

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 m² (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/m².

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°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 10th 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 (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 (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 (4th and 5th 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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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 (10th
762 and 90th 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
Tot. prec. (mm)							
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)	5.8 (16.5)	16.8 (14)
Apr.	40.5 (3.4-89.5)	-	68.4 (2)	36.7 (8.5)	38.4 (9.5)	3.2 (17)	91.6 (4)
May	60.7 (25.1-112.4)	-	86.0 (6.5)	44.2 (7)	23.4 (17)	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)	13.2 (24)	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	-
Ave. temp. (°C)							
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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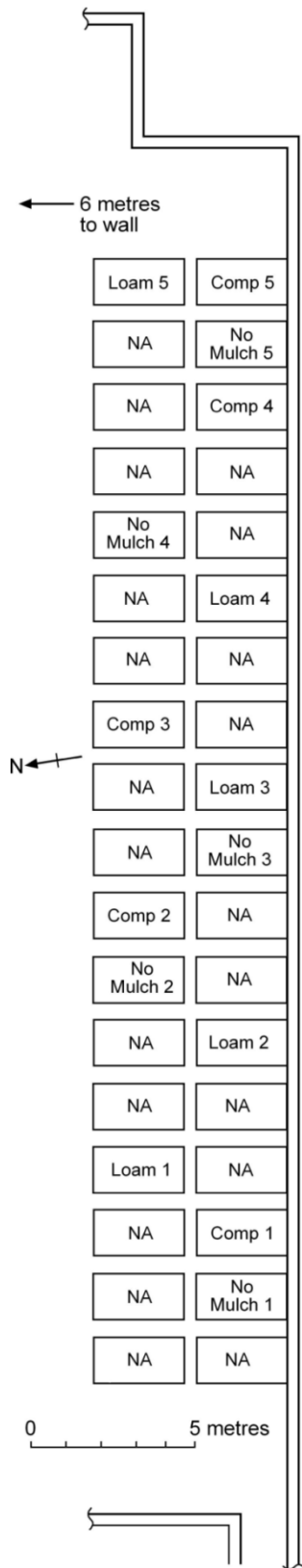
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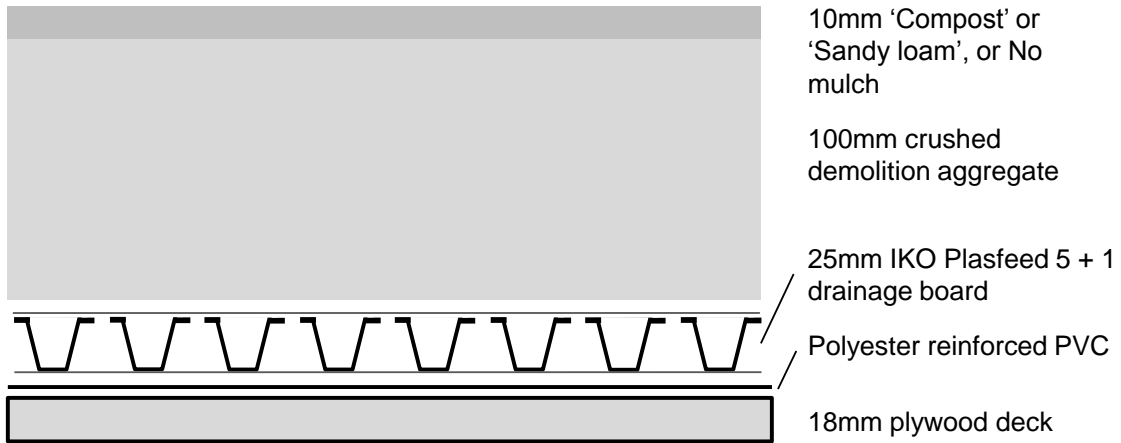
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848 **Figure 1** Stratified-random spatial distribution of the two replicate treatments Compost
 849 (Comp) and Sandy loam (Loam) and the No mulch control used in the study.



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



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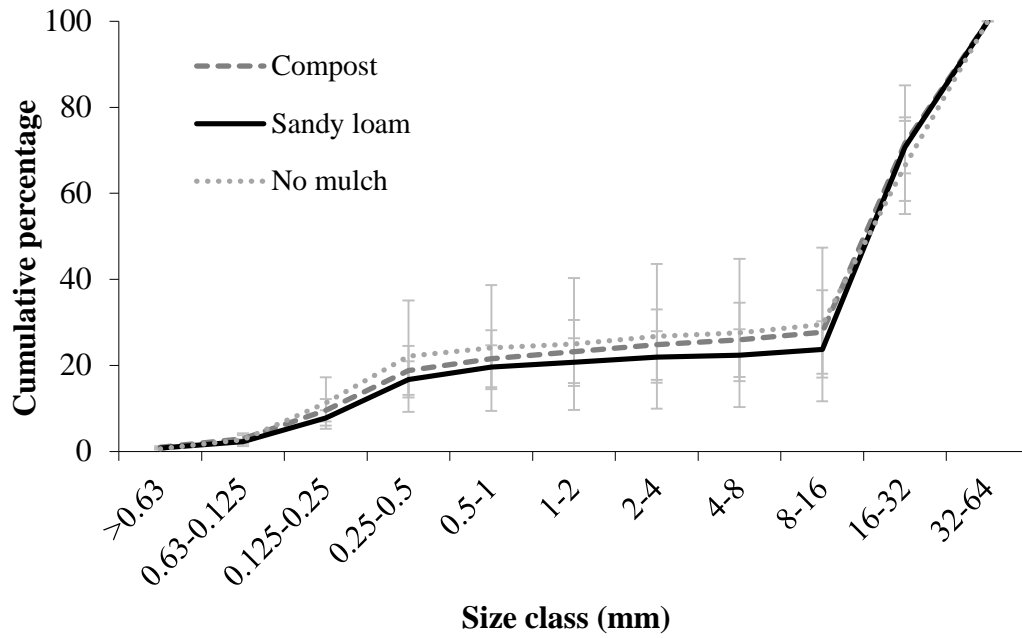
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871 **Figure 3** Mean (n = 5, +/- 95% confidence interval) cumulative percentage Wentworth
872 scale size distribution of sediments for the three study treatments.



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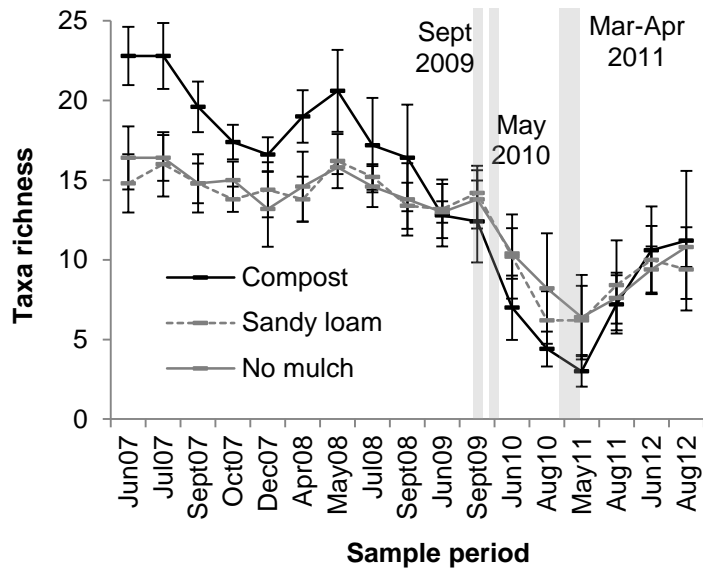
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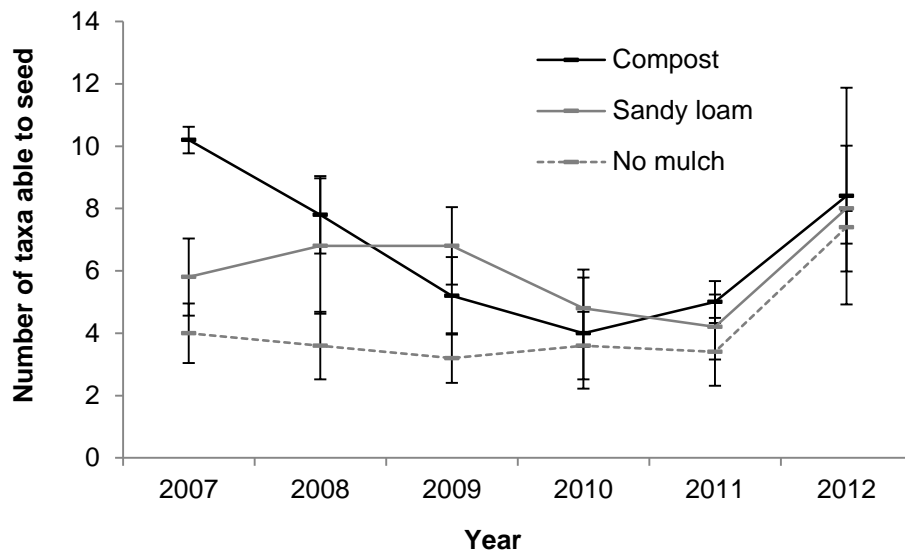
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887 **Figure 4** Variations in mean forb richness with substrate treatment across the study
 888 period (+/- 95% confidence intervals), the three grey bars roughly mark drought
 889 disturbances.



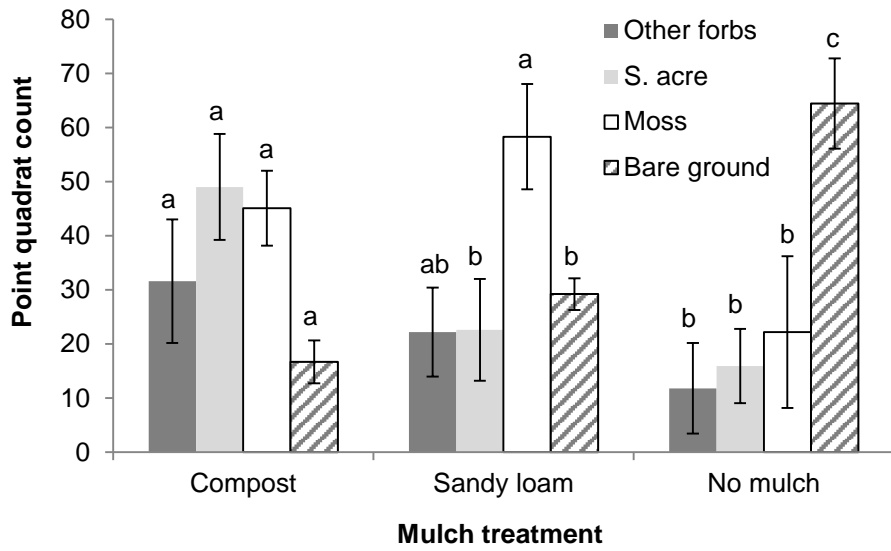
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906 **Figure 5** Variations in mean number of forb taxa seeding with substrate treatment
907 across the study period (+/- 95% confidence intervals).



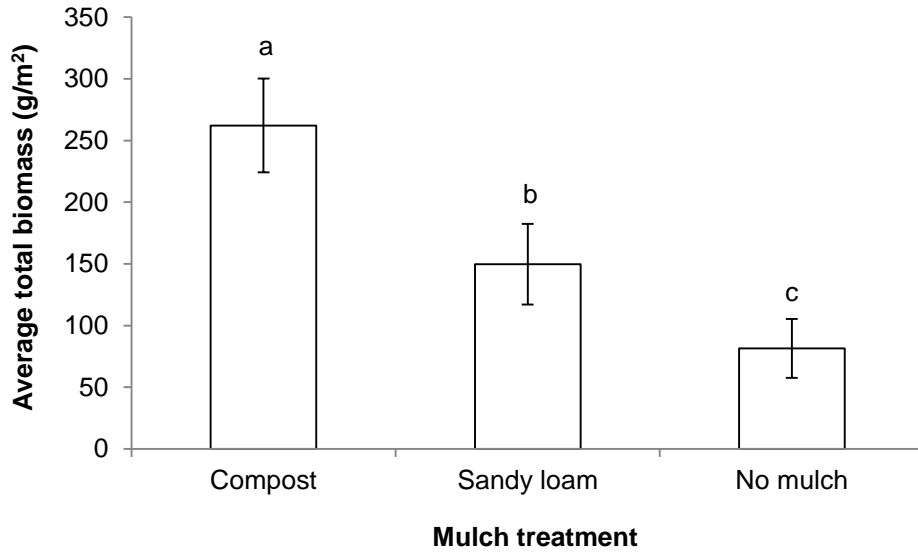
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924 **Figure 6** Variations with mulch treatment in the mean point quadrat count for forbs
 925 (without *Sedum acre*), *S. acre*, moss, and bare ground for 2012 (+/- 95% confidence
 926 intervals). Values that do not share letters were found to be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



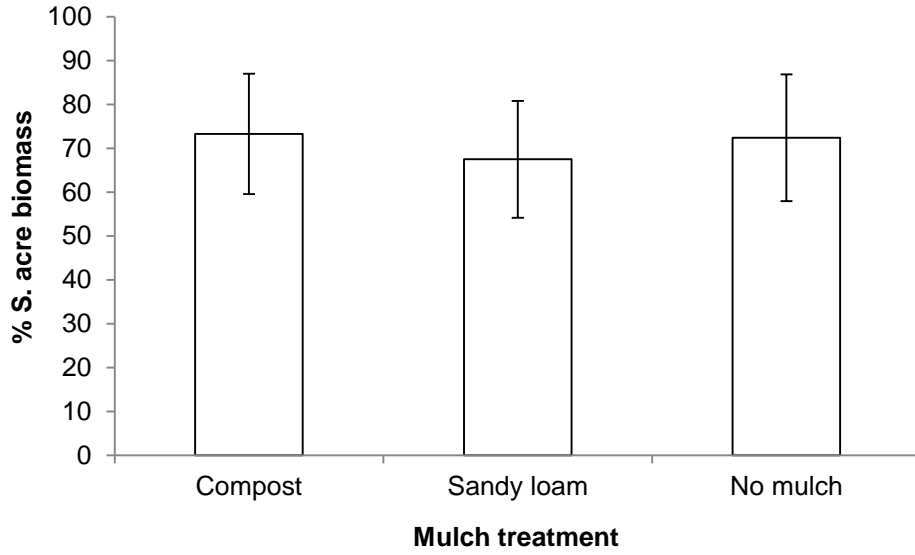
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943 **Figure 7** Variations with mulch treatment in the mean total biomass for 2012 (+/- 95%
944 confidence intervals). Values that do not share letters were found to be significantly
945 ($P < 0.05$) different using Tukey post-hoc tests.



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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.

% by weight	Latin name	Common English name
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</i> ssp. <i>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
Papaveraceae				
<i>Papaver dubium</i> L. *	Long-headed Poppy (A)	x	x	x
<i>Papaver rhoeas</i> L. *	Common Poppy (A)	x	x	x
Chenopodiaceae				
<i>Chenopodium album</i> L.	Fat-hen (A)	x	x	x
<i>Chenopodium polyspermum</i> L.	Many-seeded Goosefoot (A)			x
Caryophyllaceae				
<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
Polygonaceae				
<i>Rumex acetosella</i> L.	Sheep's Sorrel (P)	x	x	
<i>Rumex obtusifolius</i> L.	Broad-leaved Dock (P)	x		x
Viola				
<i>Viola tricolor</i> L. *	Wild Pansy (A→P)	x	x	x
Brassicaceae				
<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		
Recedaceae				
<i>Reseda lutea</i> L. *	Wild Mignonette (B→P)	x	x	x
Crassulaceae				
<i>Sedum acre</i> L. *	Biting Stonecrop (P)	x	x	x
Rosaceae				
<i>Fragaria vesca</i> L.	Wild Strawberry (P)	x	x	x
<i>Sanguisorba minor</i> Scop *	Salad Burnet (P)	x	x	x
Fabaceae				

<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
Onagraceae				
<i>Epilobium ciliatum</i> Raf.	American Willowherb (P)	x	x	x
Apiaceae				
<i>Daucus carota</i> L. *	Wild Carrot (B)	x	x	x
Boraginaceae				
<i>Echium vulgare</i> L. *	Viper's-bugloss (B)	x	x	x
Lamiaceae				
<i>Prunella vulgaris</i> L. *	Selfheal (P)	x	x	x
<i>Origanum vulgare</i> L. *	Wild Marjorum (P)	x	x	x
Plantaginaceae				
<i>Plantago media</i> L. *	Hoary Plantain (P)	x	x	
Scrophulariaceae				
<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
Asteraceae				
<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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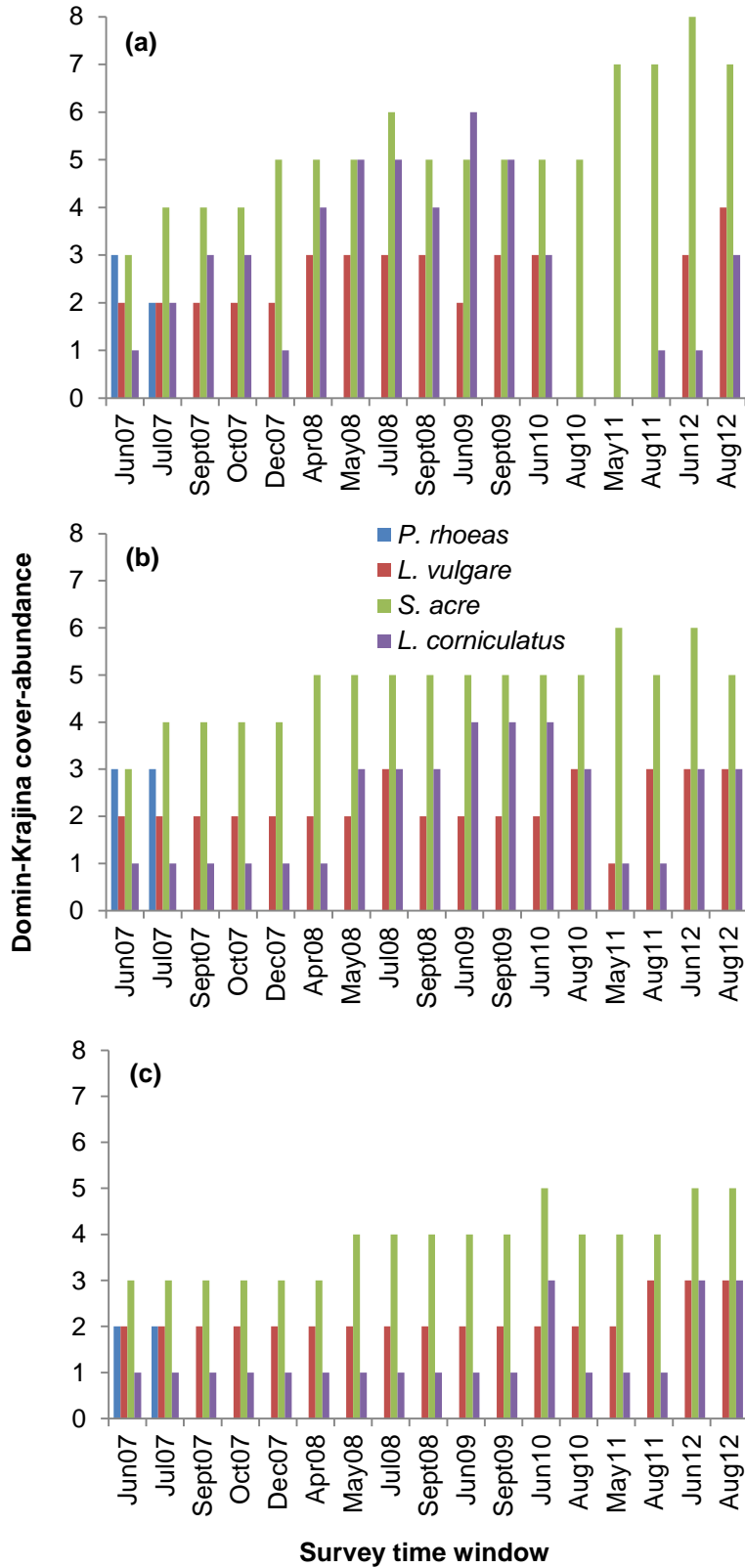
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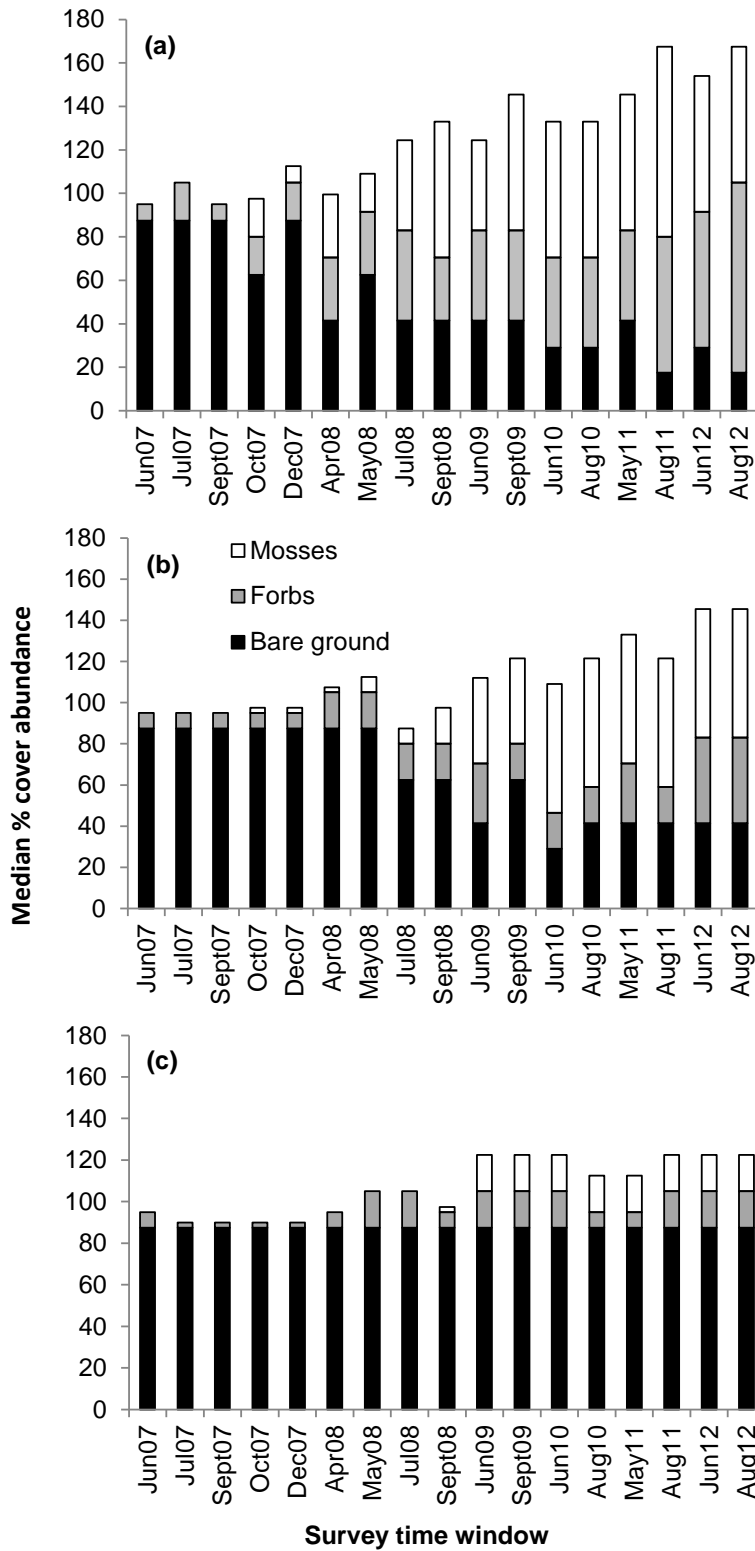
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1090 **Supplementary materials 7** Change in the modal Domin-Krajina cover-abundance of
 1091 four seeded species of forb over time for the three mulch treatments: (a) Compost, (b)
 1092 Sandy loam, and (c) No mulch.



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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