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

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Abstract

Green roofs can potentially be used to tackle a variety of environmental problems, and can be used as development mitigation for the loss of ground-based habitats. Brown (biodiversity) roofs are a type of green roof designed to imitate brownfield habitat, but the best way of engineering these habitats requires more research. We tested the effects of altering organic matter content on the development of vegetation assemblages of experimental brown (biodiversity) roof mesocosms. Three mulch treatments were tested: (1) Sandy loam, where 10mm of sandy loam mulch (about 3% organic matter by dry weight) was added to 100mm of recycled aggregate; (2) Compost, where the mulch also contained some garden compost (about 6% organic matter by dry weight); and (3) No mulch, where no mulch was added. Mesocosms were seeded with a wildflower mix that included some *Sedum acre*, and vegetation development was investigated over a six-year period. Species richness, assemblage character, number of plants able to seed, and above-ground plant biomass were measured. Drought disturbance was an important control on plant assemblages in all mulch treatments, but there were significant treatment response interactions. The more productive Compost treatment was associated with larger plant coverage and diversity before the occurrence of a sequence of drought disturbances, but was more strongly negatively affected by the disturbances than the two less productive treatments. We suggest that this was due to the over-production of plant biomass in the more productive treatment, which made the plants more vulnerable to the effects of drought disturbance, leading to a kind of ‘boom-bust’ assemblage dynamic. The ‘ideal’ amount of added organic matter for these green roof systems was very low, but other types of green roof that have a larger water holding capacity, and/or more drought resistant plant floras, will likely require more organic matter or fertiliser. Nonetheless, nutrient-supported productivity in green roof systems should be kept low in order to avoid boom-bust plant assemblage dynamics. Research into the best way of engineering green roof habitats should take place over a long enough multi-year time period to include the effects of temporally infrequent disturbances.

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

Highlights

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

1 Introduction

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

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

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

Like other types of green roofs, plant growth on brown roofs is strongly controlled by characteristics of the growth substrate such as depth, porosity, water retention, organic matter content, nutrient availability, and soil microbe assemblages (Dunnett and Kingsbury 2004, Nagase and Dunnett 2011, Olly et al. 2011, Bates et al. 2013, 2015, Graceson et al. 2014b, Molineux et al. 2014). Well-designed brown roofs share many of the substrate characteristics of brownfield habitat, such as containing areas of bare ground, diverse substrate types and depths, and replication of brownfield substrate characteristics (Brenneisen 2006, Kadas 2006, Bates et al. 2009, Madre et al. 2014). Brown roof substrates will therefore often be made up of recycled demolition materials or industrial waste aggregates and include large clasts, which can limit water holding capacity, making them vulnerable to drought disturbance (Kadas 2006, Molineux et al. 2009, Bates et al. 2013, 2015).

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

This document describes the effects over a six-year (medium-term) period, of the experimental addition of two types of mulch on the diversity, character and amount of brown roof vegetation. This experiment aimed to assess the relative suitability of the two organic matter treatments for the growth of brownfield-like, wildflower vegetation on green roof mesocosms. Specifically, our objectives were to test the effect of organic matter content, time and weather conditions on the: species richness of the forb assemblage, characteristics of that assemblage, ability of plant species to complete their life-cycle (i.e. to seed), structure of the habitat (e.g. coverage of bare ground and moss), and distribution of above-ground plant biomass in that assemblage.

2 Materials and methods

2.1. Study roof test array

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

Each mesocosm was separated by at least a 50cm air gap, meaning that plants were only able to spread propagules between replicates via wind or bird movement. Mesocosms were distributed using a stratified-randomised approach. Each column in Figure 1 represented a strata, and the upper and lower half of the rows represented a strata. Positions of treatments/controls were allocated randomly, providing no more than three of each treatment/control were distributed in each strata. This approach equalised, as far as possible, the effects of unwanted environmental variation (e.g. difference in exposure to wind, and potential bias due to sampling order), but still allowed randomisation within strata.

2.2. Study mesocosms

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

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

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

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

2.3. Vegetation surveys

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

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

2.3.1. Cover-abundance surveys

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

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

2.3.2. Point quadrat surveys

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

2.3.3. Biomass analyses

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

2.4. Weather Data

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

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

2.5. Statistical analyses

Effects of the between-subjects factor mulch treatment on the within-subjects dependent variables richness and number seeded, in each sampling time window were tested using mixed ANOVAs. Species richness, measured on each sampling occasion, had 17 within-subject levels. Number seeded, which was measured during each year, had six within-subject levels. Studentised residuals were calculated for each model and checked for normality using normal Q-Q plots. No strong outliers were detected in the studentised residuals (<+/- 3 standard deviations). Levene's Tests of Homogeneity of Variance were used to assess equality of variance between the three levels of mulch treatment. For each mixed ANOVA there was very little departure from normality, few outliers, and little indication of heterogeneity of variance. Mauchly's Tests of Sphericity showed that the variances of the differences were equal, so sphericity assumed degrees of freedom were used for tests of within-subject effects. For richness and number seeded, mixed ANOVAs indicated a significant interaction between time and mulch effect, so simple main effects were determined using univariate and repeated measures ANOVAs, for each time window and treatment respectively. Tukey HSD post hoc tests ($P<0.05$) and pairwise comparisons of means ($P<0.05$) with Bonferroni confidence interval adjustments were used to determine which values differed significantly, for each time window and treatment respectively.

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

3 Results

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

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

Strong temporal trends occurred in the biostructural data (Supplementary materials 8). Bare ground coverage remained consistently high in the No mulch control, stabilised at around 40% cover abundance after three years in the Sandy loam treatment, and continued to decline throughout the study period in the Compost treatment. The coverage of forbs and moss remained low in the No mulch controlthroughout the study period, but forb coverage increased after one year, and moss coverage increased after two years. Both overall forb and moss coverage generally increased over time in both the Sandy loam and Compost treatments, but the increase was more consistent and greater in the latter.

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

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

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

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

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

4 Discussion

4.1. Assemblage development and effects of drought

Plant richness on green roofs can decline in the first few years after construction because of: (1) species unsuitability to the environmental conditions, (2) the commencement of competitive exclusion of ruderal annual and perennial plants, and (3) perhaps because of poorly established soil microbial assemblages on new roofs (Dunnett and Kingsbury 2004, Rowe et al. 2012, Lundholm et al. 2014, cf. Molineaux et al. 2014). However carefully designed, the physical establishment conditions on every green roof will vary to some extent due to the weather conditions, roof character (e.g. height, aspect, shading, exposure), and variations in installation procedure. This is especially true when using recycled, rather than designed growth substrates, because of the varying substrate character. Inevitably, some of the seeded species fail to establish (or germinate), and there is a reduction in the number of species in the first year or two after construction, as species unsuited to the environmental conditions die out. For ruderal annual plants to persist over multiple growth seasons they require re-colonisation or a viable seed bank and sufficient resources (e.g. space, nutrients, water and light) to allow the germination and establishment of new seedlings each year. The establishment of biennial and perennial species in the second year means that most available resources are already sequestered and it is difficult for annuals to do well after the first year without disturbances creating resource space (e.g. Fenner 1978, Mcconnaughay and Bazzaz 1987). There was some indication of recovery of some ruderal annual plants following drought disturbances, but this recovery was weak, individuals were stunted, and cover-abundance was usually too low to appear in the datasets.

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

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

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

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

There was some evidence to suggest that the plant assemblages on all treatments had developed a level of resilience to further drought disturbances following the first dry periods (September 2009 and May 2010 both occurred between the same two sampling windows). The recovery from the second dry period (March to April 2011) was more rapid, and a further long dry period in March 2012 (not >14 days) had little apparent effect. Clearly, each dry period was not directly comparable in terms of water availability because variations in wind, solar radiation and air temperature, and the timing of dry periods would have affected the resilience of plants to them. However, it is reasonable to speculate that some of the improved assemblage resilience to the later dry periods was the result of changes to assemblage character following earlier disturbances. Less hardy plants and less stress-tolerant plant species with shorter roots, less drought adaptation or less favourable micro-substrate conditions, may already have been eradicated from the assemblages by antecedent drought disturbances, with the remainder therefore more resilient to future drought disturbances. After several years, green roof plant assemblages tend towards a more stable state, with short-term changes in response to variations in water availability, but relative stability when viewed over the long term (Köhler 2006, Köhler and Poll 2010). The less marked response to later drought disturbances in the current experiment could indicate that the mesocosms were moving towards a more stable state.

4.2. Implications for the design of green roofs

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

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

Some theories suggest that under the same disturbance regime, species diversity should demonstrate a humped relationship, with highest diversity at low to intermediate levels of productivity (Grime 1973, Huston 1979, Michalet et al. 2006). However, a range of productivity - diversity relationships have been predicted and observed, particularly positive monotonic relationships with productivity (Abrams 1995, Mittelbach et al. 2001, Gillman and Wright 2006, Adler et al. 2011). Despite the difficulties associated with comparing different types of organic matter and comparing amounts of organic matter by volume with by weight, it is clear that the current study had low levels of organic matter in the growth substrates compared to other green roofs experiments (e.g. Emilsson 2008, Molineux et al. 2009, Nagase and Dunnett 2011, Graceson et al. 2014b). The current study could therefore be considered to sit at the lower end of the green roof productivity spectrum, testing the effects of a relatively small range of productivity for green roof habitats. At the end of the study period, forb richness was very similar in both treatments and the control; however it has been argued that the overall diversity was highest in the intermediate Sandy loam treatment, so there is some tentative support for an intermediate level of productivity supporting the highest diversity. Whatever the shape of the diversity productivity relationship in this system, increasing productivity to even the low levels associated with the Compost treatment did not increase diversity. The most suitable amount of added organic matter in these brown roof systems was low.

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

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

There are many advantages potentially associated with the addition of organic matter, such as favourably altering the water holding capacity, dry bulk density and air filled porosity of green roof substrates (Graceson et al. 2014a). However, the addition of too much organic matter in green roof systems whose vegetation is not entirely composed of drought resistant flora such as *Sedum*, is likely to create a 'boom bust' system where plants grow too well, then die back in periods of dry weather (Nagase and Dunnett 2011, Bates et al. 2013). So the amount of organic matter added to green roof substrates has to be carefully considered, and the ideal amount will vary with the water holding capacity of the substrate and the desired species in the plant assemblage.

5 Conclusions

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

Acknowledgements

This research was funded by the European Union through the UNESCO SWITCH sustainable urban water project. We thank Dusty Gedge and Emorsgate Seeds for advising on the seed mix used, Rossa Donovan for initial input into the project, Kevin Burkhill and Anne Ankcorn for the preparation of Figure 1, Maria Fernanda Aller and Véronique Durand for help with the array construction, Siobhan King and Diego Martelli for field and lab-work assistance, IKO for the provision and advice on the use of green build materials, and Coleman and Company for the provision of recycled aggregates. Weather data were used with permission from the UK Meteorological Office MIDAS Land Surface Stations data (1853-current), [Internet] NCAS British

Atmospheric Data Centre, 2006, downloaded July 2014. Available from: http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_ukmo-midas.

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

	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. (ºC)							
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	-

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

Table 3 Simple main effects for the relationship between (A) taxa richness and time modelled using univariate ANOVA and (B) taxa richness and mulch treatment using 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

Table 4 Simple main effects for the relationship between (A) number seeded and time 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

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

Measure	df	F	Sig.
Average quadrat count 'other forbs' 2012	2	4.99	0.026
Average quadrat count *Sedum acre* 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 % *S. acre* biomass 2012	2	0.23	0.796

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

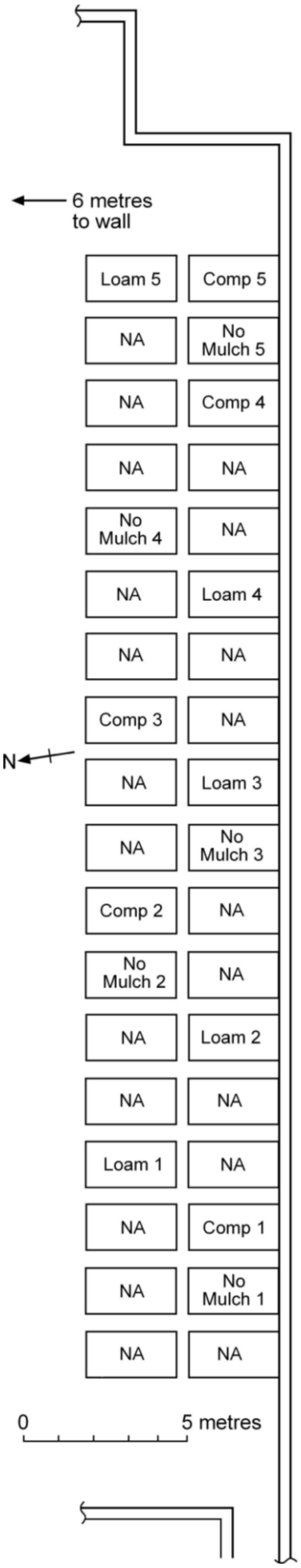


Figure 2 Design of the green roof study mesocosms.

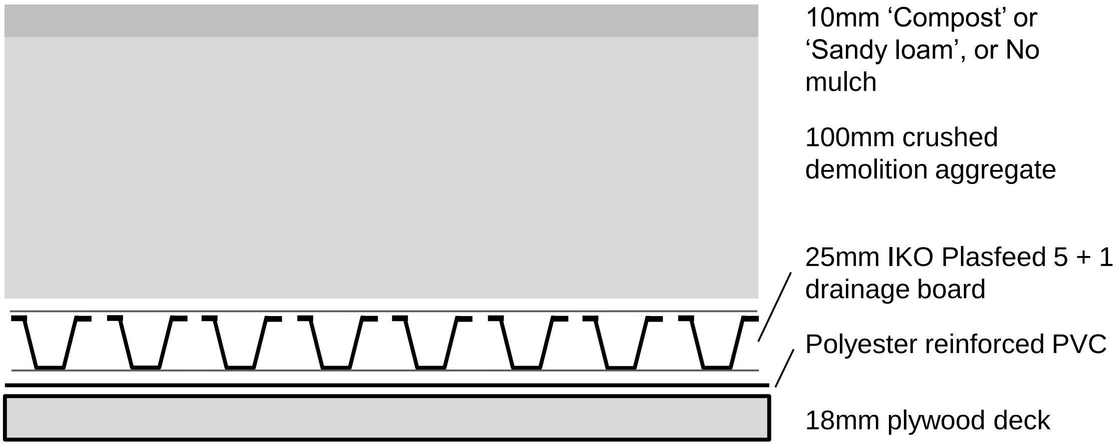


Figure 3 Mean (n = 5, +/- 95% confidence interval) cumulative percentage Wentworth scale size distribution of sediments for the three study treatments.

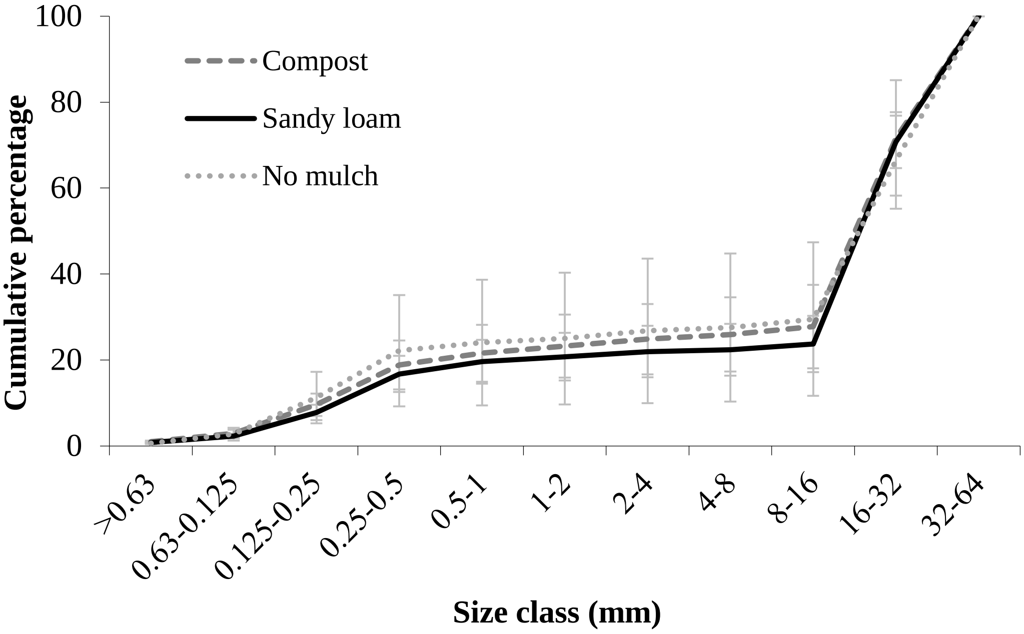


Figure 4 Variations in mean forb richness with substrate treatment across the study period (+/- 95% confidence intervals), the three grey bars roughly mark drought disturbances.

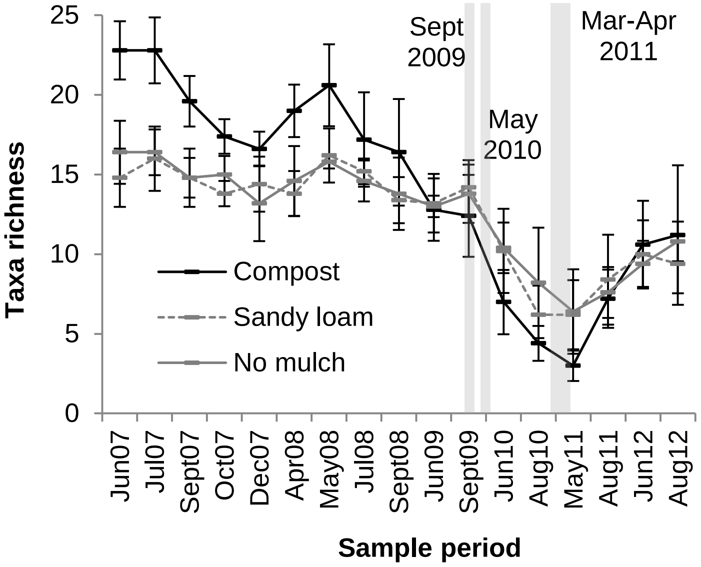


Figure 5 Variations in mean number of forb taxa seeding with substrate treatment across the study period (+/- 95% confidence intervals).

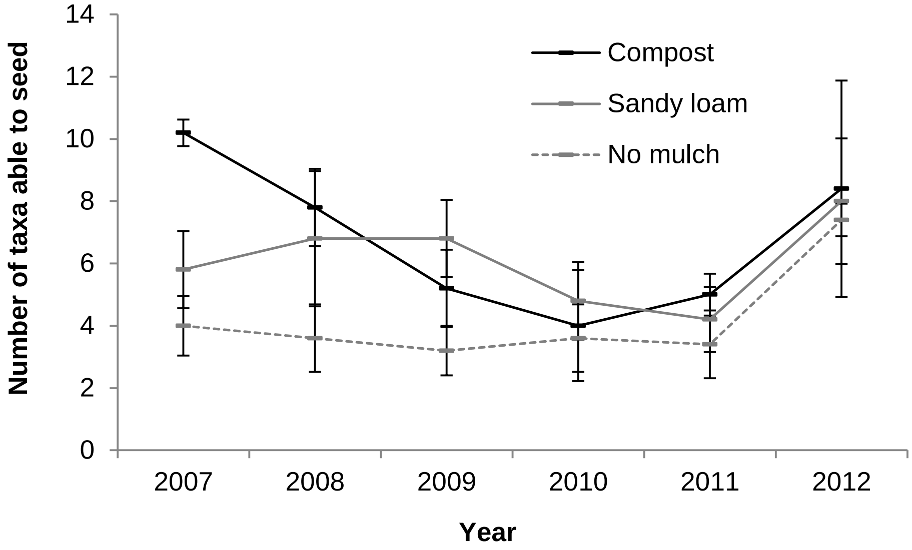


Figure 6 Variations with mulch treatment in the mean point quadrat count for forbs (without *Sedum acre*), *S. acre*, moss, and bare ground for 2012 (+/- 95% confidence intervals). Values that do not share letters were found to be significantly (P<0.05) different using Tukey HSD multiple comparisons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

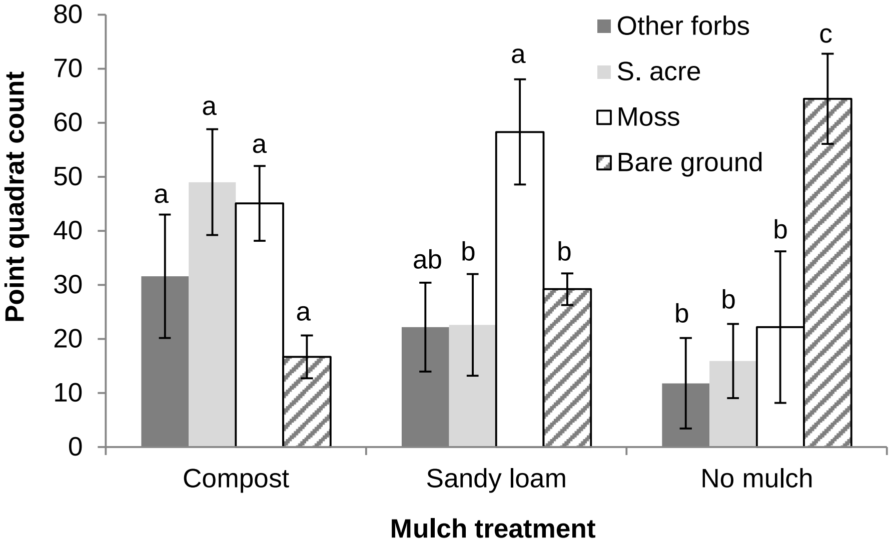


Figure 7 Variations with mulch treatment in the mean total biomass for 2012 (+/- 95% confidence intervals). Values that do not share letters were found to be significantly (P<0.05) different using Tukey post-hoc tests.

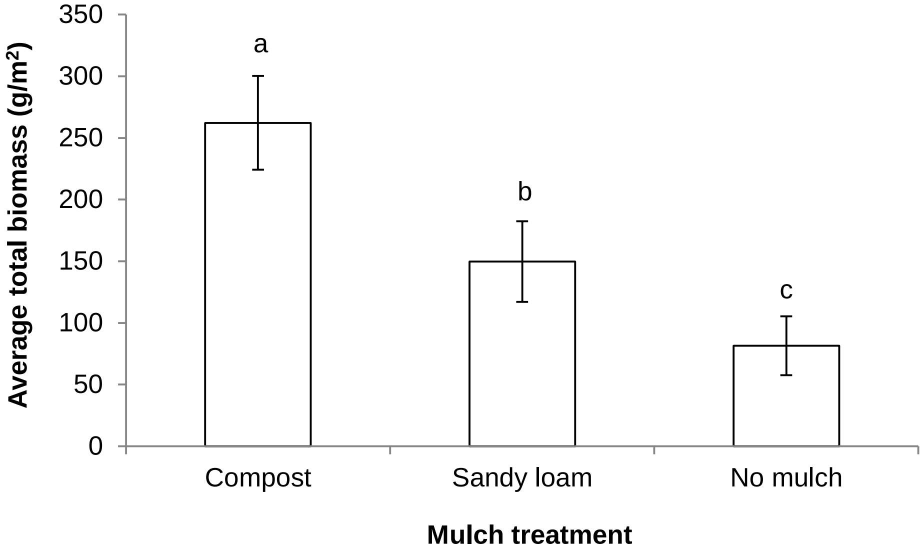
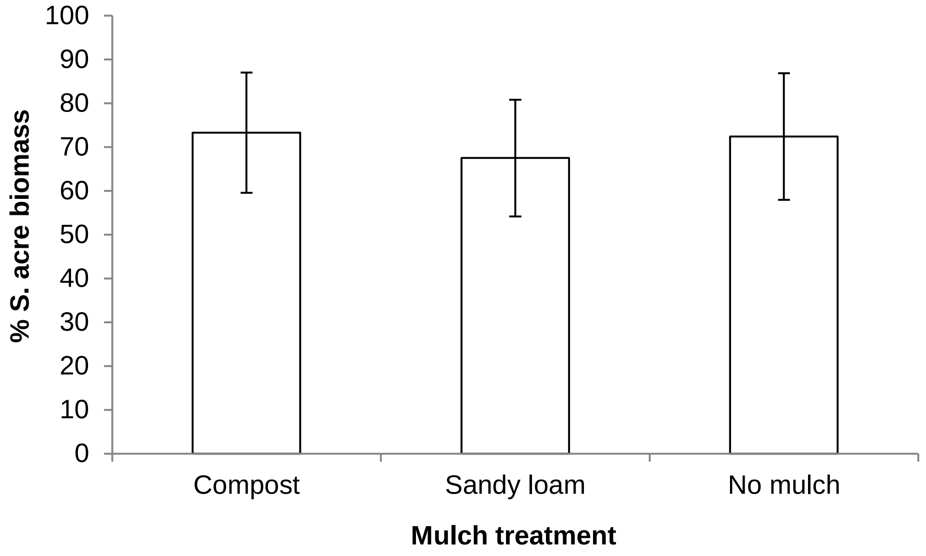


Figure 8 Variations with mulch treatment in the mean biomass of *Sedum acre* as a percentage of all plant biomass for 2012 (+/- 95% confidence intervals). No significant ($P<0.05$) differences were detected.



Supplementary materials

Supplementary materials 1 Seed mix used in the study.

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

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

Survey time windows displayed as follows: code (day/month/year - day/month/year): Jun07 (21/6/07 – 2/7/07), Jul07 (31/7/07 – 1/8/07), Sept07 (4/9/07 – 7/9/07), Oct07 (15/10/07 – 18/10/07), Dec07 (11/12/07 – 14/12/07), Apr08 (4/4/08 – 11/4/08), May08 (21/5/08 – 2/6/08), Jul08 (16/7/08 – 24/7/08), Sept08 (18/9/08 – 29/9/08), Jun09 (1/6/09 – 3/6/09), Sept09 (17/9/09 – 21/9/09), Jun10 (28/6/10 – 30/6/10), Aug10 (27/8/10 – 31/8/10), May11 (24/5/11 – 25/5/11), Aug11 (18/8/11 – 19/8/11), Jun12 (6/6/12 – 14/6/12) and Aug12 (14/8/12 – 3/9/12).

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

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

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

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

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

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

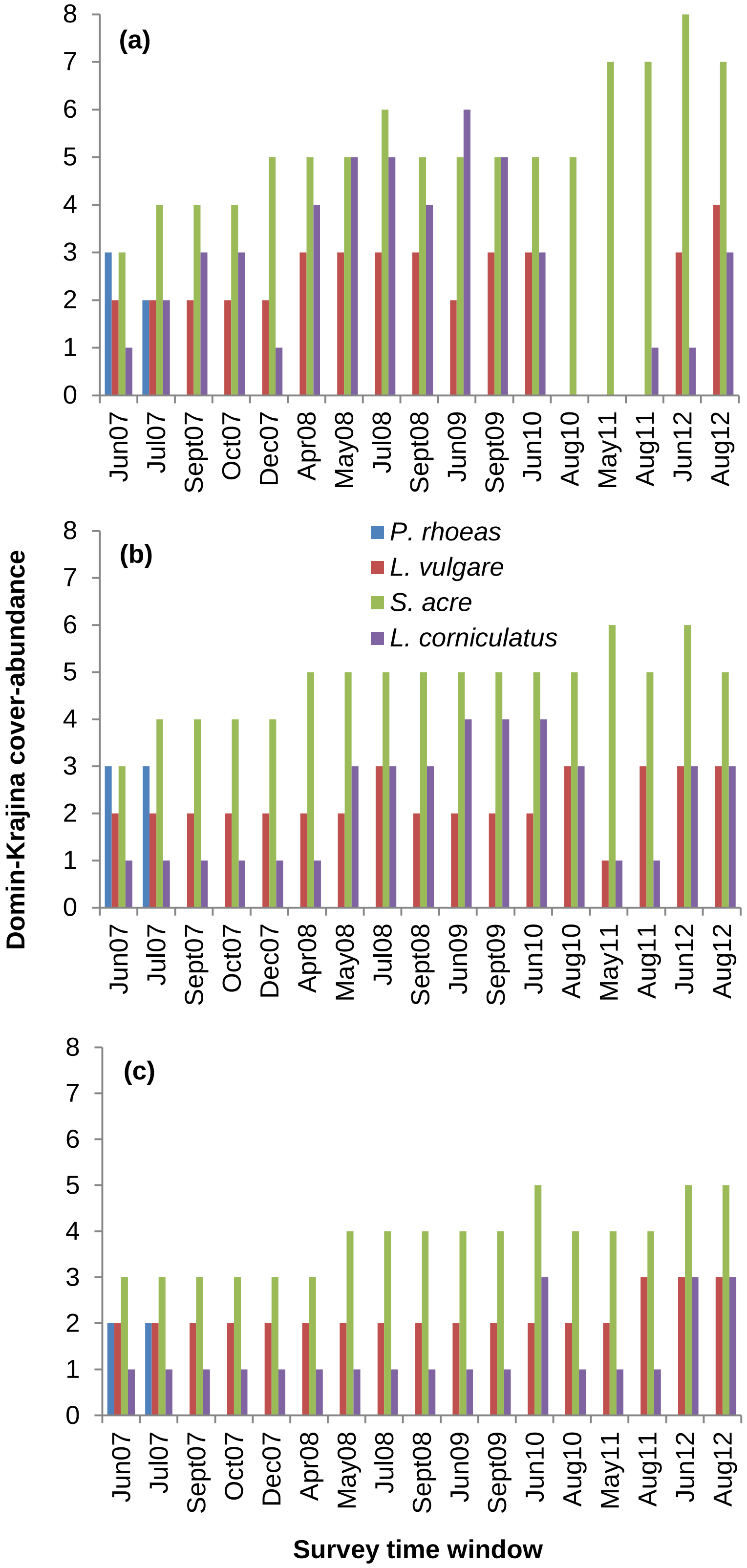
Lotus corniculatus L. *	Common Bird's-foot-trefoil (P)	x	x	x
Trifolium arvense L. *	Hare's-foot Clover (A)	x	x	x
Trifolium dubium Sibth.	Lessor Trefoil (A)	x	x	
Trifolium repens L.	White Clover (P)	x	x	x
Onagraceae				
Epilobium ciliatum Raf.	American Willowherb (P)	x	x	x
Apiaceae				
Daucus carota L.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

Supplementary materials 6 Forb species able to seed by year (‘10’ = 2010 for example) on the different mulch treatments.

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

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

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



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