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Soil microarthropod community dynamics in extensive green roofs

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ABSTRACT

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

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

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

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

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

1. Introduction

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

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

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

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

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

2. Materials and methods

2.1 Field sites

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

2.2 Sampling

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

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

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

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

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

2.3 Biotic factors

2.3.1 Arbuscular mycorrhizal fungi

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

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

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

2.3.2 Plant cover and diversity

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

2.4 Abiotic factors

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

2.5 Statistical analysis

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

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

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

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

3 Results

3.1 Total microarthropods

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

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

Order	Mean individuals m^{-2}	Relative abundance (%)	No. sp./ morphospecies
Collembola (ad & juv)	20637.8 (± 1056.7)	62.13	5
Acarina (ad & juv)	12359.7 (± 888.5)	37.21	15[a]
Hemiptera (ad & juv)	54.4 (± 8.7)	0.16	6[a]
Aranae (ad & juv)	9.6 (± 2.3)	0.03	1
Chilopoda (ad & juv)	13.1 (± 3.7)	0.04	1[a]
Coleoptera (ad)	6.4 (± 1.4)	0.02	3
Diptera (ad)	9.9 (± 1.7)	0.03	1[a]
Unidentified insect larvae	89.2 (± 5.1)	0.3	11[a]

[a] morphospecies, as opposed to species

3.2 Collembola

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

Collembolan density varied between 0 – 120 000 individuals m^{-2} (average ≈ 19 000 (±1000) m^{-2}, median ≈ 14 000m^{-2}). Total abundance did not vary between roofs but varied greatly over time ($F_{6.4,\ 128.3} = 47.8$, $p < 0.001$) with peaks in March of each year (Fig. 1).

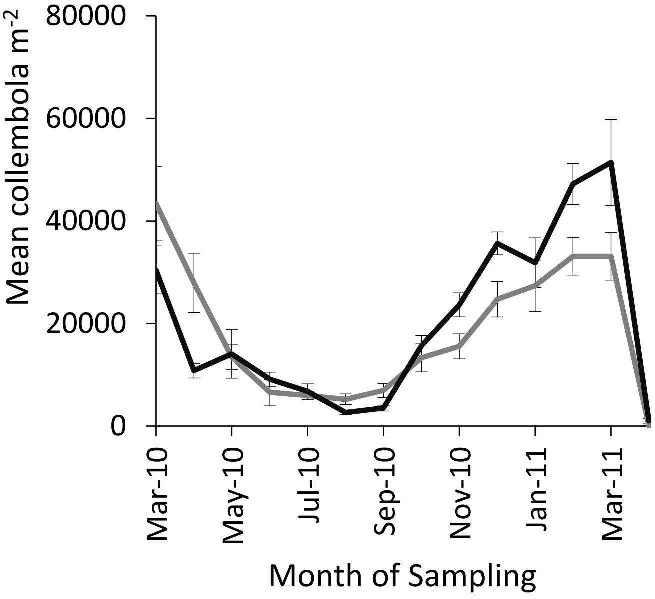

Fig. 1. Mean collembolan between March 2010 and April 2011. Black denotes Roof A; grey denotes Roof B. Error bars represent SEM.

Density decreased with rising average monthly temperature (Roof A: $R^2 = 0.175$, $F_{1,\ 166} = 35.2$, $p < 0.001$; Roof B: $R^2 = 0.249$, $F_{1,\ 142} = 47.1$, $p < 0.001$) with population crashes occurring when water content was low, followed by a recovery time as water content increased (Figs. 1 & 2).

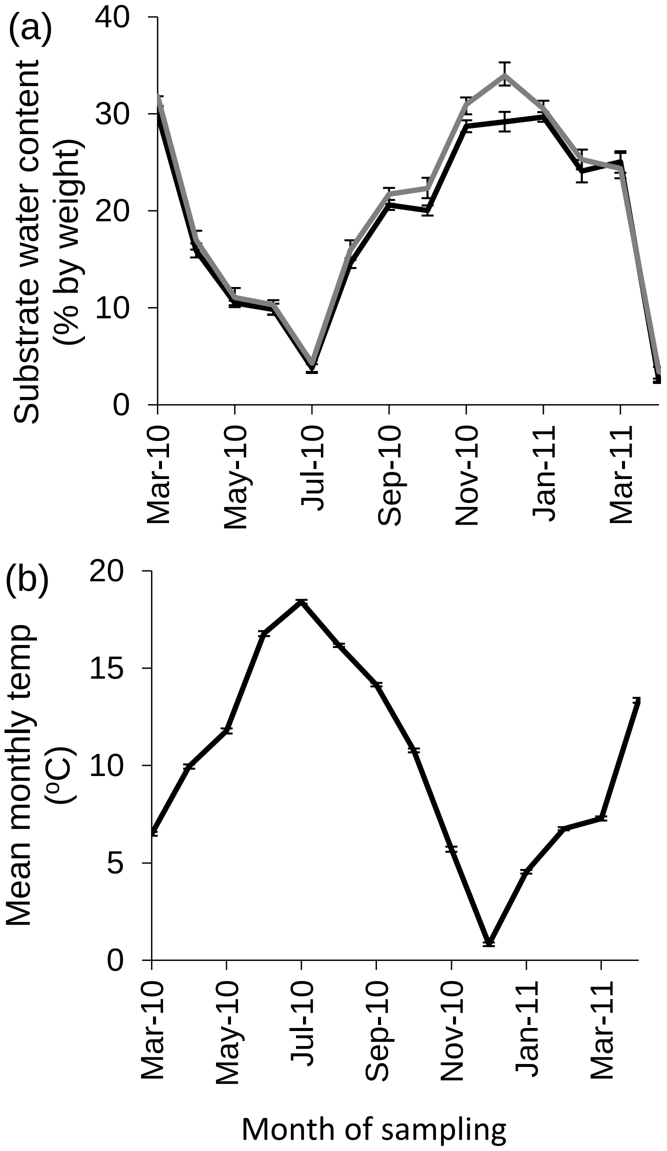

Fig. 2. (a) Percentage water of green roof substrate (by weight) for Roof A (black) and Roof B (grey) between March 2010 and April 2011. (b) Mean monthly temperature for the local area (˚C) for the same period. Error bars represent SEM.

Deuterosminthurus pallipes was slower to recover from these than *S. aureus.* Collembolan abundance showed a logarithmic relationship with substrate water content

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

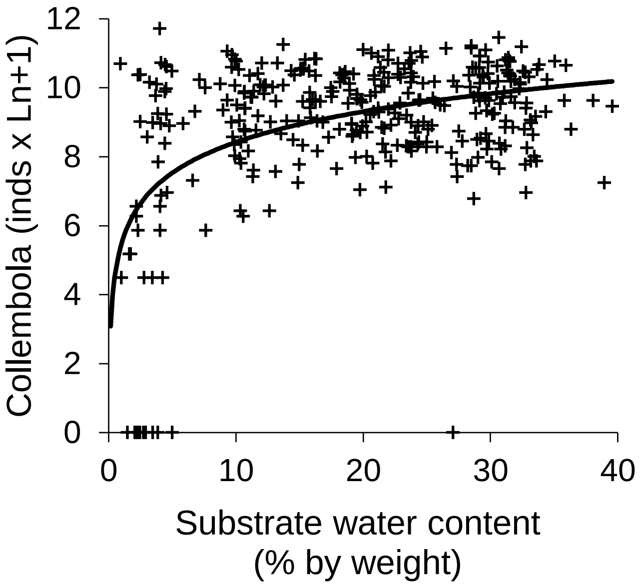

Fig. 3. Numbers of collembola (*ln* + 1) plotted against percentage substrate water content (by weight, ratio of 1) for samples on both green roofs between March 2010 and April 2011. A logarithmic relationship is displayed.

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

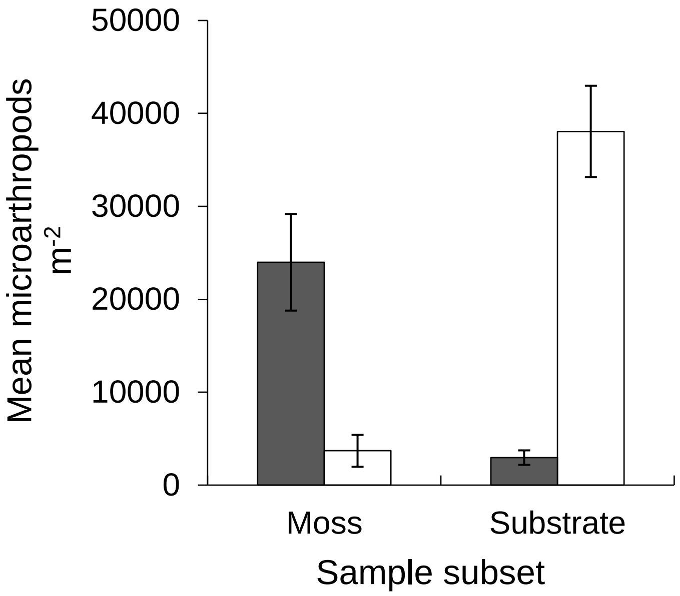

Fig. 4. Microhabitat preferences for mites and collembola in June 2010 on both roofs, determined by extracting microarthropods from the surface moss layer and underlying substrate layer separately. Dark bars represent mites, white bars represent collembola. Error bars represent SEM.

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

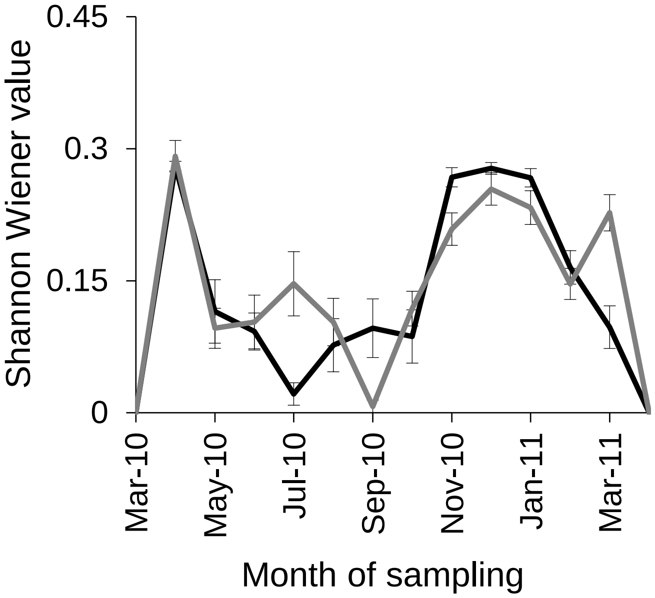

Fig. 5. Shannon Wiener indices for collembola diversity between March 2010 and April 2011. Black denotes Roof A; grey denotes Roof B. Error bars represent SEM.

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

3.3 Mites

Fifteen morphospecies of mite were present on the roofs and density varied between 180 and 109 000 mites m^{-2} (average ≈ 12 000 (± 800) m^{-2}, median ≈ 7000 m^{-2}). The two most abundant mites were a prostigmatid, *Eupodes viridis*, which was particularly abundant in summer 2010, and an oribatid mite from the Scutoverticidae family. These represented 23% and 62% of mites respectively. Mite abundance did not differ between roofs (Fig. 6) but did change over time ($F_{3.1,\,61.8} = 11.1$, $p < 0.001$) with higher abundances in August/September 2010 (*E. viridis*) and December 2010 and March 2011 (Scutoverticidae) (Fig. 6). The Scutoverticid was usually the most dominant mite.

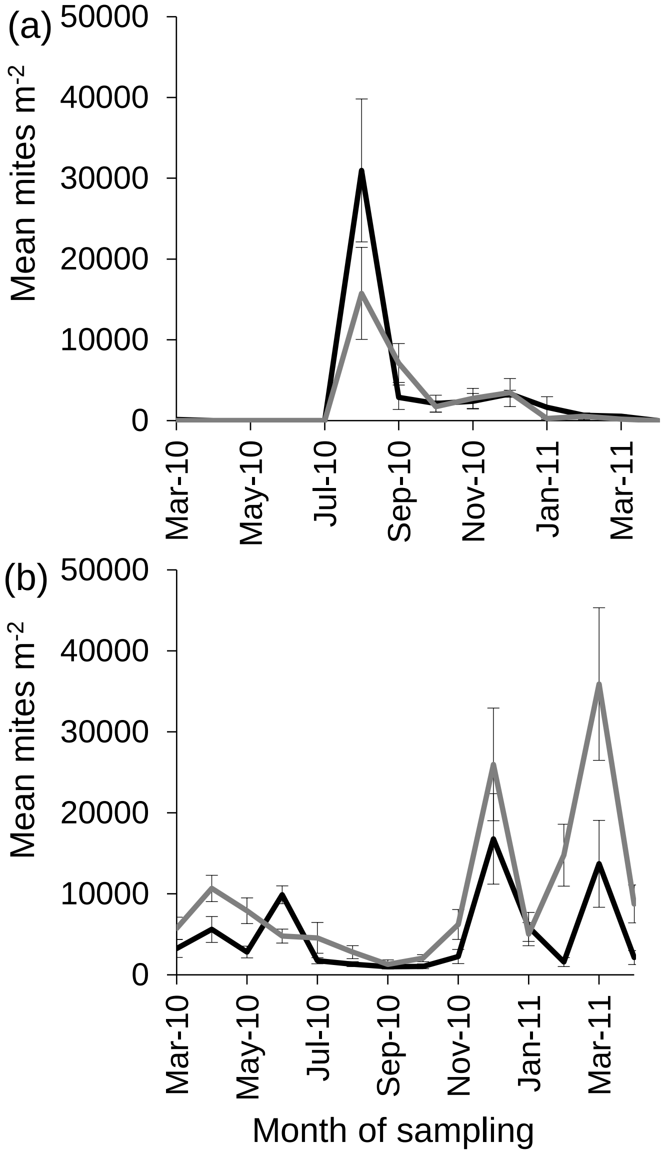

Fig. 6. Abundance plots of the two commonest mites encountered on two green roofs between March 2010 and April 2011. Black denotes Roof A, grey denotes Roof B and error bars represent SEM. (a) *E.viridis* (b) Scutoverticidae.

Mite abundance was not affected by any of the variables measured. No relationship was found between mite abundance and substrate water content or temperature. No association between mites and plant cover, plant diversity or mycorrhizal colonisation of nearby roots was found either. However mites showed a strong preference for the moss fraction of the habitat ($F_{1,44} = 34.3$, $p < 0.001$) (Fig. 4), creating a clear spatial separation between mites and collembola.

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

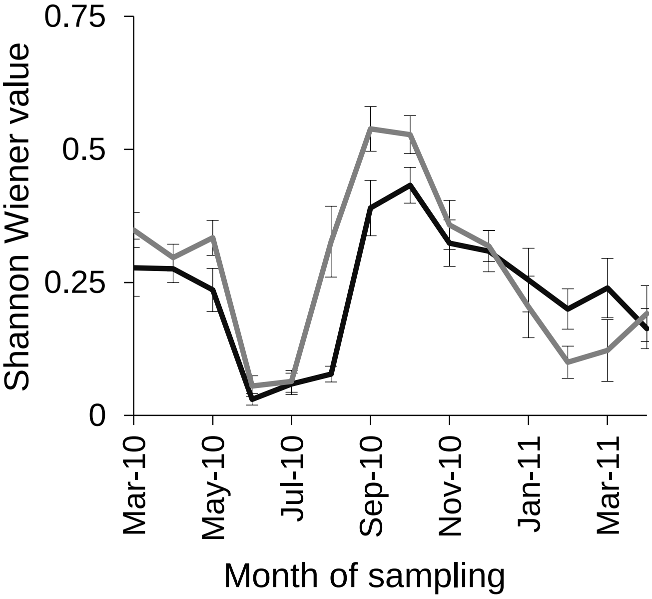

Fig. 7. Shannon Wiener indices for mites between March 2010 and April 2011. Black represents Roof A, grey Roof B and error bars represent SEM.

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

3.4 Biotic factors

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

(± 2) on Roof A and 13% (± 4) on Roof B, but very low in arbuscules, averaging 0.25% (± 0.2) on each roof.

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

3.5 Abiotic factors

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

4. Discussion

4.1 Total microarthropods

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

The species assemblage on these roofs is comparable to other early successional environments. Similar communities of soil microarthropods are found in desert soils (Wallwork, 1972) and glacial foreland soils (Kaufmann et al., 2002). In both, the fauna is dominated by mites and collembola but some other organisms, such as larvae, also occur. Soils with lower abundances but a higher diversity of collembola and mites (but no other species) include Antarctic soils (Caruso and Bargagli, 2007; Convey and Smith, 1997) and polluted urban sites such as roadside lawns and roundabouts (Eitminaviciute 2006a,b). In these examples mites tend to be dominant over collembolans, converse to our findings where the collembolan count was higher, if more variable, than mites. Our sites perform poorly compared to reclaimed mining sites (Dunger et al., 2001; Wanner and Dunger, 2002) where both abundance and diversity of microarthropods was higher.

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

4.1.2 Collembola

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

Collembolan density was negatively affected by high temperature and low soil moisture, but the latter only below a certain threshold. Petersen (2011) found that the density of Symphypleona (*S. aureus, D. pallipes, B. hortensis, D. bicinctus*) subjected to warm, dry treatments for one month in Britain were unaffected. However, in warm, sparsely vegetated Spanish sites (more like a green roof), drought negatively affected Symphypleona, particularly *S.aureus*, despite its ability to produce drought resistant eggs (Alvarez et al., 1999). Contrary to our findings, *D. pallipes* was unaffected in their study. The longer period of drought in our study, or an unmeasured buffering factor, such as food availability, could cause these disparities. Beyond what is needed to survive, collembolan abundance is driven by an unknown factor, such as competition or diet (Petersen, 2002). It is clear that on our roofs, *S. aureus* and *D. pallipes* share some tolerance to the harsh conditions.

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

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

Fewer species were encountered than in Schrader and Böning (2006), whose roofs in Hannover were of a similar age, height and depth but whose substrate consisted of expanded clay or shale pellets, not crushed brick. Hannover also has a different climate to South-East England, though no studies have determined the effect of either climate or substrate type on green roof soil communities as yet. Diversity was also lower than that expected in urban UK soils (Fountain and Hopkin, 2004), and this may be due to the lower organic matter present on the green roofs than in ground-level soil, an important factor for soil microarthropods (Ettema and Wardle, 2002). It is recommended that future studies compare the two to determine if this is indeed the case.

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

4.1.3 Mites

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

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

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

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

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

4.1.4 Relationships with biotic factors

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

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

4.1.5 Habitat preferences

Collembola and mites showed distinct spatial separation, dominating the underlying substrate and moss respectively. Scutoverticidae have a well-documented association with mosses (Schäffer et al., 2010b) and the separation of the two could suggest competition avoidance. Despite inhabiting the underlying substrate, collembola were positively affected by moss cover on one of the roofs. Neither dominant species of collembola are known to be moss-associated but the moss crust could provide secondary benefits such as moisture retention (Chamizo et al., 2012) or may support fungi, a collembolan dietary component (Gange, 2000).

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

4.2 Conclusions

Extensive green roofs are either in an interrupted or extremely slow successional process capable of supporting only the hardiest of soil microarthropods. They present a boom and bust community, with some key functional groups missing, but support a few ephemeral colonisers, such as beetle and fly larvae. Few species manage to survive in the long-term due to hot, arid conditions, an impoverished soil food web and low plant diversity. Amelioration of these conditions and manipulation of the soil food web to provide a diverse food source could benefit microarthropod and plant communities on these roofs.

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

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

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

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

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Glossary of terms

- Arbuscular mycorrhizal fungi – Fungi which form symbiotic (usually beneficial) partnerships with vascular plants, intracellularly (within their roots).
- Arbuscules – Branched structure of AM fungi within vascular plant roots used for nutrient exchange
- Basidiomycete – Fungal phylum
- Collembola – Group of organisms belonging to the arthropod phylum, also known as springtails
- Detritivore – Organsims that obtain energy by consuming decomposing organic matter
- Hyphae – Filamentous structure of fungi usually constituting the main mode of vegetative growth
- Furca – Structure unique to collembola used for jumping
- Microarthropod – Small to microscopic members of the arthropod phylum (organisms with exoskeletons, segmented bodies and jointed appendages)
- Quadrat – Metal grid used for vegetation surveys
- Refugia – An area providing shelter
- Vesicles – Storage structures of AM fungi, found within vascular plant roots
- Xerophillic – Organisms that are tolerant of dry conditions

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Supplementary data

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

Plants ***Sedum***

- *Sedum album*
- *Sedum acre*
- *Sedum kamtschaticum*
- *Sedum rupestre*
- *Sedum spurium*

Seasonal colonisers

- *Arabidopsis thaliana*
- *Anthyllis vulneraria*
- *Cirsium arvense*
- *Geranium robertianum*
- *Jacobaea vulgaris*
- *Leontodon hispidus*
- *Melilotus officinalis*
- *Sonchus asper*
- *Sonchus oleraceus*
- *Taraxacum officinalis*
- *Trifolium arvense*
- *Trifolium dubium*

Tree saplings

- *Acer pseudoplatanus*
- *Betula pendula*
- *Pinus sylvestris*

Fungi

Melanoleuca polioleuca

Omphalina pyxidata