

1 Effects of varying organic matter content on the development of  
2 green roof vegetation: a six year experiment

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14  
15 **Abstract**

16 Green roofs can potentially be used to tackle a variety of environmental problems, and  
17 can be used as development mitigation for the loss of ground-based habitats. Brown  
18 (biodiversity) roofs are a type of green roof designed to imitate brownfield habitat, but  
19 the best way of engineering these habitats requires more research. We tested the effects  
20 of altering organic matter content on the development of vegetation assemblages of  
21 experimental brown (biodiversity) roof mesocosms. Three mulch treatments were  
22 tested: (1) Sandy loam, where 10mm of sandy loam mulch (about 3% organic matter by  
23 dry weight) was added to 100mm of recycled aggregate; (2) Compost, where the mulch  
24 also contained some garden compost (about 6% organic matter by dry weight); and (3)  
25 No mulch, where no mulch was added. Mesocosms were seeded with a wildflower mix  
26 that included some *Sedum acre*, and vegetation development was investigated over a  
27 six-year period. Species richness, assemblage character, number of plants able to seed,  
28 and above-ground plant biomass were measured. Drought disturbance was an important  
29 control on plant assemblages in all mulch treatments, but there were significant  
30 treatment response interactions. The more productive Compost treatment was associated  
31 with larger plant coverage and diversity before the occurrence of a sequence of drought  
32 disturbances, but was more strongly negatively affected by the disturbances than the  
33 two less productive treatments. We suggest that this was due to the over-production of

34 plant biomass in the more productive treatment, which made the plants more vulnerable  
35 to the effects of drought disturbance, leading to a kind of ‘boom-bust’ assemblage  
36 dynamic. The ‘ideal’ amount of added organic matter for these green roof systems was  
37 very low, but other types of green roof that have a larger water holding capacity, and/or  
38 more drought resistant plant floras, will likely require more organic matter or fertiliser.  
39 Nonetheless, nutrient-supported productivity in green roof systems should be kept low  
40 in order to avoid boom-bust plant assemblage dynamics. Research into the best way of  
41 engineering green roof habitats should take place over a long enough multi-year time  
42 period to include the effects of temporally infrequent disturbances.

43 **Keywords** brown roof; development mitigation; drought disturbance; productivity  
44 diversity; recycled aggregate; succession

45

46 **Highlights**

- 47 • Drought disturbance was a key factor influencing the green roof plant  
48 assemblages
- 49 • The assemblage response to drought disturbance was mediated by the  
50 productivity of the system
- 51 • Drought disturbance caused more reduction in plant coverage in the higher  
52 productivity systems
- 53 • A good understanding of green roof plant assemblages requires multiple years of  
54 data

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70 **1 Introduction**

71  
72 Green roofs are associated with a wide range of potential environmental and  
73 societal benefits including building insulation and cooling, improved roof materials  
74 longevity, improved well-being, air pollution removal, reduced storm-water runoff,  
75 urban cooling, and habitat provision (Bengtsson 2005, Brenneisen 2006, Mentens et al.  
76 2006, Oberndorfer et al. 2007, Yang et al. 2008, Castleton et al. 2010, Francis and  
77 Lorimer 2011, Rowe 2011, Rumble and Gange 2013, Li et al. 2014, Loder 2014).  
78 Extensive green roofs use relatively thin (<20cm) growth substrates, and do not usually  
79 require the substantial roof reinforcement and maintenance input often associated with  
80 intensive green roofs (Oberndorfer et al. 2007). Therefore, extensive green roofs could  
81 be installed on new-builds or retrofitted to existing buildings across wide areas,  
82 potentially contributing to the alleviation of a range of environmental problems  
83 (Dunnett and Kingsbury 2004, Getter and Rowe 2006). The approaches and materials  
84 used to construct an extensive green roof will however strongly influence its  
85 environmental benefits (Simmons et al. 2008, Bates et al. 2009, Rowe 2011). So, for  
86 example, designing a roof to try and maximise its potential biodiversity benefit might  
87 trade-off against its ability to delay and store storm water (Bates et al. 2009).

88 This research focuses on a type of extensive green roof designed mainly for  
89 habitat creation, which are often called brown or biodiversity roofs (Gedge 2003, Grant  
90 2006, Bates et al. 2013, 2015, Ishimatsu and Ito 2013). Brown roofs are designed to  
91 replicate brownfield habitats, which are also known as derelict, post-industrial, or  
92 wasteland sites. Because of the need for new development and their perceived low  
93 visual appeal, brownfield sites are often lost to development (Harrison and Davies 2002,  
94 Thornton and Nathanail 2005, Dallimer et al. 2011, Sadler et al. 2011, Hofmann et al.

95 2012). However brownfield habitats can be diverse and valuable wildlife habitats  
96 (Gilbert 1989, Small et al. 2003, Woodward et al. 2003), and are now often considered  
97 habitats worthy of conservation (Harrison and Davies 2002, Donovan et al. 2005). The  
98 construction of brown roofs attempts to partially mitigate the loss of brownfield habitat  
99 on the ground by creating brownfield habitats on roofs (Gedge 2003, Grant 2006, Sadler  
100 et al. 2011). Brown roofs can be associated with rare species and diverse wildlife  
101 assemblages (Brenneisen 2006, Kadas 2006, Francis and Lorimer 2011), but  
102 more research is required to properly understand which design approaches and  
103 construction materials best support biodiversity. Vegetation takes time to establish on  
104 green roofs, and many vegetation characteristics vary from season to season due to  
105 periods of water shortage and successional processes, so medium and long-term  
106 investigations of green roofs will likely generate more robust findings than short-term  
107 ones (Köhler 2006, Dunnett et al. 2008, Köhler and Poll 2010, Nagase and Dunnett  
108 2010, Rowe et al. 2012, Bates et al. 2013, 2015, Ishimatsu and Ito 2013, Lundholm et  
109 al. 2014, Thuring and Dunnett 2014).

110         Like other types of green roofs, plant growth on brown roofs is strongly  
111 controlled by characteristics of the growth substrate such as depth, porosity, water  
112 retention, organic matter content, nutrient availability, and soil microbe assemblages  
113 (Dunnett and Kingsbury 2004, Nagase and Dunnett 2011, Olly et al. 2011, Bates et al.  
114 2013, 2015, Graceson et al. 2014b, Molineux et al. 2014). Well-designed brown roofs  
115 share many of the substrate characteristics of brownfield habitat, such as containing  
116 areas of bare ground, diverse substrate types and depths, and replication of brownfield  
117 substrate characteristics (Brenneisen 2006, Kadas 2006, Bates et al. 2009, Madre et al.  
118 2014). Brown roof substrates will therefore often be made up of recycled demolition

119 materials or industrial waste aggregates and include large clasts, which can limit water  
120 holding capacity, making them vulnerable to drought disturbance (Kadas 2006,  
121 Molineux et al. 2009, Bates et al. 2013, 2015).

122         Some theories predict that species diversity has a humped relationship with  
123 productivity, is highest at low to intermediate levels of productivity, and that this varies  
124 with disturbance regime (Grime 1973, Huston 1979, Michalet et al. 2006). However, a  
125 wide variety of productivity - diversity relationships have been predicted and detected,  
126 and there is also particular support for a positive monotonic relationship with  
127 productivity (Abrams 1995, Mittelbach et al. 2001, Gillman and Wright 2006, Adler et  
128 al. 2011). The main controls of plant productivity on green roofs are likely to be water  
129 availability, and nutrient availability from fertiliser or organic matter. During long  
130 periods of water shortage, substantial plant mortality can result, and a low productivity  
131 due to a lack of water can become a drought disturbance. We believe that the interplay  
132 of productivity and disturbance in both brown and green roof systems may well control  
133 plant assemblage dynamics. Responses to productivity and disturbance are species  
134 specific, and consideration of general life history strategies of plants, such as the  
135 Competitive Stress-tolerant Ruderal strategies of Grime (1977) in green roof research  
136 (Lundholm et al. 2014) have proved fruitful.

137         This document describes the effects over a six-year (medium-term) period, of  
138 the experimental addition of two types of mulch on the diversity, character and amount  
139 of brown roof vegetation. This experiment aimed to assess the relative suitability of the  
140 two organic matter treatments for the growth of brownfield-like, wildflower vegetation  
141 on green roof mesocosms. Specifically, our objectives were to test the effect of organic  
142 matter content, time and weather conditions on the: species richness of the forb

143 assemblage, characteristics of that assemblage, ability of plant species to complete their  
144 life-cycle (i.e. to seed), structure of the habitat (e.g. coverage of bare ground and moss),  
145 and distribution of above-ground plant biomass in that assemblage.

## 146 **2 Materials and methods**

### 147 *2.1. Study roof test array*

148           The study site was at The University of Birmingham, UK (52°27'01.54"N,  
149 1°55'43.41"W), which has a temperate maritime climate. The green roof test array was  
150 installed on a flat 5-storey building roof and completed in May 2007. The edge of the  
151 roof had a solid safety parapet of about 1.5m height, but due to the need to distribute  
152 weight through the building support columns, the green roof mesocosms were elevated  
153 about 1m above the roof and so were more directly exposed to wind and air circulation  
154 above *and* below the mesocosms (Figure 1). This meant that the study mesocosms  
155 would likely have different temperature and evapotranspiration regimes than if the  
156 mesocosms had been sited on the roof surface. However, doing the same experiment on  
157 a roof without a solid safety parapet, or on a roof of a different height might produce  
158 similar differences in microclimate., andthe *between-treatment* findings should remain  
159 robust.

160           Each mesocosm was separated by at least a 50cm air gap, meaning that plants  
161 were only able to spread propagules between replicates via wind or bird movement.  
162 Mesocosms were distributed using a stratified-randomised approach. Each column in  
163 Figure 1 represented a strata, and the upper and lower half of the rows represented a  
164 strata. Positions of treatments/controls were allocated randomly, providing no more than  
165 three of each treatment/control were distributed in each strata. This approach equalised,

166 as far as possible, the effects of unwanted environmental variation (e.g. difference in  
167 exposure to wind, and potential bias due to sampling order), but still allowed  
168 randomisation within strata.

## 169 2.2. *Study mesocosms*

170 The study mesocosms were designed to replicate real extensive green roofs, with  
171 drainage and filter layers underlying the different growth media treatments (Figure 2).  
172 The mesocosm containers were built from 2.44x1.22m plywood sheets with 47mm wide  
173 by 150mm deep timber sides, which were water-proofed and root-protected using  
174 polyester reinforced PVC. The ‘egg-box’ drainage board that covered the floor of the  
175 mesocosm container had fines filters at the top and bottom, and fines were prevented  
176 from flowing around the edge of this board with the installation of an IKO filter fleece  
177 around the edge. The mesocosms were on a 2 degree slope and drained in one corner  
178 with a 50mm diameter domestic bath plug-hole.

179 Recycled crushed demolition aggregate (40mm down) was added to  
180 approximately 100mm depth (approximately 110mm in the control, see below). This  
181 aggregate was a material produced from the demolition of buildings that had been  
182 stripped of glass, paint and other contaminants, with further treatment to remove silts  
183 and clays. The material can be highly variable, but in this case was mainly concrete,  
184 pebbles, brick, ceramics, and sand. Tests of leachate chemistry in the first year showed  
185 that leachate pH did not vary between treatment and averaged 8.2 (unpublished results),  
186 producing circumneutral to slightly alkaline growth conditions. The main coarse  
187 crushed concrete component of demolition material, for the size make-up used in the  
188 current study, typically absorbs about 2-4% water (Hansen 1992, Poon and Chan 2006),

189 so despite containing some brick and ceramics, the demolition aggregate had a  
190 relatively limited moisture holding capacity.

191 For the two mulch treatments the substrate was topped with approximately  
192 10mm of mulch. Both treatments and the control were surface seeded with the same,  
193 mostly native, herbaceous seed mix used in the larger scale study of Bates et al. (2013),  
194 at a density of around 1.6g per m<sup>2</sup> (Supplementary Materials 1). The seed mix contained  
195 some *Sedum acre* L. with the aim of facilitating improved neighbouring plant  
196 performance (Butler and Orians 2011) during times of water deficit, although Lundholm  
197 et al. (2014) did not find strong evidence for this effect.

198 Five replicates of two different treatments and a control were used in the study:  
199 (1) Sandy loam, (2) Compost, and (3) No mulch control. ‘Sandy loam’ had a sandy  
200 loam that contained about 3% organic matter (by dry weight) applied as mulch. The  
201 mulch added in the ‘Compost’ treatment was a mix of this same sandy loam and mature  
202 garden compost, which contained around 6% organic matter (by dry weight). The ‘No  
203 mulch’ control had no mulch added. Whole profile substrate samples were taken after  
204 the addition of the mulch for size analyses using dry sieving and loss on ignition at 550  
205 °C for estimation of organic matter content. The organic matter content was 0.90% by  
206 weight (95% confidence interval +/- 0.14, N = 5) for Compost, 0.58% by weight (95%  
207 CI +/- 0.16, N = 5) for Sandy Loam, and 0.29% by weight (95% CI +/- 0.08, N = 5) for  
208 No Mulch. The sediment size distribution of the three treatments varied little (Figure 3).

### 209 2.3. *Vegetation surveys*

210 We used several methods to survey the vegetation: (i) Domin-Krajina cover  
211 abundance (Domin 1928, Krajina 1933) surveys over the whole six-year study period



212 (2007-12), which included measures of (a) total forb richness, and (b) the number of  
213 forb species able to seed each year, (ii) point quadrat surveys, and (iii) biomass analysis  
214 (ii and iii only in the final year of study, 2012).

### 215 *2.3.1. Cover-abundance surveys*

216           Seventeen cover-abundance surveys were carried out over 2007 to 2012. In 2007  
217 and 2008 they were done at a higher temporal frequency to investigate seasonal changes  
218 in vegetation cover. This was then reduced in the following years (2009-12) as the focus  
219 became an analysis of inter-annual trends, with the timing of surveys designed to  
220 coincide with the late spring/early summer peak in plant biomass (May to June) and the  
221 period after most species had flowered and gone to seed (August to September). The  
222 timing of surveys was also dependent on safe weather conditions and building access  
223 (Supplementary Materials 2).

224           Cover-abundance surveys comprised both floristic and biostructural  
225 components. For the floristic surveys all vascular plants, except graminoids, were  
226 identified to species level where possible. The cover-abundance of each taxon in each  
227 mesocosm was estimated by the same person (AJB) using the Domin-Krajina scale  
228 (Supplementary materials 3). This semi-quantitative measure involved the rapid visual  
229 estimation of abundance at low density, or cover at higher density, and although subject  
230 to some degree of error it provided a good summary of the coverage of different taxa  
231 (cf. Smartt et al. 1976). Species richness and details of which taxa had seeded or were  
232 about to seed were also taken. The biostructural components measured were the Domin-  
233 Krajina cover-abundance of bare ground, moss, graminoids and forbs (Supplementary  
234 materials 3).

235 2.3.2. *Point quadrat surveys*

236 Each mesocosm was surveyed twice in 2012 in the same two survey time  
237 windows as the cover-abundance surveys. A 0.5 x 0.5m, 100-point quadrat (9.5% of the  
238 total mesocosm area) was placed away from the edge of each mesocosm in an area  
239 visually judged to be representative of the overall mesocosm. Forb species, moss, bare  
240 ground and graminoids (graminoid cover was low so was not included in analyses) were  
241 recorded if they occurred directly beneath the points of the quadrat. The data gathered in  
242 this way were roughly equivalent to percent cover, however total cover could be over  
243 100 due to layering of the different floristic and biostructural components (e.g. moss  
244 underlying forb species). A comparative discussion of the two methods is included in  
245 Supplementary Materials 4, but generally the two methods showed similar overall  
246 patterns.

247 2.3.3. *Biomass analyses*

248 All above-ground growth of forbs and graminoids situated within the point  
249 quadrats were harvested for analysis of biomass. Coverage of *Sedum acre* was less  
250 spatially variable than other forb taxa, so it was harvested from a representative  
251 0.25x0.25m quadrat from within the larger point quadrat. Taxa were oven dried at 50°C  
252 until repeated weighing showed no further moisture loss (usually 2-4 days). *S. acre* and  
253 *Trifolium arvense* did not lose all their moisture at this temperature, so were dried at  
254 60°C. Biomass was recorded as g/m<sup>2</sup>.

255 2.4. *Weather Data*

256 Precipitation and air temperature data were taken from the Coventry: Coundon  
257 (Latitude = 52.42N, Longitude = 1.53W; ~25km from the study site) UK

258 Meteorological Office MIDAS Land Surface Stations dataset. A weather station was  
259 situated at the roof site from June 2007 to June 2008 inclusive, but the electronics were  
260 destroyed by an electrical storm so no further data were gathered. The Coventry:  
261 Coudon dataset showed good correlation with the roof dataset over this period with a  
262 linear regression  $R^2$  of 0.998 for monthly average temperature, with an intercept of  
263 minus  $0.7^\circ\text{C}$  (i.e. the roof was colder); and with a linear regression  $R^2$  of 0.939 for total  
264 precipitation, with an intercept of 15.6mm (i.e. there was more rainfall on the roof,  
265 probably mostly due to differences in the acoustic [roof] vs tipping bucket [Coventry:  
266 Coudon] mechanism of the rainfall gages). Coventry: Coudon data from the study  
267 period and the four previous years (2003-2012) were used as baseline data for  
268 comparison with weather conditions in the study years. Total monthly precipitation,  
269 average monthly temperature and monthly maximum number of days without rainfall  
270 were calculated (Table 1). Periods of around two weeks or more without rain on green  
271 roofs can cause many species of forbs to reach permanent wilting point (Nagase and  
272 Dunnett 2010, Bates et al. 2013, 2015). These dry periods were identified in the rainfall  
273 data and used to aid the interpretation of the results. The monthly average rainfall for all  
274 of the dry periods identified were in the lower 10<sup>th</sup> percentile of the ten year baseline  
275 data.

## 276 *2.5. Statistical analyses*

277       Effects of the between-subjects factor mulch treatment on the within-subjects  
278 dependent variables richness and number seeded, in each sampling time window were  
279 tested using mixed ANOVAs. Species richness, measured on each sampling occasion,  
280 had 17 within-subject levels. Number seeded, which was measured during each year,  
281 had six within-subject levels. Studentised residuals were calculated for each model and

282 checked for normality using normal Q-Q plots. No strong outliers were detected in the  
283 studentised residuals ( $< \pm 3$  standard deviations). Levene's Tests of Homogeneity of  
284 Variance were used to assess equality of variance between the three levels of mulch  
285 treatment. For each mixed ANOVA there was very little departure from normality, few  
286 outliers, and little indication of heterogeneity of variance. Mauchly's Tests of Sphericity  
287 showed that the variances of the differences were equal, so sphericity assumed degrees  
288 of freedom were used for tests of within-subject effects. For richness and number  
289 seeded, mixed ANOVAs indicated a significant interaction between time and mulch  
290 effect, so simple main effects were determined using univariate and repeated measures  
291 ANOVAs, for each time window and treatment respectively. Tukey HSD post hoc tests  
292 ( $P < 0.05$ ) and pairwise comparisons of means ( $P < 0.05$ ) with Bonferroni confidence  
293 interval adjustments were used to determine which values differed significantly, for  
294 each time window and treatment respectively.

295 Point quadrat counts and measurements of plant biomass ( $\text{g/m}^2$ ) taken in June  
296 and August 2012 from each mesocosm were averaged to give more representative  
297 annual values. Point quadrat counts of forbs (excluding *S. acre*), *S. acre*, moss and bare  
298 ground; total plant biomass ( $\text{g/m}^2$ ); and percent biomass comprised of *S. acre*, were  
299 analysed using One-Way ANOVAs. Normality was checked using normal Q-Q plots.  
300 Levene's tests of homogeneity of variance showed that variance was homogenous. The  
301 ANOVA F-statistic and Tukey post-hoc tests were therefore used to assess overall  
302 significance and multiple comparisons between treatments. All analyses were done in  
303 IBM® SPSS® Statistics Version 20.0.0 following guidance in Laerd Statistics (2013).

### 304 **3 Results**

305 A total of forty five forb taxa were recorded from the mesocosms in all. Of the 25  
306 species in the seed mix, four were never recorded, and a further five species did not seed  
307 in any year (Supplementary materials 5 and 6). The total number of taxa recorded, and  
308 the specific taxa recorded over the whole study period were similar over the three mulch  
309 treatments (Supplementary materials 5). However, Compost supported 43 taxa, Sandy  
310 loam supported 39 taxa and No mulch supported 35 taxa overall.

311 Across all treatments some consistent temporal trends appeared and are  
312 summarized for four species in Supplementary materials 7. There was an initial year-  
313 one flush of annual species, such as *Centaurea cyanus*, *Agrostemma githago*, *Papaver*  
314 *dubium* and *Papaver rhoeas*. Some of these annuals persisted in small numbers (and  
315 often as dwarfed individuals) throughout the study period, particularly after drought die-  
316 back of other species. Perennial species, such as *Prunella vulgaris*, *Leucanthemum*  
317 *vulgare* and *Lotus corniculatus* tended to take longer to establish, usually starting to  
318 seed in years two or three, with coverage increasing during this period (Supplementary  
319 materials 6 and 7). All mesocosms showed declines in coverage of many taxa following  
320 the sequence of dry periods (two-week periods without rainfall) in September 2009,  
321 May 2010 and March-April 2011. However, the severity of this drought response varied  
322 by treatment, with Compost showing the most severe response, and the No mulch  
323 control showing the least response (Supplementary materials 7). The succulent *Sedum*  
324 *acre* showed least response to the dry periods, steadily increasing in coverage  
325 throughout the study period, with coverage only declining as a result of die-back after  
326 summer flowering (Supplementary materials 7).

327 Strong temporal trends occurred in the biostructural data (Supplementary  
328 materials 8). Bare ground coverage remained consistently high in the No mulch control,

329 stabilised at around 40% cover abundance after three years in the Sandy loam treatment,  
330 and continued to decline throughout the study period in the Compost treatment. The  
331 coverage of forbs and moss remained low in the No mulch control throughout the study  
332 period, but forb coverage increased after one year, and moss coverage increased after  
333 two years. Both overall forb and moss coverage generally increased over time in both  
334 the Sandy loam and Compost treatments, but the increase was more consistent and  
335 greater in the latter.

336         A mixed ANOVA of forb richness between treatments and the seventeen survey  
337 time windows showed that there was a significant treatment time interaction (Table 2).  
338 Compost forb richness declined over the first two years, but was higher than in the  
339 Sandy loam treatment and No mulch control until the sequence of dry periods, during  
340 which Compost forb richness was lower than the Sandy loam treatment and No mulch  
341 control (Figure 4). Simple main effect univariate and repeated measures ANOVAs  
342 showed that forb richness varied significantly with both treatment and time (Table 3).  
343 The forb richness was usually significantly higher in the Compost than for Sandy loam  
344 treatment and No mulch control in the first two study years. However, forb richness was  
345 only nearly significantly lower ( $P$  exactly 0.05) than the Sandy loam treatment and No  
346 mulch control during the two dry years (2010 and 2011) (Table 3). Both treatments and  
347 control showed significant variations in forb richness over time, with richness higher in  
348 the first two to three years than during the two dry years. This difference was strongest  
349 in the Compost treatment, and least strong in the Sandy loam treatment (Table 3).  
350 Interestingly the forb richness in the Compost treatment was significantly lower in 2009  
351 before the periods of low rainfall, than at the beginning of the experiment. In all three  
352 mulch treatments, the forb richness never regained the pre dry period levels (Figure 4).

353           A mixed ANOVA of the number of forb taxa able to seed also showed a  
354 significant treatment time interaction (Table 2). The measure declined for the Compost  
355 treatment but remained relatively stable for the Sandy loam treatment and No mulch  
356 control over the first four years (Figure 5). In the first year of study both mulch  
357 treatments and the control had significantly different numbers of forb taxa able to seed,  
358 with Compost higher than Sandy loam, and Sandy loam higher than No mulch. In the  
359 following two years, Compost and Sandy loam both had a significantly higher number  
360 of species able to seed than No mulch (Table 4). The number of species able to seed in  
361 the Compost treatment was significantly higher in the first two years than the following  
362 one to three years. The number of species able to seed in the Sandy loam treatment was  
363 significantly higher in 2009 than 2010. Whereas the number of species able to seed in  
364 the No mulch control was significantly higher in the last year of the study than all other  
365 years (Table 4, Figure 5).

366           One-way ANOVAs of mean point quadrat counts of *S. acre*, other forbs, moss  
367 and bare ground for 2012 showed statistically significant differences for all response  
368 variables (Table 5, Figure 6). Point quadrat counts of other forbs and *S. acre* were both  
369 significantly higher in the Compost treatment than the Sandy loam treatment and No  
370 mulch control. There was also significantly more moss in the Compost and Sandy loam  
371 treatments than the No mulch control. In contrast No mulch had a significantly higher  
372 amount of bare ground than Sandy loam and Compost. Sandy loam also had  
373 significantly more bare ground than the Compost treatment (Table 5, Figure 6).

374           A one-way ANOVA of mean total plant biomass for 2012 showed that the  
375 Compost treatment had significantly more plant biomass than Sandy loam and No  
376 mulch, and that Sandy loam had significantly more plant biomass than No mulch (Table

377 5, Figure 7). The composition of this biomass remained fairly similar between the two  
378 treatments and control, with the percentage of total plant biomass comprised of *S. acre*  
379 not significantly different between the treatments (Table 5, Figure 8).

## 380 **4 Discussion**

### 381 *4.1. Assemblage development and effects of drought*

382 Plant richness on green roofs can decline in the first few years after construction  
383 because of: (1) species unsuitability to the environmental conditions, (2) the  
384 commencement of competitive exclusion of ruderal annual and perennial plants, and (3)  
385 perhaps because of poorly established soil microbial assemblages on new roofs  
386 (Dunnett and Kingsbury 2004, Rowe et al. 2012, Lundholm et al. 2014, cf. Molineaux  
387 et al. 2014). However carefully designed, the physical establishment conditions on  
388 every green roof will vary to some extent due to the weather conditions, roof character  
389 (e.g. height, aspect, shading, exposure), and variations in installation procedure. This is  
390 especially true when using recycled, rather than designed growth substrates, because of  
391 the varying substrate character. Inevitably, some of the seeded species fail to establish  
392 (or germinate), and there is a reduction in the number of species in the first year or two  
393 after construction, as species unsuited to the environmental conditions die out. For  
394 ruderal annual plants to persist over multiple growth seasons they require re-  
395 colonisation or a viable seed bank and sufficient resources (e.g. space, nutrients, water  
396 and light) to allow the germination and establishment of new seedlings each year. The  
397 establishment of biennial and perennial species in the second year means that most  
398 available resources are already sequestered and it is difficult for annuals to do well after  
399 the first year without disturbances creating resource space (e.g. Fenner 1978,



400 McConnaughay and Bazzaz 1987). There was some indication of recovery of some  
401 ruderal annual plants following drought disturbances, but this recovery was weak,  
402 individuals were stunted, and cover-abundance was usually too low to appear in the  
403 datasets.

404         A significant reduction in the forb species richness was observed over the first  
405 three years after construction, but only in the Compost treatment. The first three growth  
406 seasons after construction were not subjected to extended (>14 day) periods without  
407 rain, so it seems unlikely that drought disturbance was the cause of this decline in  
408 richness. Instead it seems probable that this reduction in species richness was to some  
409 extent due to competitive exclusion of some species by more competitive species better  
410 able to take advantage of the higher productivity conditions in the Compost treatments  
411 (cf. Grime 1973, 1977, Huston 1979). The legumes *Lotus corniculatus* and *Trifolium*  
412 *arvense* did particularly well in the first three years after construction in the Compost  
413 treatment, and may have begun to out compete and competitively exclude other species.

414         During the 2010 and 2011 growth seasons (4<sup>th</sup> and 5<sup>th</sup> year of development)  
415 there were extended periods without rainfall that caused mortality and strongly reduced  
416 the cover-abundance of most species of forbs and reduced the species richness in all  
417 treatments. Such drought disturbances are an important controlling factor on plant  
418 assemblages of green roofs, especially in those with a low capacity to retain water  
419 (Monterusso et al. 2005, Nagase and Dunnett 2010, Rowe et al. 2012, Bates et al. 2013,  
420 2015). Coverage of stress tolerant moss and the succulent *S. acre* either remained stable  
421 or continued to increase through this disturbed period in both treatments and the control,  
422 as might be expected given their adaptations for surviving xeric conditions (Dunnett and  
423 Kingsbury 2004, Emilsson and Rolf 2005, Monterusso et al. 2005, Nagase and Dunnett

424 2010, Rowe et al. 2012, Lundholm et al. 2014). More competitive species with few  
425 adaptations to xeric conditions, such as *Lotus corniculatus* and *Leucanthemum vulgare*,  
426 declined markedly. The decline in cover-abundance in these species varied with mulch  
427 treatment, with the strongest declines seen in the Compost treatment and the weakest in  
428 the No mulch control. This pattern of a more marked decline over time in the Compost  
429 treatment, compared to the Sandy loam treatment and No mulch control was also seen  
430 for the overall forb richness, resulting in a significant treatment interaction.

431         Larger size and more leaves can confer a competitive advantage over other  
432 species (e.g. Rösch et al. 1997, Keddy et al. 2002), but too much leaf mass can also  
433 make a plant more vulnerable to drought (Rowe et al. 2006, Butler and Orians 2011,  
434 Nagase and Dunnett 2011). It would seem that the greater productivity in the compost  
435 treatment made these plants more vulnerable to drought disturbance than smaller less  
436 leafy plants in the less fertile treatments. This decline occurred despite the tendency for  
437 substrates with more organic matter content to hold more water (cf. Nagase and Dunnett  
438 2011, Graceson et al. 2014a). The pattern of the most fertile treatments performing the  
439 best initially, but declining more strongly during drought disturbances shown in the  
440 current experiment, was also found in the similar, but larger-scale and observational  
441 study of Bates et al. (2013).

442         There was some evidence to suggest that the plant assemblages on all treatments  
443 had developed a level of resilience to further drought disturbances following the first  
444 dry periods (September 2009 and May 2010 both occurred between the same two  
445 sampling windows). The recovery from the second dry period (March to April 2011)  
446 was more rapid, and a further long dry period in March 2012 (not >14 days) had little  
447 apparent effect. Clearly, each dry period was not directly comparable in terms of water

448 availability because variations in wind, solar radiation and air temperature, and the  
449 timing of dry periods would have affected the resilience of plants to them. However, it  
450 is reasonable to speculate that some of the improved assemblage resilience to the later  
451 dry periods was the result of changes to assemblage character following earlier  
452 disturbances. Less hardy plants and less stress-tolerant plant species with shorter roots,  
453 less drought adaptation or less favourable micro-substrate conditions, may already have  
454 been eradicated from the assemblages by antecedent drought disturbances, with the  
455 remainder therefore more resilient to future drought disturbances. After several years,  
456 green roof plant assemblages tend towards a more stable state, with short-term changes  
457 in response to variations in water availability, but relative stability when viewed over  
458 the long term (Köhler 2006, Köhler and Poll 2010). The less marked response to later  
459 drought disturbances in the current experiment could indicate that the mesocosms were  
460 moving towards a more stable state.

#### 461 *4.2. Implications for the design of green roofs*

462         The ideal amount of added organic matter is to some extent a value judgement  
463 dependant both on the favoured habitat characteristics used, and the broader  
464 environmental aims of green roof installation. Brown (biodiversity) roofs are designed  
465 primarily for the mitigation of brownfield habitat loss, but the secondary broader  
466 environmental aims could vary widely. If, for example, the most important secondary  
467 aim was to maximise carbon sequestration (e.g. Getter et al. 2009), the Compost  
468 treatment would be favoured, because this treatment had more plant biomass over most  
469 of the six years. However if, for example, consistency of aesthetics, avoiding ‘messy’  
470 die-back as far as possible, was important (e.g. Loder 2014) the No mulch, or Sandy

471 loam treatments would perhaps be favoured due to less potential for drought disturbance  
472 die-back.

473           From a habitat perspective, the Compost treatment supported the most forb  
474 species overall, the highest initial forb species richness and the largest overall biomass;  
475 the No mulch control had the highest amount of bare ground and had the most stable  
476 plant assemblages; and the Sandy loam treatment was intermediate in terms of overall  
477 forb species richness, biomass, plant assemblage stability and amount of bare ground.  
478 An assessment that weighted the importance of the different biostructural (e.g. bare  
479 ground) and biodiversity components (e.g. forb richness) of diversity evenly, and  
480 favoured resistance to drought disturbance, would conclude that the intermediate Sandy  
481 loam treatment was the ‘best’ from a habitat perspective.

482           Some theories suggest that under the same disturbance regime, species diversity  
483 should demonstrate a humped relationship, with highest diversity at low to intermediate  
484 levels of productivity (Grime 1973, Huston 1979, Michalet et al. 2006). However, a  
485 range of productivity - diversity relationships have been predicted and observed,  
486 particularly positive monotonic relationships with productivity (Abrams 1995,  
487 Mittelbach et al. 2001, Gillman and Wright 2006, Adler et al. 2011). Despite the  
488 difficulties associated with comparing different types of organic matter and comparing  
489 amounts of organic matter by volume with by weight, it is clear that the current study  
490 had low levels of organic matter in the growth substrates compared to other green roofs  
491 experiments (e.g. Emilsson 2008, Molineux et al. 2009, Nagase and Dunnett 2011,  
492 Graceson et al. 2014b). The current study could therefore be considered to sit at the  
493 lower end of the green roof productivity spectrum, testing the effects of a relatively  
494 small range of productivity for green roof habitats. At the end of the study period, forb

495 richness was very similar in both treatments and the control; however it has been argued  
496 that the overall diversity was highest in the intermediate Sandy loam treatment, so there  
497 is some tentative support for an intermediate level of productivity supporting the highest  
498 diversity. Whatever the shape of the diversity productivity relationship in this system,  
499 increasing productivity to even the low levels associated with the Compost treatment  
500 did not increase diversity. The most suitable amount of added organic matter in these  
501 brown roof systems was low.

502           In one of the two most similar experiments to the current investigation, Nagase  
503 and Dunnett (2011) trialled four different amounts of green waste organic matter (0, 10,  
504 25 and 50% by volume) mixed into a commercial crushed brick based substrate in  
505 grass-herb assemblages under different watering regimes. They found that 10% organic  
506 matter was the best treatment because 0% organic matter supported less biomass than  
507 other treatments, and 25 and 50% organic matter produced too much growth in plants,  
508 so that they were not able to withstand periods of low water availability. Graceson et al.  
509 (2014b) tested crushed tile and crushed brick substrates containing 20 and 30% green  
510 waste (by volume) with a flowering meadow mix that contained some *Sedum* species.  
511 Over the two year experiment, which included dry periods, total biomass and *Sedum*  
512 biomass was higher with more compost, but the forb (not including *Sedum*) biomass  
513 was lower with more compost. It seems probable to us that this was due to excessive  
514 growth in the higher organic matter content treatments, which left some species more  
515 vulnerable to drought disturbance, as was observed by Nagase and Dunnett (2011),  
516 Bates et al. (2013) and in the current study. However it should be noted that Graceson et  
517 al. (2014b) did not come to the same conclusion.

518           In the current study, it has been argued that the ‘best’ plant assemblage in habitat  
519 terms was the intermediate organic matter treatment, but this represented a low amount  
520 of added organic matter. It is possible that Nagase and Dunnett (2011) and Graceson et  
521 al. (2014b) might also have observed more consistent growth of drought resilient non-  
522 *Sedum* forbs had they tested substrates with an even lower amount of organic matter  
523 content. However, the results of the current study have to be put into context; the  
524 recycled demolition aggregate used does not hold as much water as the crushed brick  
525 and crushed tile substrates of Nagase and Dunnett (2011) and Graceson et al. (2014b) so  
526 the frequency of drought disturbances will be higher. A plant in ideal condition on a  
527 green roof has the highest productivity in terms of size, leaf area, and number of leaves  
528 possible whilst still being able to withstand low water availability. This ideal level of  
529 productivity will vary in different green roofs (varying in climate, exposure, substrate  
530 depth, substrate water holding capacity, etc.) depending on the overall availability of  
531 water. So the ideal level of organic matter will be higher in green roofs where more  
532 water is available. Nonetheless, too much organic matter will encourage plants to  
533 become too large, with leaves that are too large and too numerous, making the plant  
534 vulnerable to low water availability.

535           There are many advantages potentially associated with the addition of organic  
536 matter, such as favourably altering the water holding capacity, dry bulk density and air  
537 filled porosity of green roof substrates (Graceson et al. 2014a). However, the addition of  
538 too much organic matter in green roof systems whose vegetation is not entirely  
539 composed of drought resistant flora such as *Sedum*, is likely to create a ‘boom bust’  
540 system where plants grow too well, then die back in periods of dry weather (Nagase and  
541 Dunnett 2011, Bates et al. 2013). So the amount of organic matter added to green roof

542 substrates has to be carefully considered, and the ideal amount will vary with the water  
543 holding capacity of the substrate and the desired species in the plant assemblage.

## 544 **5 Conclusions**

545 This study demonstrates the importance of studying vegetation development on green  
546 roofs in a field-setting for a sufficient multi-year period, in order that the effects of less  
547 frequent drought disturbances are included in the findings. A treatment time interaction  
548 showed that the ‘best’ amount of added organic matter at the beginning of the  
549 experiment was not the ‘best’ over the whole six years of study, due to lower drought  
550 resilience in the higher organic matter treatment. For brown roofs that support good  
551 plant species richness, high availability of various biostructural microhabitats and  
552 resilience to drought disturbances, the ideal amount of added organic matter is very low.  
553 The ideal amount of added organic matter for other types of green roofs is likely to vary  
554 with the water holding capacity of the substrate and the desired plant assemblage.

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565 Atmospheric Data Centre, 2006, downloaded July 2014. Available from:

566 [http://badc.nerc.ac.uk/view/badc.nerc.ac.uk\\_ATOM\\_dataent\\_ukmo-midas](http://badc.nerc.ac.uk/view/badc.nerc.ac.uk_ATOM_dataent_ukmo-midas).

## 567 **References**

- 568
- 569 Abrams, P. A. 1995. Monotonic or Unimodal Diversity Productivity Gradients - What Does  
570 Competition Theory Predict. *Ecology* **76**:2019-2027.
- 571 Adler, P. B., E. W. Seabloom, E. T. Borer, H. Hillebrand, Y. Hautier, A. Hector, W. S. Harpole, L.  
572 R. O'Halloran, J. B. Grace, T. M. Anderson, J. D. Bakker, L. A. Biederman, C. S. Brown, Y.  
573 M. Buckley, L. B. Calabrese, C. J. Chu, E. E. Cleland, S. L. Collins, K. L. Cottingham, M. J.  
574 Crawley, E. I. Damschen, K. F. Davies, N. M. DeCrappeo, P. A. Fay, J. Firn, P. Frater, E. I.  
575 Gasarch, D. S. Gruner, N. Hagenah, J. H. R. Lambers, H. Humphries, V. L. Jin, A. D. Kay,  
576 K. P. Kirkman, J. A. Klein, J. M. H. Knops, K. J. La Pierre, J. G. Lambrinos, W. Li, A. S.  
577 MacDougall, R. L. McCulley, B. A. Melbourne, C. E. Mitchell, J. L. Moore, J. W. Morgan,  
578 B. Mortensen, J. L. Orrock, S. M. Prober, D. A. Pyke, A. C. Risch, M. Schuetz, M. D.  
579 Smith, C. J. Stevens, L. L. Sullivan, G. Wang, P. D. Wragg, J. P. Wright, and L. H. Yang.  
580 2011. Productivity Is a Poor Predictor of Plant Species Richness. *Science* **333**:1750-  
581 1753.
- 582 Bates, A. J., R. Mackay, R. B. Greswell, and J. P. Sadler. 2009. SWITCH in Birmingham, UK:  
583 experimental investigation of the ecological and hydrological performance of extensive  
584 green roofs. *Reviews in Environmental Science and Bio/Technology* **8**:295-300.
- 585 Bates, A. J., J. P. Sadler, R. B. Greswell, and R. Mackay. 2015. Effects of recycled aggregate  
586 growth substrate on green roof vegetation development: A six year experiment.  
587 *Landscape and Urban Planning* **135**:22-31.
- 588 Bates, A. J., J. P. Sadler, and R. Mackay. 2013. Vegetation development over four years on two  
589 green roofs in the UK. *Urban Forestry & Urban Greening* **12**:98-108.
- 590 Bengtsson, L. 2005. Peak flows from thin sedum-moss roof. *Nordic Hydrology* **36**:269-280.
- 591 Brenneisen, S. 2006. Space for urban wildlife: Designing green roofs as habitats in Switzerland.  
592 *Urban Habitats* **4**:27-36.
- 593 Butler, C., and C. M. Orians. 2011. Sedum cools soil and can improve neighboring plant  
594 performance during water deficit on a green roof. *Ecological Engineering* **37**:1796-  
595 1803.
- 596 Castleton, H. F., V. Stovin, S. B. M. Beck, and J. B. Davison. 2010. Green roofs; building energy  
597 savings and the potential for retrofit. *Energy and Buildings* **42**:1582-1591.
- 598 Dallimer, M., Z. Y. Tang, P. R. Bibby, P. Brindley, K. J. Gaston, and Z. G. Davies. 2011. Temporal  
599 changes in greenspace in a highly urbanized region. *Biology Letters* **7**:763-766.
- 600 Domin, K. 1928. The relations of the Tatra mountain vegetation to the edaphic factors of the  
601 habitat: a synecological study. *Acta Botanica Bohemica* **617**:133-164.
- 602 Donovan, R., J. Sadler, and J. Bryson. 2005. Urban biodiversity and sustainable development.  
603 *Engineering Sustainability* **2005**:105-114.
- 604 Dunnett, N., and N. Kingsbury. 2004. *Planting green roofs and living walls*. Timber Press,  
605 Portland, Oregon.
- 606 Dunnett, N., A. Nagase, and A. Hallam. 2008. The dynamics of planted and colonising species  
607 on a green roof over six growing seasons 2001-2006: influence of substrate depth.  
608 *Urban Ecosystems* **11**:373-384.
- 609 Emilsson, T. 2008. Vegetation development on extensive vegetated green roofs: influence of  
610 substrate composition, establishment method and species mix. *Ecological Engineering*  
611 **33**:265-277.



612 Emilsson, T., and K. Rolf. 2005. Comparison of establishment methods for extensive green  
613 roofs in southern Sweden. *Urban Forestry & Urban Greening* **3**:103-111.

614 Fenner, M. 1978. Comparison of the Abilities of Colonizers and Closed-Turf Species to Establish  
615 from Seed in Artificial Swards. *Journal of Ecology* **66**:953-&.

616 Francis, R. A., and J. Lorimer. 2011. Urban reconciliation ecology: The potential of living roofs  
617 and walls. *Journal of Environmental management* **92**:1429-1437.

618 Gedge, D. 2003. '...From rubble to redstarts...'. *in* *Greening Rooftops for Sustainable*  
619 *Communities, Chicago*.

620 Getter, K. L., and D. B. Rowe. 2006. The role of extensive green roofs in sustainable  
621 development. *Hortscience* **41**:1276-1285.

622 Getter, K. L., D. B. Rowe, G. P. Robertson, B. M. Cregg, and J. A. Andresen. 2009. Carbon  
623 Sequestration Potential of Extensive Green Roofs. *Environmental Science &*  
624 *Technology* **43**:7564-7570.

625 Gilbert, O. 1989. *The ecology of urban habitats*. Chapman & Hall, London.

626 Gillman, L. N., and S. D. Wright. 2006. The influence of productivity on the species richness of  
627 plants: A critical assessment. *Ecology* **87**:1234-1243.

628 Graceson, A., M. Hare, N. Hall, and J. Monaghan. 2014a. Use of inorganic substrates and  
629 composted green waste in growing media for green roofs. *Biosystems Engineering*  
630 **124**:1-7.

631 Graceson, A., J. Monaghan, N. Hall, and M. Hare. 2014b. Plant growth responses to different  
632 growing media for green roofs. *Ecological Engineering* **69**:196-200.

633 Grant, G. 2006. Extensive green roofs in London. *Urban Habitats* **4**:51-65.

634 Grime, J. P. 1973. Competitive Exclusion in Herbaceous Vegetation. *Nature* **242**:344-347.

635 Grime, J. P. 1977. Evidence for the existence of three primary strategies in plants and its  
636 relevance to ecological and evolutionary theory. *The American Naturalist* **111**:1169-  
637 1194.

638 Hansen, T. C. 1992. *Recycling of demolished concrete and masonry*. Report of Technical  
639 Committee 37-DRC Demolition and Reuse of Concrete. Chapman and Hall, London.

640 Harrison, C., and G. Davies. 2002. Conserving biodiversity that matters: practitioners'  
641 perspectives on brownfield development and urban nature conservation in London.  
642 *Journal of Environmental management* **65**:95-108.

643 Hofmann, M., J. R. Westermann, I. Kowarik, and E. van der Meer. 2012. Perceptions of parks  
644 and urban derelict land by landscape planners and residents. *Urban Forestry & Urban*  
645 *Greening* **11**:303-312.

646 Huston, M. 1979. General Hypothesis of Species-Diversity. *American Naturalist* **113**:81-101.

647 Ishimatsu, K., and K. Ito. 2013. Brown/biodiverse roofs: a conservation action for threatened  
648 brownfields to support urban biodiversity. *Landscape and Ecological Engineering*  
649 **9**:299-304.

650 Kadas, G. 2006. Rare invertebrates colonizing green roofs in London. *Urban Habitats* **4**:66-86.

651 Keddy, P., K. Nielsen, E. Weiher, and R. Lawson. 2002. Relative competitive performance of  
652 species of terrestrial herbaceous plants. *Journal of Vegetation Science* **13**:5-16.

653 Köhler, M. 2006. Long-term vegetation research on two extensive green roofs in Berlin. *Urban*  
654 *Habitats* **4**:3-26.

655 Köhler, M., and P. H. Poll. 2010. Long-term performance of selected old Berlin greenroofs in  
656 comparison to younger extensive greenroofs in Berlin. *Ecological Engineering* **36**:722-  
657 729.

658 Krajina, V. J. 1933. Die Pflanzengesellschaften des Mlynica-Tales in den Vysoke Tatry (Hohe  
659 Tatra). Mit besonderer Berücksichtigung der ökologischen Verhältnisse. Beihefte zum  
660 *Botanischen Centralblatt* **50**:774-957; **51**:1-224.

661 Laerd Statistics. 2013. Laerd Statistics IBM SPSS guides <https://statistics.laerd.com>.

662 Li, D., E. Bou-Zeid, and M. Oppenheimer. 2014. The effectiveness of cool and green roofs as  
663 urban heat island mitigation strategies. *Environmental Research Letters* **9**.

664 Loder, A. 2014. 'There's a meadow outside my workplace': A phenomenological exploration of  
665 aesthetics and green roofs in Chicago and Toronto. *Landscape and Urban Planning*  
666 **126**:94-106.

667 Lundholm, J., A. Heim, S. Tran, and T. Smith. 2014. Leaf and life history traits predict plant  
668 growth in a green roof ecosystem. *Plos One* **9(6)**: e101395.  
669 doi:10.1371/journal.pone.0101395.

670 Madre, F., A. Vergnes, N. Machon, and P. Clergeau. 2014. Green roofs as habitats for wild plant  
671 species in urban landscapes: First insights from a large-scale sampling. *Landscape and*  
672 *Urban Planning* **122**:100-107.

673 McConnaughay, K. D. M., and F. A. Bazzaz. 1987. The Relationship between Gap Size and  
674 Performance of Several Colonizing Annuals. *Ecology* **68**:411-416.

675 Mentens, J., D. Raes, and M. Hermy. 2006. Green roofs as a tool for solving the rainwater  
676 runoff problem in the urbanized 21st century? *Landscape and Urban Planning* **77**:217-  
677 226.

678 Michalet, R., R. W. Brooker, L. A. Cavieres, Z. Kikvidze, C. J. Lortie, F. I. Pugnaire, A. Valiente-  
679 Banuet, and R. M. Callaway. 2006. Do biotic interactions shape both sides of the  
680 humped-back model of species richness in plant communities? *Ecology Letters* **9**:767-  
681 773.

682 Mittelbach, G. G., C. F. Steiner, S. M. Scheiner, K. L. Gross, H. L. Reynolds, R. B. Waide, M. R.  
683 Willig, S. I. Dodson, and L. Gough. 2001. What is the observed relationship between  
684 species richness and productivity? *Ecology* **82**:2381-2396.

685 Molineux, C. J., C. H. Fentiman, and A. C. Gange. 2009. Characterising alternative recycled  
686 waste materials for use as green roof growing media in the UK. *Ecological Engineering*  
687 **35**:1507-1513.

688 Molineux C. J., S. P. Connop, and A. C. Gange. 2014. Manipulating soil microbial communities in  
689 extensive green roof substrates. *Science of the Total Environment* **493**:632-638.

690 Monterusso, M. A., D. B. Rowe, and C. L. Rugh. 2005. Establishment and persistence of *Sedum*  
691 spp. and native taxa for green roof applications. *Hortscience* **40**:391-396.

692 Nagase, A., and N. Dunnett. 2010. Drought tolerance in different vegetation types for  
693 extensive green roofs: Effects of watering and diversity. *Landscape and Urban Planning*  
694 **97**:318-327.

695 Nagase, A., and N. Dunnett. 2011. The relationship between percentage of organic matter in  
696 substrate and plant growth in extensive green roofs. *Landscape and Urban Planning*  
697 **103**:230-236.

698 Oberndorfer, E., J. Lundholm, B. Bass, R. R. Coffman, H. Doshi, N. Dunnett, S. Gaffin, M. Kohler,  
699 K. K. Y. Liu, and D. B. Rowe. 2007. Green roofs as urban ecosystems: ecological  
700 structures, functions, and services. *Bioscience* **57**:823-833.

701 Olly, L. M., A. J. Bates, J. P. Sadler, and R. Mackay. 2011. An initial experimental assessment of  
702 the influence of substrate depth on floral assemblage for extensive green roofs. *Urban*  
703 *Forestry & Urban Greening* **10**:311-316.

704 Poon, C. S., and D. X. Chan. 2006. Feasible use of recycled concrete aggregates and crushed  
705 clay brick as unbound road sub-base. *Construction and Building Materials* **20**:578-585.

706 Rose F., and C. O'Reilly. 2006. The wild flower key. Frederick Warne

707 Rösch, H., M. W. VanRooyen, and G. K. Theron. 1997. Predicting competitive interactions  
708 between pioneer plant species by using plant traits. *Journal of Vegetation Science*  
709 **8**:489-494.

710 Rowe, D. B. 2011. Green roofs as a means of pollution abatement. *Environmental Pollution*  
711 **159**:2100-2110.

712 Rowe, D. B., K. L. Getter, and A. K. Durhman. 2012. Effect of green roof media depth on  
713 Crassulacean plant succession over seven years. *Landscape and Urban Planning*  
714 **104**:310-319.

715 Rowe, D. B., M. A. Monterusso, and C. L. Rugh. 2006. Assessment of heat-expanded slate and  
716 fertility requirements in green roof substrates. *Horttechnology* **16**:471-477.

717 Rumble, H., and A. C. Gange. 2013. Soil microarthropod community dynamics in extensive  
718 green roofs. *Ecological Engineering* **57**:197-204.

719 Sadler, J., A. Bates, R. Donovan, and S. Bodnar. 2011. Building for biodiversity: accomodating  
720 people and wildlife in cities. Pages 286-297 *in* J. Niemelä, J. H. Breuste, G.  
721 Guntenspergen, N. E. McIntyre, T. Elmqvist, and P. James, editors. *Urban ecology.*  
722 *Patterns, processes and applications.* Oxford University Press, Oxford.

723 Simmons, M. T., B. Gardiner, S. Windhager, and J. Tinsley. 2008. Green roofs are not created  
724 equal: the hydrologic and thermal performance of six different extensive green roofs  
725 and reflective and non-reflective roofs in a sub-tropical climate. *Urban Ecosystems*  
726 **11**:339-348.

727 Small, E. C., J. P. Sadler, and M. G. Telfer. 2003. Carabid beetle assemblages on urban derelict  
728 sites in Birmingham, UK. *Journal of Insect Conservation* **6**:233-246.

729 Smartt, P. F. M., S. E. Meacock, and J. M. Lambert. 1976. Investigations into Properties of  
730 Quantitative Vegetational Data .2. Further Data Type Comparisons. *Journal of Ecology*  
731 **64**:41-78.

732 Thornton, G., and P. Nathanail. 2005. Are incentives for regenerating UK brownfield sites  
733 sustainable? *Land Contamination & Reclamation* **13**:327-338.

734 Thuring, C. E., and N. Dunnett. 2014. Vegetation composition of old extensive green roofs  
735 (from 1980s Germany). *Ecological Processes* **3**:4.

736 Woodward, J. C., M. D. Eyre, and M. L. Luff. 2003. Beetles (Coleoptera) on brownfield sites in  
737 England: an important conservation resource? *Journal of Insect Conservation* **7**:223-  
738 231.

739 Yang, J., Q. Yu, and P. Gong. 2008. Quantifying air pollution removal by green roofs in Chicago.  
740 *Atmospheric Environment* **42**:7266-7273.

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760 **Table 1** Total monthly precipitation (Tot. prec.) and average monthly temperature (Ave.  
761 temp.) during each month, together with baseline average data mean over ten years (10<sup>th</sup>  
762 and 90<sup>th</sup> percentiles in brackets). Numbers in parenthesis for months are the maximum  
763 number of days without rainfall (> two weeks without rainfall in bold).  
764

	Ave. 2003-2012	2007	2008	2009	2010	2011	2012
<b>Tot. prec. (mm)</b>							
Jan.	54.7 (19.4-92.0)	-	93.4	61.5	53.0	43.8	39
Feb.	40.0 (19.1-87.2)	-	25.3	33.0	55.0	57.0	22.8
Mar.	38.7 (6.9-67.2)	-	66.0 (5.5)	25.4 (9.5)	50.2 (11)	<b>5.8 (16.5)</b>	16.8 (14)
Apr.	40.5 (3.4-89.5)	-	68.4 (2)	36.7 (8.5)	38.4 (9.5)	<b>3.2 (17)</b>	91.6 (4)
May	60.7 (25.1-112.4)	-	86.0 (6.5)	44.2 (7)	<b>23.4 (17)</b>	40.2 (7.5)	53.6 (10)
June	70.7 (26.8-162.5)	-	37.4 (8)	53.2 (7.5)	46.4 (9.5)	40.0 (8)	140.2 (2)
July	76.2 (40.2-144.4)	-	85.2 (7.5)	103.0 (4)	40.2 (9.5)	40.6 (11.5)	102.2 (7)
Aug.	77.3 (26.7-141.4)	-	110.0 (7)	42.0 (7.5)	136.0 (3)	56.2 (7.5)	58.2 (7)
Sept.	46.2 (14.1-92.1)	31.8 (13)	94.4 (9.5)	<b>13.2 (24)</b>	57.6 (7.5)	25.2 (4)	-
Oct.	63.3 (31.2-106.8)	42.7 (10)	64.4 (5.5)	30.0 (4)	61.4 (7)	41.8 (9)	-
Nov.	65.6 (34.1-116.6)	50.8 (7.5)	78.4 (3)	106.0 (1)	50.0 (2.5)	45.6 (7)	-
Dec.	54.4 (18.9-103.3)	59.3	46.4	51.6	18.8	61.0	-
<b>Ave. temp. (°C)</b>							
Jan.	4.7 (1.6-7.1)	-	6.6	2.9	1.4	3.8	5.3
Feb.	4.5 (2.7-6.4)	-	5.1	4.0	2.6	6.5	4.0
Mar.	6.6 (4.7-7.9)	-	6.1	6.9	6.0	6.8	8.0
Apr.	9.4 (7.1-11.8)	-	7.7	10.0	9.2	11.9	7.0
May	12.2 (11.3-13.2)	-	13.3	12.2	11.3	12.4	11.9
June	15.4 (15.3-19.9)	-	14.8	15.1	15.9	14.3	13.4
July	16.7 (15.3-19.9)	-	16.6	16.1	17.3	15.7	15.5
Aug.	16.5 (15.2-18.4)	-	16.3	16.6	15.1	15.7	16.4
Sept.	14.4 (12.9-16.5)	14.0	13.2	14.1	13.6	15.1	-
Oct.	10.8 (8.9-13.0)	11.0	9.4	11.2	10.1	12.5	-
Nov.	7.2 (5.2-9.1)	7.0	6.7	8.3	5.0	9.2	-
Dec.	4.3 (0.3-6.3)	4.8	3.7	3.1	0.0	5.7	-

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773 **Table 2** Mixed ANOVA interaction results for species richness and number seeded.  
774 Interactions in both models were significant, so simple main effects were tested  
775 separately.

Mixed ANOVA				
	Interaction	df	F	Sig.
Taxa richness	Time x mulch	32	6.50	<0.001
Number seeded	Time x mulch	10	4.72	<0.001

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796 **Table 3** Simple main effects for the relationship between (A) taxa richness and time  
 797 modelled using univariate ANOVA and (B) taxa richness and mulch treatment using  
 798 repeated measures ANOVA.

(A) Univariate ANOVA	df	F	Sig.	Post hoc P<0.05
Jun07	2	22.92	<0.001	Compost>Sandy loam & No mulch
Jul07	2	18.99	<0.001	Compost>Sandy loam & No mulch
Sept07	2	14.05	0.001	Compost>Sandy loam & No mulch
Oct07	2	14.40	0.001	Compost>Sandy loam & No mulch
Dec07	2	4.13	0.043	Compost>No mulch
Apr08	2	11.20	0.002	Compost>Sandy loam & No mulch
May08	2	4.94	0.003	Compost>Sandy loam & No mulch
Jul08	2	2.28	0.145	-
Sept08	2	1.96	0.183	-
Jun09	2	0.07	0.931	-
Sept09	2	0.94	0.416	-
Jun10	2	3.64	0.058	-
Aug10	2	2.98	0.089	-
May11	2	3.90	0.050	Not significant with Tukey post hoc P = 0.068
Aug11	2	0.37	0.701	-
Jun12	2	0.35	0.714	-
Aug12	2	0.50	0.618	-
(B) Repeated measures ANOVA	df	F	Sig.	Pairwise comparison of means P<0.05
Compost	16	60.84	<0.001	Jun07>Jun09, Sept09, Jun10, Aug10, May11, Aug11, Jun12; Jul07>Jun09, Sept09, Jun10, Aug10, May11, Aug11; Sept07>Jun10, Aug10, May11, Aug11; Oct07>Jun10, Aug10, May11; Dec07>Aug10, May11, Aug11; Apr08>Jun10, Aug10, May11, Aug11; May08>Jun10, Aug10, May11, Aug11; Jul08>Jun10, Aug11; Jun09>Aug10, Aug11
Sandy loam	16	15.90	<0.001	Jul08>Aug10
No mulch	16	20.24	<0.001	Jun07>May11, Aug11; Jul07>Aug11, Aug12; Sept07>Aug12; Oct07>Jun10, Aug11, Jun12; May08>Aug11; Jul08>Jun12; Sept09>Jun10

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807 **Table 4** Simple main effects for the relationship between (A) number seeded and time  
 808 modelled using univariate ANOVA and (B) number seeded and mulch treatment.

(A) Univariate ANOVA	df	F	Sig.	Post hoc P<0.05
2007	2	52.62	<0.001	Compost> Sandy loam & No mulch; Sandy loam> No mulch
2008	2	8.81	0.004	Compost> No mulch; Sandy loam> No mulch
2009	2	11.90	0.001	Compost> No mulch; Sandy loam> No mulch
2010	2	0.86	0.447	-
2011	2	3.20	0.077	-
2012	2	0.21	0.814	-
(B) Repeated measures ANOVA	df	F	Sig.	Pairwise comparison of means P<0.05
Compost	5	28.75	<0.001	2007>2009, 2010, 2011; 2008>2009
Sandy loam	5	3.75	0.015	2009>2010
No mulch	5	15.35	<0.001	2012>2008, 2009, 2010, 2011

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826 **Table 5** One-way ANOVA results of mulch treatment effects for four average quadrat  
827 counts, average total biomass and *Sedum acre* as an average percentage of biomass for  
828 2012.

Measure	df	F	Sig.
Average quadrat count 'other forbs' 2012	2	4.99	0.026
Average quadrat count <i>Sedum acre</i> 2012	2	18.02	<0.001
Average quadrat count moss 2012	2	13.37	0.001
Average quadrat count bare ground 2012	2	88.92	<0.001
Average total biomass 2012	2	36.79	<0.001
Average % <i>S. acre</i> biomass 2012	2	0.23	0.796

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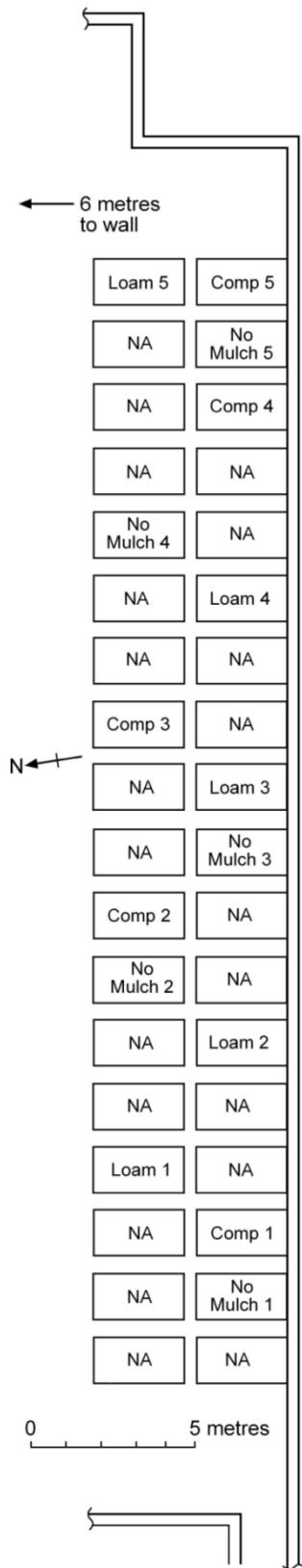
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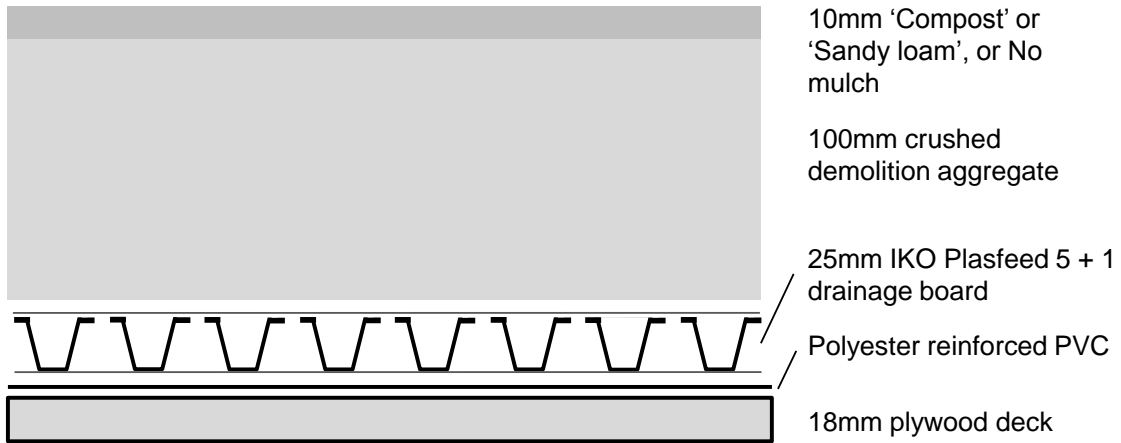
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848 **Figure 1** Stratified-random spatial distribution of the two replicate treatments Compost  
 849 (Comp) and Sandy loam (Loam) and the No mulch control used in the study.



851 **Figure 2** Design of the green roof study mesocosms.



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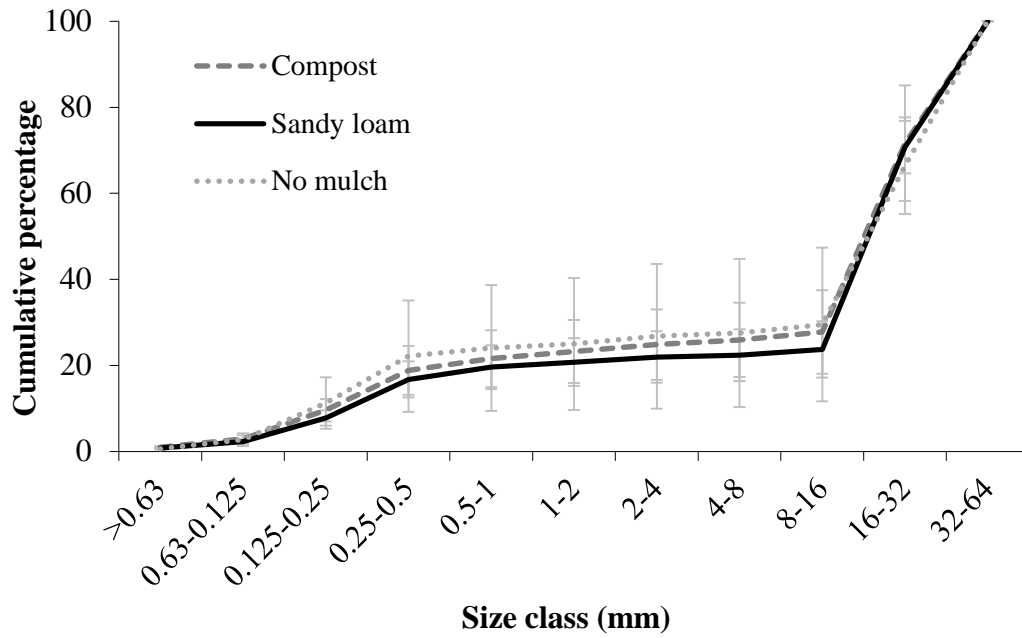
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871 **Figure 3** Mean (n = 5, +/- 95% confidence interval) cumulative percentage Wentworth  
872 scale size distribution of sediments for the three study treatments.



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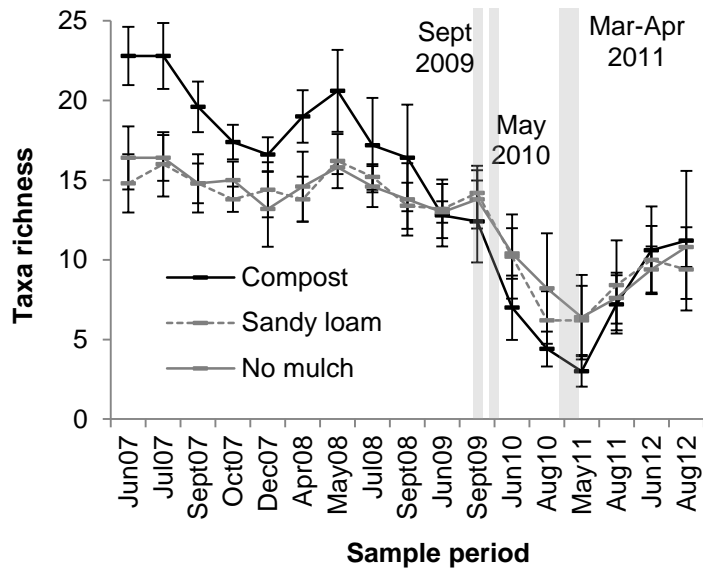
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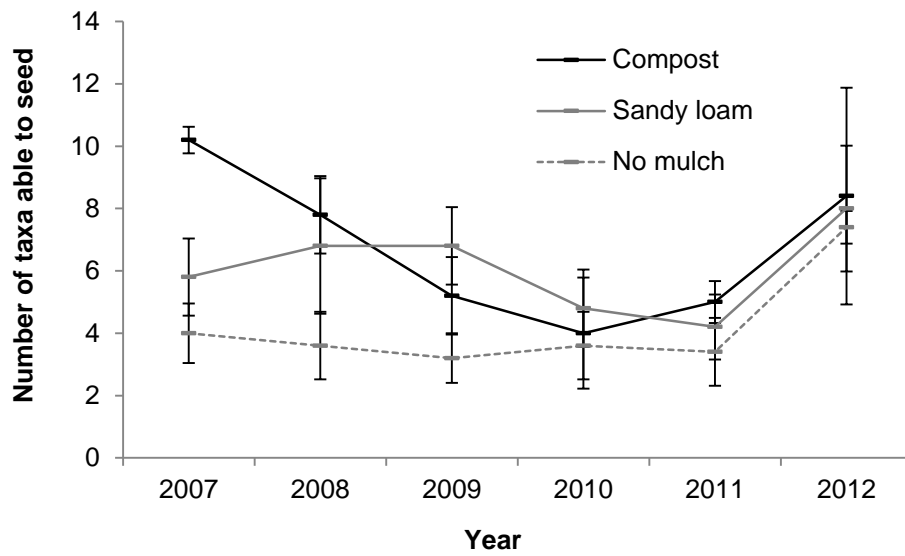
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887 **Figure 4** Variations in mean forb richness with substrate treatment across the study  
 888 period (+/- 95% confidence intervals), the three grey bars roughly mark drought  
 889 disturbances.



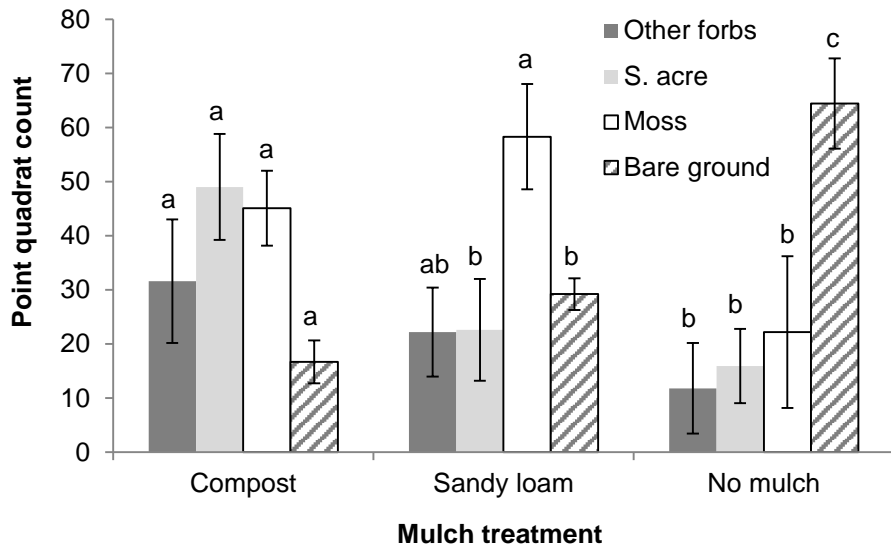
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906 **Figure 5** Variations in mean number of forb taxa seeding with substrate treatment  
907 across the study period (+/- 95% confidence intervals).



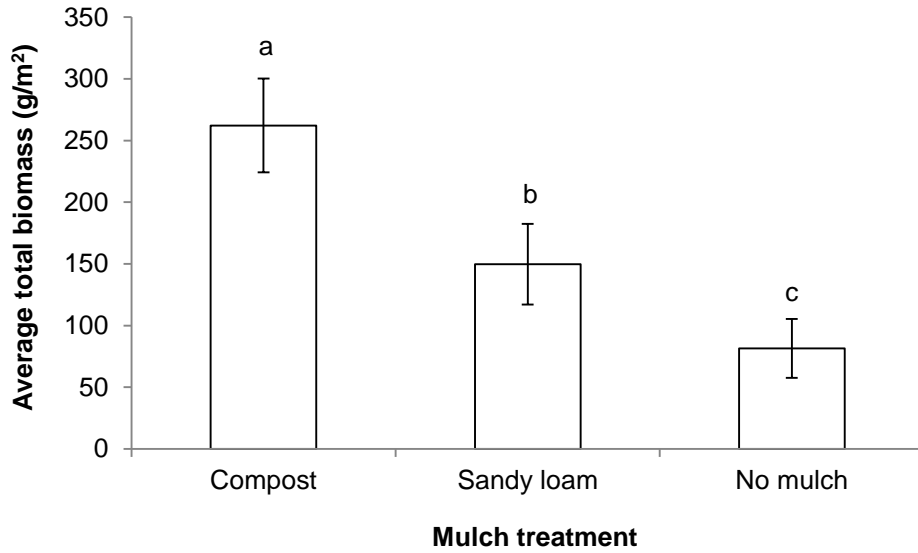
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924 **Figure 6** Variations with mulch treatment in the mean point quadrat count for forbs  
 925 (without *Sedum acre*), *S. acre*, moss, and bare ground for 2012 (+/- 95% confidence  
 926 intervals). Values that do not share letters were found to be significantly (P<0.05)  
 927 different using Tukey HSD multiple comparisons tests.



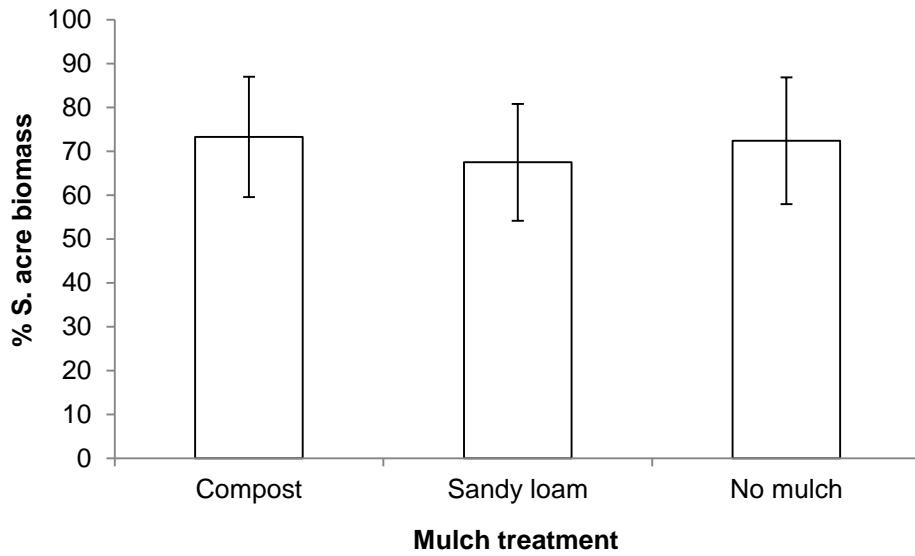
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943 **Figure 7** Variations with mulch treatment in the mean total biomass for 2012 (+/- 95%  
944 confidence intervals). Values that do not share letters were found to be significantly  
945 ( $P < 0.05$ ) different using Tukey post-hoc tests.



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962 **Figure 8** Variations with mulch treatment in the mean biomass of *Sedum acre* as a  
963 percentage of all plant biomass for 2012 (+/- 95% confidence intervals). No significant  
964 ( $P < 0.05$ ) differences were detected.



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981 **Supplementary materials**982 **Supplementary materials 1** Seed mix used in the study.

<b>% by weight</b>	<b>Latin name</b>	<b>Common English name</b>
5.6	<i>Agrimonia eupatoria</i>	Agrimony
5.6	<i>Agrostemma githago</i>	Corn Cockle
4.6	<i>Anthyllis vulneraria</i>	Kidney Vetch
4.6	<i>Centaurea cyanus</i>	Cornflower
4.6	<i>Centaurea nigra</i>	Common Knapweed
2.8	<i>Daucus carota</i>	Wild Carrot
4.6	<i>Echium vulgare</i>	Viper's-bugloss
5.6	<i>Knautia arvensis</i>	Field Scabious
4.6	<i>Leontodon hispidus</i>	Rough Hawkbit
3.7	<i>Leucanthemum vulgare</i>	Oxeye Daisy
0.9	<i>Linaria vulgaris</i>	Common Toadflax
4.6	<i>Lotus corniculatus</i>	Birdsfoot Trefoil
1.9	<i>Origanum vulgare</i>	Wild Marjoram
1.9	<i>Papaver dubium</i>	Long-headed Poppy
3.7	<i>Papaver rhoeas</i>	Common Poppy
4.6	<i>Plantago media</i>	Hoary Plantain
4.6	<i>Prunella vulgaris</i>	Selfheal
4.6	<i>Ranunculus bulbosus</i>	Bulbous Buttercup
4.6	<i>Reseda lutea</i>	Wild Mignonette
5.6	<i>Sanguisorba minor ssp. minor</i>	Salad Burnet
6.3	<i>Sedum acre</i>	Biting Stonecrop
4.6	<i>Silene vulgaris</i>	Bladder Campion
0.9	<i>Trifolium arvense</i>	Hare's-foot Clover
0.9	<i>Verbascum thapsus</i>	Great Mullein
3.7	<i>Viola tricolor</i>	Wild Pansy

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991 **Supplementary materials 2** Survey time windows for vegetation survey and sampling.

992 Survey time windows displayed as follows: code (day/month/year - day/month/year):

993 Jun07 (21/6/07 – 2/7/07), Jul07 (31/7/07 – 1/8/07), Sept07 (4/9/07 – 7/9/07), Oct07

994 (15/10/07 – 18/10/07), Dec07 (11/12/07 – 14/12/07), Apr08 (4/4/08 – 11/4/08), May08

995 (21/5/08 – 2/6/08), Jul08 (16/7/08 – 24/7/08), Sept08 (18/9/08 – 29/9/08), Jun09 (1/6/09

996 – 3/6/09), Sept09 (17/9/09 – 21/9/09), Jun10 (28/6/10 – 30/6/10), Aug10 (27/8/10 –

997 31/8/10), May11 (24/5/11 – 25/5/11), Aug11 (18/8/11 – 19/8/11), Jun12 (6/6/12 –

998 14/6/12) and Aug12 (14/8/12 – 3/9/12).

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1016 **Supplementary materials 3** A detailed description of the Domin-Krajina cover  
1017 abundance method used.

1018 The cover abundance scale used was: + = solitary, 1 = seldom, insignificant cover, 2 =  
1019 <1% cover, 3 = 1-5% cover, 4 = 5-10% cover, 5 = 10-25% cover, 6 = 25-33% cover, 7  
1020 = 33-50% cover, 8 = 50-75% cover, 9 = >75% cover, and 10 = approximately 100%  
1021 cover. Modal values of the replicates of each treatment were used in floristic analyses, if  
1022 there were two cover-abundance classes with the same count, the highest class was  
1023 chosen. For the biostructural analyses, modes of the Domin-Krajina coverage scores  
1024 (abundance scores were ignored, if a draw the highest chosen) across replicates were  
1025 converted to median percent cover abundance (e.g. 7 = 33-50%, converted to 41.5%) for  
1026 better visual representation of the coverage of each biostructural element. It should be  
1027 noted that the total median percent cover abundance would often be greater than 100%  
1028 because the biostructural elements moss, graminoids and forbs can overlap in vertical  
1029 coverage, and two biostructural categories could round-up to more than there was  
1030 actually present (e.g. forbs of approximately 35% coverage, with a median percent  
1031 cover abundance of 41.5%, plus bare ground of approximately 55% coverage, with a  
1032 median percent cover abundance of 62.5% = 103.5% total median percent cover  
1033 abundance).

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1040 **Supplementary materials 4** A comparative discussion of the point quadrat and Domin-  
1041 Krajina cover abundance methods.

1042 Compared to cover-abundance, the point quadrat method tended to produce higher forb  
1043 cover and lower bare ground cover. This was likely because in the mesocosm  
1044 construction process, the raking of the aggregate to fill the mesocosms tended to  
1045 produce a coarser area around the edge of the mesocosms where it was harder for some  
1046 forb species to grow, which consequentially had lower forb cover and higher bare  
1047 ground cover. This coarser area was recorded in cover-abundance surveys, but not in the  
1048 point quadrat surveys.

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1060 **Supplementary materials 5** List of forb species found on the different mulch  
 1061 treatments and control. Seeded species are marked with \*. Annual (A), biennial (B), and  
 1062 perennial information taken from Rose and O'Reilly (2006).

Taxa	Common name	Compost	Sandy loam	No mulch
<b>Papaveraceae</b>				
<i>Papaver dubium</i> L. *	Long-headed Poppy (A)	x	x	x
<i>Papaver rhoeas</i> L. *	Common Poppy (A)	x	x	x
<b>Chenopodiaceae</b>				
<i>Chenopodium album</i> L.	Fat-hen (A)	x	x	x
<i>Chenopodium polyspermum</i> L.	Many-seeded Goosefoot (A)			x
<b>Caryophyllaceae</b>				
<i>Agrostemma githago</i> L.*	Corn Cockle (A)	x	x	x
<i>Silene latifolia</i> Poir.	White Campion (A→P)	x	x	
<i>Silene vulgaris</i> (Moench) Garcke *	Bladder Campion (P)	x	x	x
<i>Arenaria serpyllifolia</i> L.	Thyme-leaved Sandwort (A)	x	x	
<i>Cerastium fontanum</i> Baumg.	Common Mouse-ear (P)	x	x	x
<i>Sagina procumbens</i> L.	Procumbent Pearlwort (P)	x	x	x
<b>Polygonaceae</b>				
<i>Rumex acetosella</i> L.	Sheep's Sorrel (P)	x	x	
<i>Rumex obtusifolius</i> L.	Broad-leaved Dock (P)	x		x
<b>Viola</b>				
<i>Viola tricolor</i> L. *	Wild Pansy (A→P)	x	x	x
<b>Brassicaceae</b>				
<i>Sisymbrium officinale</i> (L.) Scop.	Hedge Mustard (A→B)	x		
<i>Cardamine hirsuta</i> L.	Hairy Bitter-cress (A)	x	x	x
<i>Coronopus didymus</i> (L.)	Lesser Swine-cress (A→B)	x		
<b>Recedaceae</b>				
<i>Reseda lutea</i> L. *	Wild Mignonette (B→P)	x	x	x
<b>Crassulaceae</b>				
<i>Sedum acre</i> L. *	Biting Stonecrop (P)	x	x	x
<b>Rosaceae</b>				
<i>Fragaria vesca</i> L.	Wild Strawberry (P)	x	x	x
<i>Sanguisorba minor</i> Scop *	Salad Burnet (P)	x	x	x
<b>Fabaceae</b>				

<i>Lotus corniculatus</i> L. *	Common Bird's-foot-trefoil (P)	x	x	x
<i>Trifolium arvense</i> L. *	Hare's-foot Clover (A)	x	x	x
<i>Trifolium dubium</i> Sibth.	Lessor Trefoil (A)	x	x	
<i>Trifolium repens</i> L.	White Clover (P)	x	x	x
<b>Onagraceae</b>				
<i>Epilobium ciliatum</i> Raf.	American Willowherb (P)	x	x	x
<b>Apiaceae</b>				
<i>Daucus carota</i> L. *	Wild Carrot (B)	x	x	x
<b>Boraginaceae</b>				
<i>Echium vulgare</i> L. *	Viper's-bugloss (B)	x	x	x
<b>Lamiaceae</b>				
<i>Prunella vulgaris</i> L. *	Selfheal (P)	x	x	x
<i>Origanum vulgare</i> L. *	Wild Marjoram (P)	x	x	x
<b>Plantaginaceae</b>				
<i>Plantago media</i> L. *	Hoary Plantain (P)	x	x	
<b>Scrophulariaceae</b>				
<i>Verbascum thapsus</i> L. *	Great Mullein (B)	x	x	x
<i>Linaria vulgaris</i> Mill. *	Common Toadflax (P)	x	x	x
<i>Veronica persica</i> Poir.	Common Field-speedwell (A)	x	x	x
<b>Asteraceae</b>				
<i>Centaurea cyanus</i> L. *	Cornflower (A)	x	x	x
<i>Centaurea nigra</i> L. *	Common Knapweed (P)	x	x	x
<i>Leontodon hispidus</i> L. *	Rough Hawkbit (P)	x	x	x
<i>Sonchus asper</i> (L.) Hill	Prickly Sowthistle (A)	x	x	x
<i>Sonchus oleraceus</i> L.	Smooth Sowthistle (A)	x		
<i>Mycelis muralis</i> (L.) Dumort.	Wall Lettuce (P)		x	
<i>Taraxacum</i> agg.	Dandelions (P)	x	x	x
<i>Conyza</i> spp.	Fleabane (A)	x	x	x
<i>Leucanthemum vulgare</i> Lam. *	Oxeye Daisy (P)	x	x	x
<i>Matricaria recutita</i> L.	Scented Mayweed (A→P)	x	x	x
<i>Matricaria discoidea</i> DC.	Pineappleweed (A)	x		
<i>Senecio vulgaris</i> L.	Groundsel (A)	x	x	x

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1066 **Supplementary materials 6** Forb species able to seed by year ('10' = 2010 for  
 1067 example) on the different mulch treatments.

Taxa	Compost	Sandy loam	No mulch
<i>Agrostemma githago</i>	07, 08	07, 08	08
<i>Arenaria serpyllifolia</i>	12	11	
<i>Cardamine hirsuta</i>	07	08	
<i>Centaurea cyanus</i>	07, 11, 12	07, 08, 11, 12	07, 12
<i>Centaurea nigra</i>		12	
<i>Cerastium fontanum</i>	07, 08, 09, 12	07, 08, 09, 12	08, 10, 11, 12
<i>Chenopodium album</i>	07	07	07
<i>Chenopodium polyspermum</i>			07
<i>Conyza</i> spp.	11, 12	11, 12	11, 12
<i>Coronopus didymus</i>			
<i>Daucus carota</i>		08, 09, 10, 12	
<i>Echium vulgare</i>			
<i>Epilobium ciliatum</i>	08, 12		
<i>Fragaria vesca</i>			
<i>Leontodon hispidus</i>			12
<i>Leucanthemum vulgare</i>	08, 10, 12	08, 09, 10, 11, 12	09, 10, 11, 12
<i>Linaria vulgaris</i>		08, 09, 12	
<i>Lotus corniculatus</i>	08, 09, 10, 12	08, 09, 10, 11, 12	09, 10, 11, 12
<i>Matricaria discoidea</i>	07		
<i>Matricaria recutita</i>	07, 12	07	07
<i>Mycelis muralis</i>			
<i>Origanum vulgare</i>			
<i>Papaver dubium</i>	07	07	07
<i>Papaver rhoeas</i>	07	07	07
<i>Plantago media</i>			
<i>Prunella vulgaris</i>	08, 09, 11	08, 09, 12	09, 11, 12
<i>Reseda lutea</i>			
<i>Rumex acetosella</i>		08	
<i>Rumex obtusifolius</i>			
<i>Sagina procumbens</i>	07, 08, 09, 10, 11, 12	08, 09, 12	09, 10
<i>Sanguisorba minor</i>	09, 10	09, 10	12
<i>Sedum acre</i>	08, 09, 10, 11, 12	08, 09, 10, 11, 12	08, 09, 10, 11, 12
<i>Senecio vulgaris</i>	07, 08, 11, 12	07, 08, 11, 12	08, 11, 12
<i>Silene latifolia</i>	10		
<i>Silene vulgaris</i>	09	07, 08, 09, 10, 11, 12	07, 08, 09, 10, 12
<i>Sisymbrium officinale</i>	08		
<i>Sonchus asper</i>	11, 12	11	
<i>Sonchus oleraceus</i>			
<i>Taraxacum</i> agg.	12		
<i>Trifolium arvense</i>	08, 09, 10, 11, 12	08, 09, 10, 11, 12	11, 12

<i>Trifolium dubium</i>	08, 09		
<i>Trifolium repens</i>	09, 10, 12	10	
<i>Verbascum thapsus</i>			
<i>Veronica persica</i>	07, 08, 11, 12		
<i>Viola tricolor</i>	07, 08, 12	07, 08, 12	08, 12

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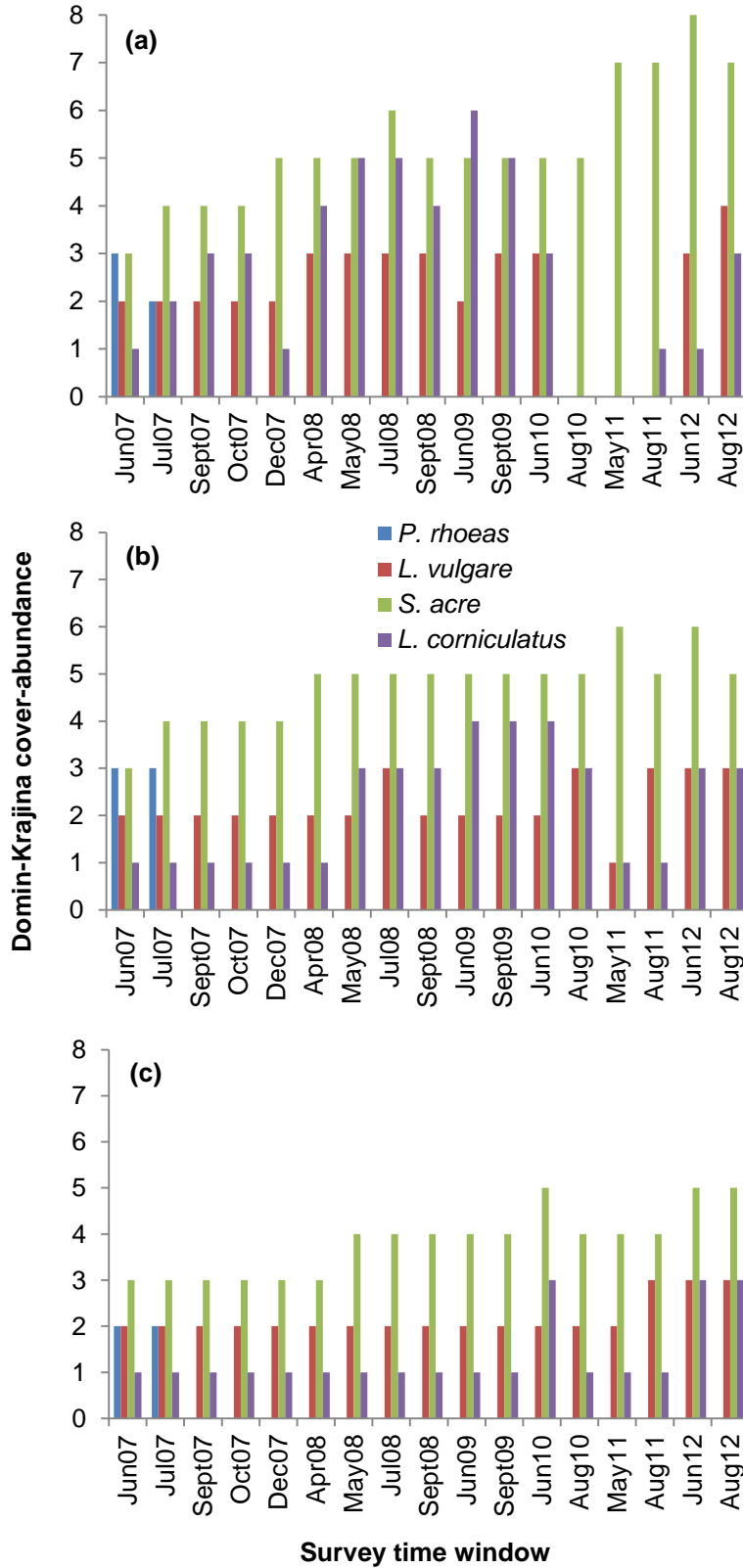
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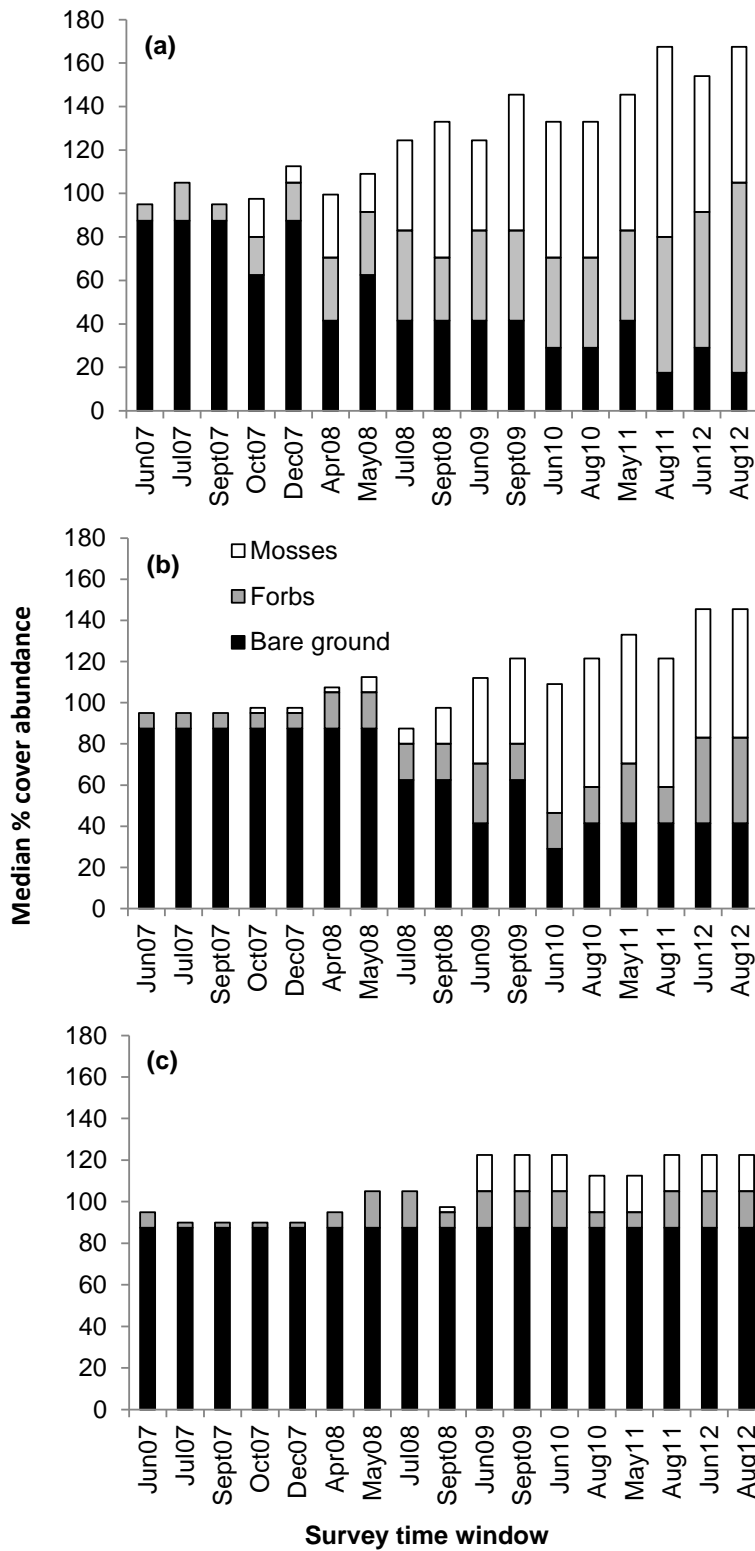
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1090 **Supplementary materials 7** Change in the modal Domin-Krajina cover-abundance of  
 1091 four seeded species of forb over time for the three mulch treatments: (a) Compost, (b)  
 1092 Sandy loam, and (c) No mulch.



1094 **Supplementary materials 8** Change in the modal median percent cover abundance of  
 1095 moss, forbs and bare ground over time: (a) Compost, (b) Sandy loam, and (c) No mulch.



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