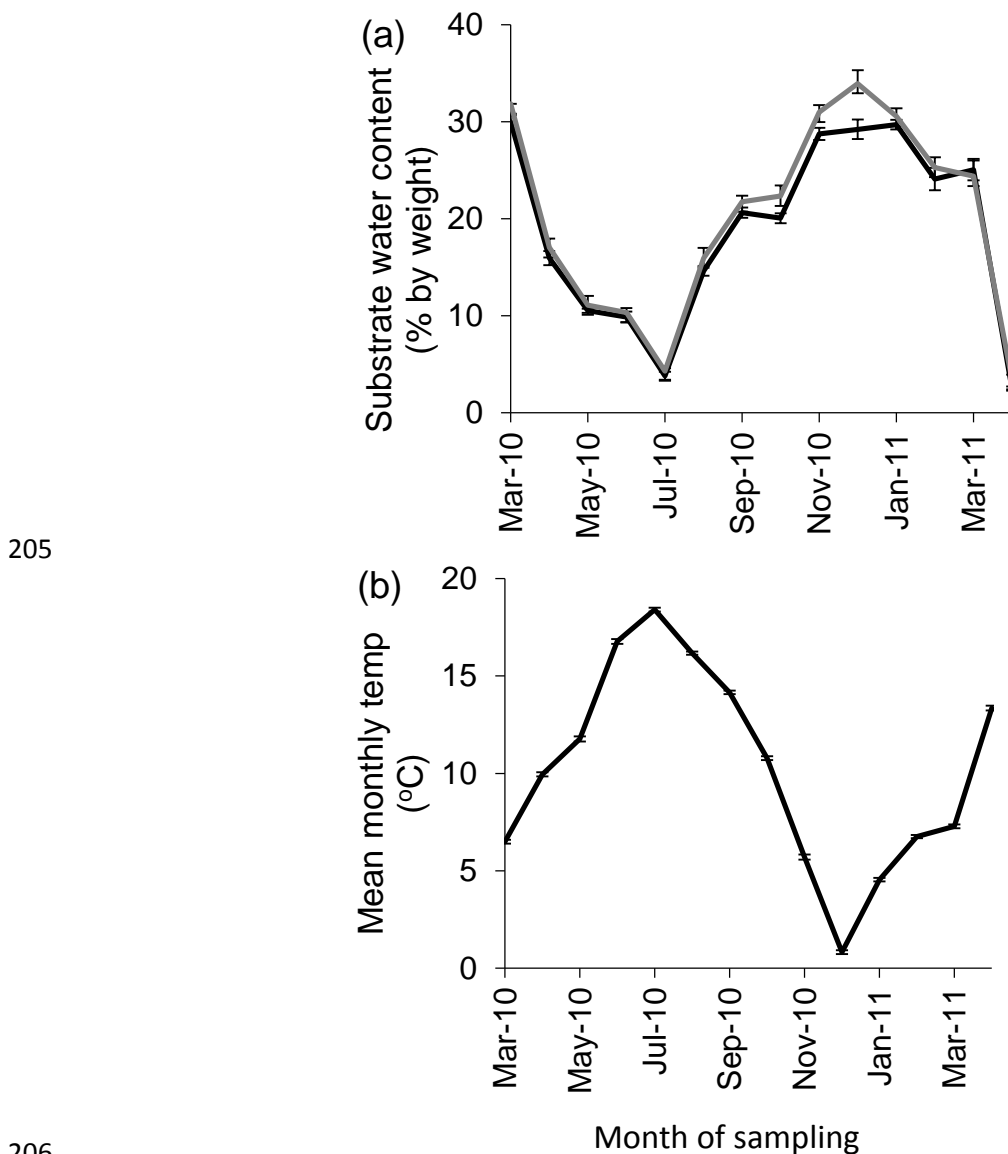


197  
 198 **Fig. 1.** Mean collembolan between March 2010 and April 2011. Black denotes Roof A;  
 199 grey denotes Roof B. Error bars represent SEM.

200

201 Density decreased with rising average monthly temperature (Roof A:  $R^2 = 0.175, F_{1, 166} = 35.2, p < 0.001$ ;  
 202 Roof B:  $R^2 = 0.249, F_{1, 142} = 47.1, p < 0.001$ ) with population

203 crashes occurring when water content was low, followed by a recovery time as water  
 204 content increased (Figs. 1 & 2).



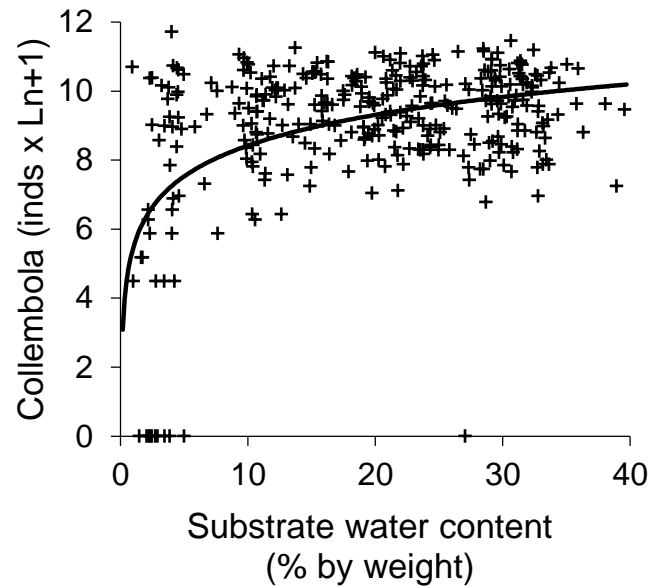
207 **Fig. 2.** (a) Percentage water of green roof substrate (by weight) for Roof A (black) and  
 208 Roof B (grey) between March 2010 and April 2011. (b) Mean monthly temperature for  
 209 the local area (°C) for the same period. Error bars represent SEM.

210

211 *Deuterosminthurus pallipes* was slower to recover from these than *S. aureus*.

212 Collembolan abundance showed a logarithmic relationship with substrate water content

213 ( $R^2 = 0.22$ ,  $F_{1,331} = 93.3$ ,  $p < 0.001$ ), with a threshold value of approximately 5%, below  
 214 which numbers decreased dramatically (Fig. 3).

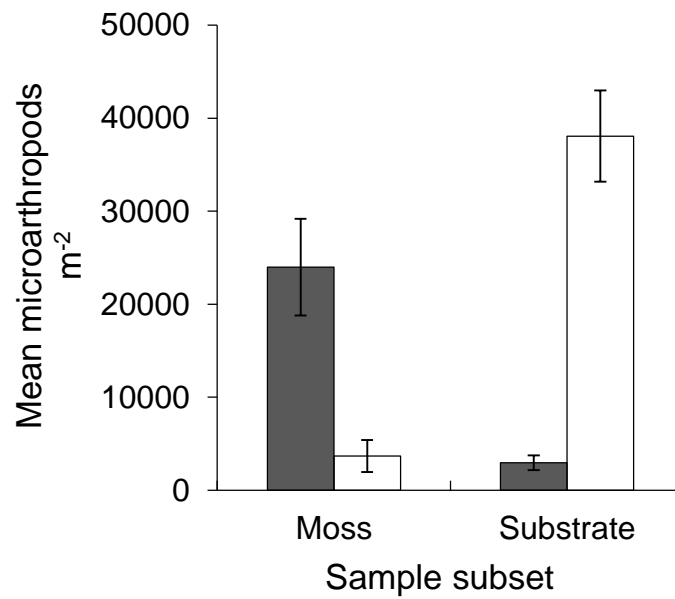


215

216 **Fig. 3.** Numbers of collembola ( $ln + 1$ ) plotted against percentage substrate water  
 217 content (by weight, ratio of 1) for samples on both green roofs between March 2010 and  
 218 April 2011. A logarithmic relationship is displayed.

219

220 Of the biotic variables measured, collembolan abundance was positively related to  
 221 moss cover, but only on Roof B ( $R^2 = 0.102$ ,  $F_{1,56} = 6.3$ ,  $p = 0.05$ ). However, on both  
 222 roofs collembola were considerably more abundant in the substrate layer than the moss  
 223 fraction ( $F_{1,44} = 59.1$ ,  $p < 0.001$ ) (Fig. 4).

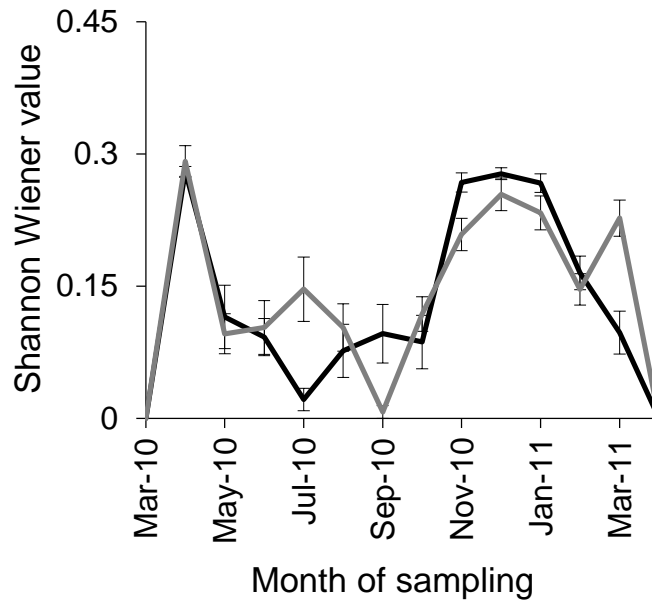


224

225 **Fig. 4.** Microhabitat preferences for mites and collembola in June 2010 on both roofs,  
 226 determined by extracting microarthropods from the surface moss layer and underlying  
 227 substrate layer separately. Dark bars represent mites, white bars represent collembola.  
 228 Error bars represent SEM.

229

230 Collembolan diversity was poor, reaching only 0.5 at its highest. Diversity was  
 231 highest in April 2010, March 2011 and over winter (Fig. 5). There were no differences  
 232 between roofs in diversity or seasonal pattern.



233

234 **Fig. 5.** Shannon Wiener indices for collembola diversity between March 2010 and April  
 235 2011. Black denotes Roof A; grey denotes Roof B. Error bars represent SEM.

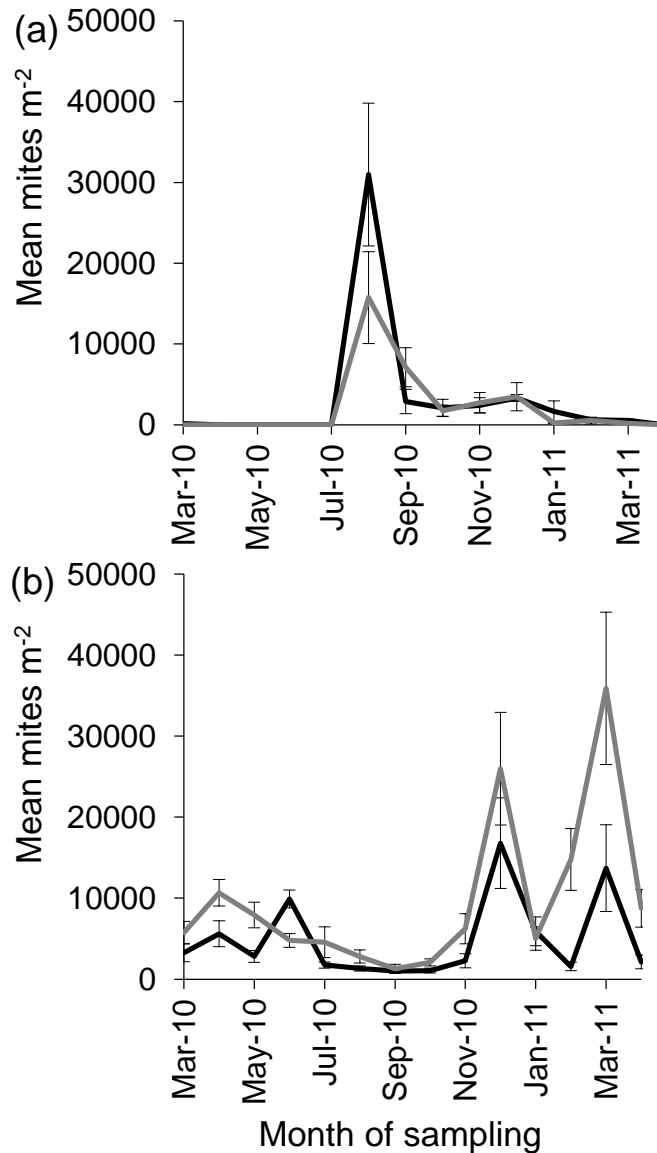
236

237 Collembolan diversity decreased with increasing daily ( $R^2 = 0.147$ ,  $F_{1, 286} = 49.3$ ,  $p$   
 238  $< 0.001$ ) and monthly ( $R^2 = 0.089$ ,  $F_{1, 310} = 30.177$ ,  $p < 0.001$ ) average temperatures  
 239 (Fig. 2b). These were the only abiotic factors to affect collembolan diversity.

### 240 3.3 Mites

241 Fifteen morphospecies of mite were present on the roofs and density varied between  
 242 180 and 109 000 mites  $m^{-2}$  (average  $\approx 12\ 000$  ( $\pm 800$ )  $m^{-2}$ , median  $\approx 7000$   $m^{-2}$ ). The two  
 243 most abundant mites were a prostigmatid, *Eupodes viridis*, which was particularly  
 244 abundant in summer 2010, and an oribatid mite from the Scutoverticidae family. These  
 245 represented 23% and 62% of mites respectively. Mite abundance did not differ between  
 246 roofs (Fig. 6) but did change over time ( $F_{3,1, 61.8} = 11.1$ ,  $p < 0.001$ ) with higher  
 247 abundances in August/September 2010 (*E. viridis*) and December 2010 and March 2011  
 248 (Scutoverticidae) (Fig. 6). The Scutoverticid was usually the most dominant mite.

249



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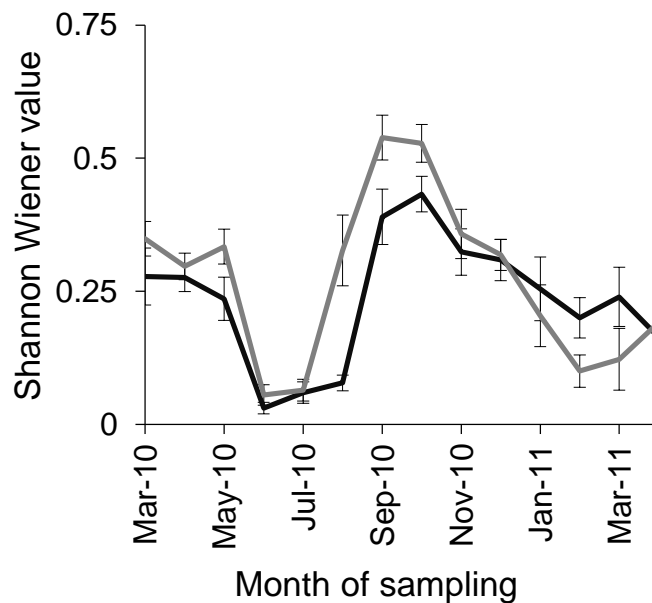
251 **Fig. 6.** Abundance plots of the two commonest mites encountered on two green roofs  
 252 between March 2010 and April 2011. Black denotes Roof A, grey denotes Roof B and  
 253 error bars represent SEM. (a) *E. viridis* (b) *Scutoverticidae*.

254

255 Mite abundance was not affected by any of the variables measured. No relationship  
 256 was found between mite abundance and substrate water content or temperature. No  
 257 association between mites and plant cover, plant diversity or mycorrhizal colonisation  
 258 of nearby roots was found either. However mites showed a strong preference for the

259 moss fraction of the habitat ( $F_{1,44} = 34.3, p < 0.001$ ) (Fig. 4), creating a clear spatial  
 260 separation between mites and collembola.

261 Mites were more diverse than collembola, reaching a maximum of 0.7 in September  
 262 2010 but decreasing to 0 in June 2010 (Fig. 7). Mite diversity remained high over winter  
 263 and also peaked in early and late summer. There was no difference in diversity or  
 264 seasonal pattern between roofs.



265

266 **Fig. 7.** Shannon Wiener indices for mites between March 2010 and April 2011. Black  
 267 represents Roof A, grey Roof B and error bars represent SEM.

268

269 Mite diversity decreased with increasing daily ( $R^2 = 0.135, F_{1,286} = 44.809, p <$   
 270  $0.001$ ) and monthly ( $R^2 = 0.1, F_{1,310} = 25.9, p < 0.001$ ) average temperature but was  
 271 affected by no other factors (Fig. 2b).

### 272 3.4 Biotic factors

273 Both roofs had an average of 49% ( $\pm 4$ ) root length colonised by mycorrhizal fungi with  
 274 some individuals as high as 76%. Roots were relatively high in vesicles, averaging 9.5%



275 ( $\pm 2$ ) on Roof A and 13% ( $\pm 4$ ) on Roof B, but very low in arbuscules, averaging 0.25%  
276 ( $\pm 0.2$ ) on each roof.

277 The plant community was dominated by *Sedum spp.* and mosses, with the latter  
278 tending to prevail in most plots. Over the five plant surveys, mosses had an average  
279 cover of 45% ( $\pm 2$ ) and *Sedum* 28% ( $\pm 1$ ). Some plots had bare areas and these  
280 accounted for 20% ( $\pm 2$ ) of average plot area. Lichen accounted for 2% ( $\pm 0.6$ ) of  
281 vegetation cover. Seasonal colonisers (see Table S1 in Supporting Information) were  
282 absent in June and July 2010 but abundant in April 2010, 2011 and November 2010.  
283 *Trifolium arvense* made up a large proportion of these, particularly in April 2010 where  
284 it accounted for an average of 14% ( $\pm 3$ ) of plant cover on Roof A and 22% ( $\pm 4$ ) on  
285 Roof B. Mean Shannon Wiener diversity for non-*Sedum* and non-moss species for April  
286 2010 for Roof A and B were 0.11 ( $\pm 0.07$ ) and 0.23 ( $\pm 0.07$ ) respectively, for April 2011  
287 were 0.08 ( $\pm 0.04$ ) and 0.09 ( $\pm 0.04$ ) respectively and November averaged 0.05 ( $\pm$   
288 0.04) on Roof A and 0.04 ( $\pm 0.03$ ) on Roof B. Two species of Basidiomycete fungi were  
289 observed on the roof, *Melanoleuca polioleuca* and *Omphalina pyxidata*.

### 290 3.5 Abiotic factors

291 Temperature for the sample period reached a maximum daily temperature of 30°C in  
292 July 2010 and a minimum daily temperature of -8.3°C in December 2010, with monthly  
293 average temperatures between 18.4°C ( $\pm 0.1$ ) in July 2010 and 0.8°C ( $\pm 0.1$ ) in December  
294 2010. Substrate water content was highest over the winter months reaching a maximum  
295 of 30% by weight in December 2010. The substrate was driest in April 2011 at 2%  
296 water content by weight (Fig. 2).

## 297 **4. Discussion**

### 298 *4.1 Total microarthropods*

299 Overall, microarthropod diversity on the roofs was low and rarely were there  
300 differences between roofs, demonstrating that the homogeneity in the roof substrate and  
301 construction are mirrored by the soil community. Both roofs were constructed in an  
302 identical way and were of the same age, suggesting that similarly constructed roofs in a  
303 given location will likely face the same challenges and harbour similar communities,  
304 making this study relevant to a large proportion of roofs in the UK. A large proportion  
305 of green roofs in the UK are built to this homogenous design and so it is likely that  
306 many of these share this impoverished community. Although collembola and mites are  
307 key organisms with regards to soil nutrient cycling (Moore et al, 1988), other key  
308 functional groups of the soil biota expected in Tullgren extraction, such as Annelida and  
309 Diplopoda (Smith et al., 2008) were missing. The uniform, depauperate communities  
310 observed emphasise the importance of providing varying green roof designs within a  
311 city, to maximise diversity of communities.

312 The species assemblage on these roofs is comparable to other early successional  
313 environments. Similar communities of soil microarthropods are found in desert soils  
314 (Wallwork, 1972) and glacial foreland soils (Kaufmann et al., 2002). In both, the fauna  
315 is dominated by mites and collembola but some other organisms, such as larvae, also  
316 occur. Soils with lower abundances but a higher diversity of collembola and mites (but  
317 no other species) include Antarctic soils (Caruso and Bargagli, 2007; Convey and  
318 Smith, 1997) and polluted urban sites such as roadside lawns and roundabouts  
319 (Eitminaviciute 2006a,b). In these examples mites tend to be dominant over  
320 collembolans, converse to our findings where the collembolan count was higher, if more

321 variable, than mites. Our sites perform poorly compared to reclaimed mining sites  
322 (Dunger et al., 2001; Wanner and Dunger, 2002) where both abundance and diversity of  
323 microarthropods was higher.

324 Other organisms found in urban soils using Berlese Tullgren funnels, such as  
325 Diplopoda, Isopoda and Annelida (Hartley et al., 2008; Santorufo et al., 2012) were  
326 absent. In conjunction with the low abundance of microarthropods on the roof, this  
327 impoverished soil food web could have serious implications for nutrient cycling, which  
328 may be less efficient than ground level soils (Sheehan et al., 2006). Despite spiders  
329 having been found in abundance on green roofs previously (Kadas, 2006), the low  
330 numbers of spiders, centipedes and predatory mites in this study indicate that the soil  
331 food web available to above ground predators could also be inadequate. The ecology  
332 and diversity of the roof as a whole, therefore, could be vastly improved by enhancing  
333 the soil community.

#### 334 4.1.2 Collembola

335 The six collembola species encountered were cosmopolitan, native UK species (Hopkin,  
336 2007). *S. aureus*, *I. palustris*, *B. hortensis* and *P. notabilis* have been previously  
337 recorded on green roofs (Schrader and Böning, 2006) but this is the first record of *D.*  
338 *pallipes* and *D. bicinctus* to our knowledge.

339 Collembolan density was negatively affected by high temperature and low soil  
340 moisture, but the latter only below a certain threshold. Petersen (2011) found that the  
341 density of Symphypleona (*S. aureus*, *D. pallipes*, *B. hortensis*, *D. bicinctus*) subjected to  
342 warm, dry treatments for one month in Britain were unaffected. However, in warm,  
343 sparsely vegetated Spanish sites (more like a green roof), drought negatively affected  
344 Symphypleona, particularly *S. aureus*, despite its ability to produce drought resistant

345 | eggs (Alvarez et al., 1999). Contrary to our findings, *D. pallipes* was unaffected in their  
346 | study. The longer period of drought in our study, or an unmeasured buffering factor,  
347 | such as food availability, could cause these disparities. Beyond what is needed to  
348 | survive, collembolan abundance is driven by an unknown factor, such as competition or  
349 | diet (Petersen, 2002). It is clear that on our roofs, *S. aureus* and *D. pallipes* share some  
350 | tolerance to the harsh conditions.

351 | Habitat colonisation by collembola relies on both dispersal ability and favourable  
352 | conditions for persistence (Auclerc et al., 2009). All six species that dispersed to the  
353 | roofs were mobile, long-legged species with active furcas, yet three did not persist.  
354 | Conditions on the roof are therefore likely to be unfavourable for them. *I. palustris* is  
355 | vulnerable to drought (Alvarez et al., 1999) but has been found on green roofs before  
356 | (Schrader and Böning, 2006) suggesting survival might be possible if drought is  
357 | alleviated.

358 | Maximum abundance of collembola was comparable to other green roofs in  
359 | Hannover (Schrader and Böning, 2006) and to urban soils (Fountain and Hopkin, 2004),  
360 | but neither of these studies report the drought-driven population crashes seen in our  
361 | populations, emphasising the importance of incorporating seasonal dynamics into  
362 | microarthropod surveys.

363 | Fewer species were encountered than in Schrader and Böning (2006), whose roofs in  
364 | Hannover were of a similar age, height and depth but whose substrate consisted of  
365 | expanded clay or shale pellets, not crushed brick. Hannover also has a different climate  
366 | to South-East England, though no studies have determined the effect of either climate or  
367 | substrate type on green roof soil communities as yet. Diversity was also lower than that  
368 | expected in urban UK soils (Fountain and Hopkin, 2004), and this may be due to the

369 lower organic matter present on the green roofs than in ground-level soil, an important  
370 factor for soil microarthropods (Ettema and Wardle, 2002). It is recommended that  
371 future studies compare the two to determine if this is indeed the case.

372 In general, collembolan abundance was comparable to other urban habitats at certain  
373 times of the year but this was unstable and overall diversity was low. Colonisation  
374 occurred throughout the sample period, but populations also dwindled to near extinction  
375 at times. A snapshot taken at one point in the year on these roofs, such as that by  
376 Schrader and Böning (2006), though valuable for producing well-rounded data sets  
377 covering different roofs, would have produced vastly different conclusions regarding  
378 the suitability of this habitat for microarthropods.

#### 379 *4.1.3 Mites*

380 Mite density was low and consisted mainly of Scutoverticidae. Abundance was slightly  
381 lower than that of ploughed soils (Perdue and Crossley, 1989) and was comparable to  
382 terrestrial sub-Antarctic habitats (Barendse et al., 2002). However, abundance has not  
383 been reported as low as our minima in either of these habitats. Even in the poorest dry  
384 Mediterranean plots, Tsiafouli et al. (2005) found densities of oribatid mites (which  
385 formed the majority of our samples) higher than ours. This, with the absence of other  
386 functional groups on the roof, supports the hypothesis that harsh conditions on the roof  
387 generally have a negative effect on mites (Taylor and Wolters, 2005). It is also plausible  
388 that a lack of prey for predatory mites (Koehler, 1999) and low levels/poor quality of  
389 organic matter for detritivores (Taylor and Wolters, 2005) produces unfavourable  
390 conditions for specialist mites. Observing the mite community at the family/species  
391 level further exemplifies this point. One mite dominated at any one time, with the two  
392 most abundant mites being characteristic of stressful environments.

393 *Eupodes viridis* has a cosmopolitan range but can be found in environments such as  
394 the sub-Antarctic (Strandtmann and Davies, 1972). Diet preference within the genus is  
395 unclear, but is thought to be wide-ranging for this species (Krantz and Walter, 2009),  
396 but its physiology, with an enlarged leg IV femora, suggests an active lifestyle. Little is  
397 known about dispersal of the genus, but some are canopy specialists so dispersal from  
398 the nearby trees is plausible (Fagan et al., 2006). Generation times of *Eupodes spp* are  
399 speculated to be slow, around two to three years (Booth and Usher, 1986), perhaps  
400 enabling it to survive harsh conditions.

401 The oribatid family Scutoverticidae is also found in extreme environments.  
402 Primarily inhabiting moss and lichen, they are also found on exposed rocks and rooftops  
403 (Schäffer et al., 2010b) and are primary colonisers of young soils (Lehmitz et al., 2011).  
404 DNA analysis has also shown them to be excellent dispersers, probably facilitated by  
405 phoresy on birds (Schäffer et al., 2010a) but also capable of wind dispersal (Lehmitz et  
406 al., 2011), useful strategies for roof dwellers. Scutoverticidae were unaffected by any  
407 factors in this study and are known to be tolerant of desiccation and temperature flux  
408 (Schäffer et al., 2010b) as well as possessing anti-predatory mechanisms such as thick  
409 armour (Krantz and Walter, 2009). The family are thought to be generalist feeders  
410 (Smrž, 2006). Generation times are suggested to be two to six months (Schäffer et al.,  
411 2010b), which would correspond with our abundance peaks. The dominance of  
412 xerophilic oribatids on the roof mirrors our conclusions regarding collembola; the hot,  
413 arid nature of the roof is capable of supporting only a small and unstable community.

414 Mite diversity was higher than collembolan diversity but also crashed in June 2010  
415 when Scutoverticidae dominated the fauna. Diversity was lower than in reclaimed

416 Mediterranean mining sites (Andrés and Mateos, 2006) but comparable to Swedish  
417 agricultural soils (Gormsen et al., 2006).

#### 418 *4.1.4 Relationships with biotic factors*

419 We hypothesised that a lack of organisms to disperse AM fungi spores would contribute  
420 to low AM fungal presence but this was not the case; AM fungi were extremely  
421 prevalent on the roof, reaching colonisation levels typical of highly mycorrhizal plants  
422 such as *Plantago lanceolata* (Ayres et al., 2006). Whether this was present in the initial  
423 *Sedum* plugs or has successively colonised is unknown. The limited space available for  
424 spread of *Sedum* roots may maximise spore contact without the need for dispersing  
425 organisms. Neither collembola, nor mites were found to associate with AM fungi, also  
426 contrary to our hypothesis. The two fruiting bodies recorded on the roofs, *M. poliroleuca*  
427 and *O. pyxidata*, are not mycorrhizal but may contribute to collembola diet, as they are  
428 known to preferentially feed on non-AM fungal species if present (Gange, 2000).

429 Contrary to our hypothesis, there was no correlation between total plant cover and  
430 collembola, mite or total soil microarthropod density or diversity. Schindler et al.,  
431 (2011) found that plant cover was correlated with soil microarthropod abundance on  
432 green roofs. However, their roofs were younger and do not mention mosses, which had  
433 a large effect in our study. Their roofs also had a more diverse flora than ours, perhaps  
434 due to differences in construction, climate or sampling season (cover and diversity of  
435 flora changed throughout the year in our study). What drives these populations when  
436 water is not a limiting factor is, therefore, still to be discovered.

#### 437 *4.1.5 Habitat preferences*

438 Collembola and mites showed distinct spatial separation, dominating the underlying  
439 substrate and moss respectively. Scutoverticidae have a well-documented association

440 with mosses (Schäffer et al., 2010b) and the separation of the two could suggest  
441 competition avoidance. Despite inhabiting the underlying substrate, collembola were  
442 positively affected by moss cover on one of the roofs. Neither dominant species of  
443 collembola are known to be moss-associated but the moss crust could provide  
444 secondary benefits such as moisture retention (Chamizo et al., 2012) or may support  
445 fungi, a collembolan dietary component (Gange, 2000).

446 The implications for green roof design are great if these spatial separations are  
447 temporally consistent. McGeoch et al. (2006) tested microhabitats in Antarctic micro-  
448 arthropod communities, finding that mites (including *Eupodes spp.*) avoid shade, whilst  
449 collembola avoid warm, dry regions. Spatial separation is therefore likely to be  
450 influenced by availability of suitable microhabitats and emphasising these in green roof  
451 designs to ameliorate the effects of warmth and drought could enhance the  
452 microarthropod community. The provision of heterogeneous habitats, both locally and  
453 at the landscape scale, have been shown to be valuable in increasing the diversity of  
454 plant communities on green roofs (Lundholm, 2006) and in other urban settings (Francis  
455 and Hoggart, 2009). It is likely that once suitable habitat is provided on green roofs,  
456 further species changes will occur as food availability becomes a limiting factor. This  
457 may be where we see effects of plant and fungal diversity on microarthropods, rather  
458 than the ability to survive harsh conditions. By enhancing the soil food web, we could  
459 directly enhance above-ground biodiversity and enable green roofs to realise their  
460 ecological potential (Cook-Patton and Bauerle, 2012).

#### 461 *4.2 Conclusions*

462 Extensive green roofs are either in an interrupted or extremely slow successional  
463 process capable of supporting only the hardiest of soil microarthropods. They present a



464 boom and bust community, with some key functional groups missing, but support a few  
465 ephemeral colonisers, such as beetle and fly larvae. Few species manage to survive in  
466 the long-term due to hot, arid conditions, an impoverished soil food web and low plant  
467 diversity. Amelioration of these conditions and manipulation of the soil food web to  
468 provide a diverse food source could benefit microarthropod and plant communities on  
469 these roofs.

470 Water is a serious limiting factor for collembola and mites on these roofs. The  
471 development of superior water retention properties could significantly benefit  
472 microarthropod diversity. Alternatives to crushed brick are available and should be  
473 seriously considered, not only for their ability to support plant growth (Molineux et al.,  
474 2009) but also for soil faunal sustainability.

475 Temperature was also a key factor and previous research (McGeoch, 2006)  
476 demonstrates how refugia can ameliorate unfavourable conditions, a lesson to be learnt  
477 for green roof construction. We emphasise the importance of varying green roof habitat  
478 designs as the similarities between communities on our field sites suggest that in high  
479 density areas of green roofs of the same design, as is perfectly conceivable in London, a  
480 monoculture could develop.

481 In conclusion, we suggest that the current standard for extensive green roof design is  
482 not adequate to support a biodiverse soil microarthropod community especially in dry  
483 South-East England, and that this could have detrimental effects on above-ground  
484 communities. Research into the successes and failures of other designs, such as  
485 intensive and semi-intensive systems, needs to be conducted to improve the delivery of  
486 extensive green roofs, whilst retaining the benefits of having a low cost, low  
487 maintenance system.

488        Increasing rooftop soil biodiversity in our cities may require not only heterogeneous  
489 designs at the roof level but also careful planning at the landscape level, rather than  
490 accepting a monoculture of industry standards.

491 **Acknowledgements**

492 Thanks to Michelle Fountain for her collembolan taxonomic expertise and to Mathias  
493 Lanoisellé for temperature data. Also to Neil Morley, Catherine Jones, Viv Schroeder  
494 and Liang Jin for help with data collection, Stephan Tietz for manuscript revisions and  
495 Mark Brown, Chloe Molineux and Charles Fentiman for their expertise and support.

496 This work was funded by a Natural Environment Research Council CASE  
497 Studentship (R70944C) in collaboration with Symbio Ltd (Wormley, Surrey) and  
498 Laverstoke Park (Overton, Hampshire). Funding parties had no involvement in the  
499 design, collection, analysis or interpretation of data or in the writing or submission of  
500 this paper.

**501 Glossary of terms**

- 502 • Arbuscular mycorrhizal fungi – Fungi which form symbiotic (usually  
503 beneficial) partnerships with vascular plants, intracellularly (within  
504 their roots).
- 505 • Arbuscules – Branched structure of AM fungi within vascular plant  
506 roots used for nutrient exchange
- 507 • Basidiomycete – Fungal phylum
- 508 • Collembola – Group of organisms belonging to the arthropod phylum,  
509 also known as springtails
- 510 • Detritivore – Organisms that obtain energy by consuming  
511 decomposing organic matter
- 512 • Hyphae – Filamentous structure of fungi usually constituting the main  
513 mode of vegetative growth
- 514 • Furca – Structure unique to collembola used for jumping
- 515 • Microarthropod – Small to microscopic members of the arthropod  
516 phylum (organisms with exoskeletons, segmented bodies and jointed  
517 appendages)
- 518 • Quadrat – Metal grid used for vegetation surveys
- 519 • Refugia – An area providing shelter
- 520 • Vesicles – Storage structures of AM fungi, found within vascular plant  
521 roots
- 522 • Xerophilic – Organisms that are tolerant of dry conditions

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**Supplementary data**

Table S1. Plant and fungal species encountered during the sample period. In addition to this lichen and bryophytes were present as well as 6 unidentifiable plant species and one species of grass, also not identified

**Plants *Sedum***

*Sedum album*

*Sedum acre*

*Sedum kamtschaticum*

*Sedum rupestre*

*Sedum spurium*

**Seasonal colonisers**

*Arabidopsis thaliana*

*Anthyllis vulneraria*

*Cirsium arvense*

*Geranium robertianum*

*Jacobaea vulgaris*

*Leontodon hispidus*

*Melilotus officinalis*

*Sonchus asper*

*Sonchus oleraceus*

*Taraxacum officinalis*

*Trifolium arvense*

*Trifolium dubium*

**Tree saplings**

*Acer pseudoplatanus*

*Betula pendula*

*Pinus sylvestris*

**Fungi**

*Melanoleuca polioleuca*

*Omphalina pyxidata*