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Using recycled aggregates in green roof substrates for plant diversity

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ABSTRACT

Extensive green roofs are becoming a popular tool for restoring green infrastructure in urban areas, particularly biodiverse habitats such as post-industrial/brownfield sites. This study investigated the use of six recycled lightweight aggregates and combinations of them in green roof growing substrate, to determine their effectiveness for enhancing plant abundance and species diversity. In two separate experiments, we examined the roles of substrate type and depth on the establishment of a perennial wildflower mix over a 15-month period. We found that some of the alternative substrates are comparable to the widely used crushed red brick aggregate (predominantly found in commercial green roof growing substrate) for supporting plant establishment. For some materials such as clay pellets, there was increased plant coverage and a higher number of plant species than in any other substrate. Substrates that were produced from a blend of two or three aggregate types also supported higher plant abundance and diversity. Generally, increasing substrate depth improved plant establishment, however this effect was not consistent across substrates. We conclude that recycled materials may be viable constituents of growing substrate for green roofs and they may improve green roof resilience, through increased plant cover and diversity. The results could provide evidence to support the construction of mosaic habitat types on single roofs using various substrate blends.

1. Introduction

Green roofs—rooftops that have been purposefully vegetated (Oberndorfer et al., 2007) either with low growing *Sedum* plants, wildflowers, grasses or shrubs and trees, are an emerging green technology that is becoming increasingly popular in urban environments due to the many benefits they provide. One such benefit is their potential to restore biodiversity in urban landscapes (Gedge, 2001; Grant et al., 2003; Sadler et al., 2011; Ishimatsu and Ito, 2013; Madre et al., 2014). There is an increasing body of evidence demonstrating that green roofs are able to support high biodiversity if designed appropriately (Brenneisen, 2006; Kadas, 2007; Baumann and Kasten, 2010; Tonietto et al., 2011) and increasing recognition that rich biodiversity in cities can have enormous potential to mitigate the effects of climate change through the enhancement of urban resilience and sustainability (Niemelä, 2014).

Extensive green roofs are generally designed with a substrate layer (up to 150 mm deep) that contains a high (up to 90%) percentage of aggregate and a small amount of organic material. This not only provides a low nutrient growing substrate ideal for green roof vegetation (Molineux et al., 2009; Molineux, 2010; Nagase and Dunnett, 2011) but also reduces extra roof weight. Problems can occur with either the addition of 'soil' and its attending clay fraction causing reduced water transmissivity or excessive compost/organic matter risking substrate shrinkage (Snodgrass and Snodgrass, 2006). Extensive green roofs are often vegetated using blankets, comprised of up to 12 different *Sedum* species and are rolled out over the substrate layer to provide an instant 'green' effect (Emilsson and Rolf, 2004). Other types of planting that are popular include wildflower and grass blankets, plug-planted systems (with either *Sedum* or wildflower species) and seeded systems. Biodiversity roofs tend to use both plug-plants and seeds and often support local species that naturally invade the roof (Bates et al., 2013) such as *Buddleia*,*Chenopodium* spp., *Trifolium* spp., tree species seedlings (*Salix* spp.) and various grass species. These types of roofs are generally designed to mimic natural wasteland areas where bare ground can be colonized by wildflowers and grasses, with succession proceeding to scrub and finally woodland, allowing a wide range of wildlife to become established (Gibson, 1998; Angold et al., 2006). These roof level habitats often naturally retard succession due to limitations of substrate depth, water holding capacity and nutrient availability

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(Olly et al., 2011; Sadler et al., 2011). However, such stresses might also maintain a higher biodiversity level if managed effectively (Benvenuti, 2014), as dominating species can be removed (Bates et al., 2013).

The aggregate content provides the growing substrate with physical characteristics such as optimal water retention and free-draining abilities as well as good aeration, to prevent anaerobic conditions associated with compacted soils (Snodgrass and Snodgrass, 2006). Water holding capacity is of particular importance for vegetation especially during the dry summer months, and is affected by not only the substrate depth (VanWoert et al., 2005; Olly et al., 2011), but also by its type/composition (Graceson et al., 2013). Although many studies have looked at the effect of commercially available substrates on green roof hydrolytic properties (Bengtsson, 2005; Morgan et al., 2013; Wang et al., 2013; Zheng et al., 2013; Berretta et al., 2014; Volder and Dvorak, 2014), there has been little research on alternative recycled materials for use in green roof growing substrate (Molineux et al., 2009; Mickovski et al., 2013). Furthermore, fewer studies still have focused on their suitability for plant performance and diversity (MacIvor et al., 2013) and the role of different aggregates in affecting the process of succession is unknown. Successional processes on green roofs are likely to be extremely slow, mainly driven by the lack of water and nutrients (Emilsson, 2008; Bates et al., 2013) and previous experiments have concentrated upon annual plants (Nagase and Dunnett, 2013). Our aim was to determine whether different aggregates can provide satisfactory growing conditions for perennial plant species. During secondary succession, perennial herbs and grasses provide the greatest array of niches and support highest numbers of associated insects (Edwards-Jones and Brown, 1993) and maximise the biodiversity value of extensive green roofs (Madre et al., 2013). To address this question, we tested these hypotheses: (1) the type of aggregate in green roof growing substrate would affect plant establishment (abundance) and species richness; and (2) substrate depth would be important in determining plant diversity.

2. Materials and methods

Several recycled aggregates were chosen for this investigation and were supplied by Shire Green Roofs Substrates Ltd. (Southwater, West Sussex, UK), including: crushed red brick—typically used in extensive green roof substrate blends—and crushed yellow brick (both from defective house brick manufacture), clay pellets (containing sewage sludge and PFA), paper ash pellets (containing recycled newspaper ‘ash’), Carbon8 pellets (containing limestone quarry waste and carbon dioxide) and Superlite (containing waste crushed aircrete). Full details of these aggregates are given in Molineux et al. (2009). The aggregates were used to create two green roof experimental test sites and the combinations of aggregates used are listed in Table 1. For all treatments, 75%/v aggregates were combined with 25%/v organics (50:50 blend of PAS100 compost and loam) to produce novel substrate blends. Where more than one aggregate was used, equal ratios of them were blended, e.g. 33.3% red brick, 33.3% clay pellets and 33.3% paper ash pellets then 75% of this mixed material combined with the same 25%/v organics. The amount of organics added to aggregates in this study was justified based on FLL Guidelines of ≤65 g/l (FLL, 2008), suggestions by Beattie and Berghage (2004) of between 10% and 25% organic matter and previous investigations by Molineux et al. (2009).

Table 1
The various substrate mixes for test plot I and test plot II.

Test plot	Substrate (treatment)	Substrate depth (cm)	Key
I	Clay pellets	5.5	C
I	Carbon8 pellets	5.5	8
I	Superlite mix	5.5	S
I	Red brick	5.5	R
I	Yellow brick	5.5	Y
I	Paper ash pellets	5.5	P
I	Red brick + clay pellets + paper ash pellets	5.5	RCP
I	Clay pellets + paper ash pellets	5.5	CP
I	Red brick + clay pellets	5.5	RC
I	Superlite mix + paper ash pellets	5.5	SP
II	Paper ash pellets	5.5	P1
II	Paper ash pellets	8	P2
II	Yellow brick	5.5	Y1
II	Yellow brick	8	Y2
II	Superlite mix	5.5	S1
II	Superlite mix	8	S2

2.1. Green roof experimental site

An experimental modular green roof was set up in May 2008 on the roof of the Bourne Laboratory (5 stories high) at Royal Holloway, University of London, Egham (Fig. 1). A series of prefabricated gravel trays (52 cm × 42 cm × 8 cm) were drilled with holes to allow for water drainage and lined with a filter membrane (ZinCo SF, ZinCo, Germany) to prevent particulate matter from washing into the drainage system. The experimental site was divided into two test plots (I and II) in order to investigate two variables: aggregate type and substrate depth respectively.

In test plot I, 50 trays contained 10 different substrate types; six was single substrates and four was of various combinations (Table 1). They were arranged in a randomized block design whereby each of the 10 substrates (treatments) appeared once per row and rows were replicated randomly, five times. Each tray was filled to 5.5 cm deep and seeded with 2.5 g of seed mix, equating to 10 g m^{-2} (Table 2). The amount of organics and seeds applied to each tray was kept constant, as was the depth of the substrates to ensure that the only variable in the experimental design was the type of aggregate. Watering came from rainfall alone (even throughout dry summer months) for a true representative, low-maintenance and extensive green roof situation. Because of this a high sowing rate of seeds was used. Previous research has found that if seeds are not watered initially for establishment (Monterusso et al., 2005), then a higher rate of sowing is required for increased individual numbers (Nagase and Dunnett, 2013).

In test plot II, there were 30 trays containing three substrates at two different depths (Table 1), 5.5 cm and 8 cm. Here, each of the six treatments was also replicated five times and seeded with 2.5 g per tray. The purpose of this test plot was to determine if substrate depth altered plant species richness and abundance within the same substrate type. Due to weight restrictions on the roof, only three aggregates could be tested, therefore substrates that had not performed as well in preliminary greenhouse trials (Molineux, 2010) were selected, to see if increasing depth could improve their performance.

2.2. Plant performance

In test plot I, plant surveys were conducted at six (November 2008), nine (February 2009) and fifteen (August 2009) months post-construction. As all plant species in seed mix were perennials, this allowed monitoring of establishment at end of year one and then overwinter and the summer of year two. On each date, the number of each plant species in each tray was recorded. Species identification followed Fitter et al. (1996). The survey of test plot II was conducted once, after 15 months.

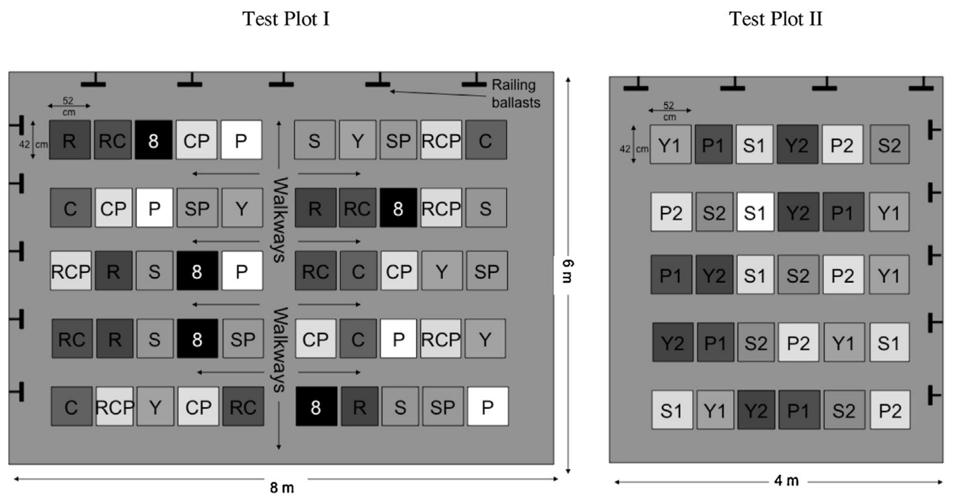

Fig. 1. Bourne roof test plots I and II, 80 (52 cm × 42 cm) trays arranged in a randomized block design. Where C = clay pellets, 8 = Carbon8 pellets, S = Superlite, R = red brick, Y = yellow brick and P = paper ash pellets.

Table 2
The 15 wildflower plant species and 1 grass species in the seed mix sown in the test plots.

Family	Genus	Species	Common name
Boraginaceae	*Echium*	*Vulgare*	Viper's-bugloss
Caprifoliaceae	*Knautia*	*arvensis*	Field Scabious
Compositae	*Centaurea*	*nigra*	Common Knapweed
Compositae	*Leucanthemum*	*vulgare*	Oxeye Daisy
Compositae	*Leontodon*	*hispidus*	Rough Hawkbit
Lamiaceae	*Origanum*	*vulgare*	Wild Marjoram
Plantaginaceae	*Plantago*	*media*	Hoary Plantain
Rubiaceae	*Galium*	*Verum*	Lady's Bedstraw
Poaceae	*Bromus*	*erectus*	Upright Brome grass
Hypericaceae	*Hypericum*	*Perforatum*	Perforate St John's-wort
Leguminosae	*Anthyllis*	*Vulneraria*	Kidney Vetch
Leguminosae	*Lotus*	*corniculatus Bird*	Bird's-foot-trefoil
Leguminosae	*Trifolium*	*Pratense*	Red Clover
Malvaceae	*Malva*	*Moschata*	Musk-mallow
Ranunculaceae	*Ranunculus*	*Acris*	Meadow Buttercup
Resedaceae	*Reseda*	*Lutea*	Wild Mignonette

2.3. Statistical analysis

Diversity was calculated using the Shannon–Weiner index. Following checking of data sets for normality and homogeneity of variances, repeated measures analysis of variance (ANOVA) was used to examine differences in numbers of plants established, species richness and diversity, employing time and substrate type as the main effects. Means were separated with a Tukey's HSD post hoc test (Fowler et al., 1998). ANOVA was also used to examine the effect of substrate depth on abundance and diversity. These analyses were conducted using the statistical package UNISTAT®.

We also employed non-metric multidimensional scaling analysis to examine differences in the plant assemblage composition after 15 months across the different aggregates, using the CAP5 package (Pisces Conservation Ltd., Lymington, UK). ANOSIM was used to examine pairwise assemblage differences.

3. Results

3.1. Aggregate type: assemblage analysis

In the first 6 months post construction of test plot I, many seedlings emerged from all trays (mean of 18.5 ± 1.7 per tray across all treatments). However over the first year many did not survive, leaving most trays looking sparse and after 15 months there was a mean of 12.5 ± 1.1 per tray (of all treatments). Fig. 2 shows the changes in plant numbers in the different substrate blends over the course of the 15 months study. Initial establishment seemed to be slower in the clay pellets, Carbon 8 pellets and Superlite mix (Fig. 2a), but once established, plant abundance tended to remain stable. In the other single aggregates (red brick, yellow brick and paper ash pellets, Fig. 2b) and the blended mixtures (Fig. 2c), initial establishment was good, but plant persistence was poor, leading to a decrease in numbers over time. Overall the change in plant abundance was significant over time ($F_{2,108} = 9.7$, $P < 0.01$), but more importantly, and there was a considerable difference in plant abundance between the substrates ($F_{9,108} = 15.4$, $P < 0.001$). This is summarised in Fig. 3a, where it can be seen that Superlite, yellow brick and paper ash pellets were not as effective for supporting plant abundance as the other aggregate types. Meanwhile, the largest numbers of plants established were found in those substrates containing red brick and/or clay pellets.

Out of the 16 species that were seeded (Table 2), 10 (*Echium vulgare*, *Leontodon hispidus*, *Origanum vulgare*, *Galium verum*, *Bromus erectus*, *Anthyllis vuleraria*, *Lotus corniculatus*, *Trifolium pratense*, *Malva moschata* and *Ranunculus acris*) established successfully in at least one of the trays. Once germination had occurred, there was no overall change in plant species richness over time, but a dramatic difference between the aggregates ($F_{9,108} = 18.6$, $P < 0.001$). Fig. 4a and b shows species richness from the single aggregate blends and Fig. 4c shows the number of species found in the blended substrates. Species richness in the different aggregates did not follow an identical trend to plant abundance. The number of plant species was higher in the clay pellets and the mixes of red brick/clay pellets/paper ash pellets and red brick/clay pellets treatments closely followed by the crushed red brick and the clay/paper ash pellet mix. The carbon8 pellets, Superlite mix, paper ash pellets and the yellow brick substrate were the least species rich substrates overall (Fig. 3b). Diversity increased over time ($F_{2,12} = 5.4$, $P < 0.05$) and differed greatly between the aggregates ($F_{9,108} = 14.2$, $P < 0.001$). This followed a similar pattern to species richness (so data not shown), in that Superlite, paper ash pellets and yellow brick were the least diverse, while aggregates with red brick and/or clay pellets produced the most diverse assemblages. The assemblage pattern was confirmed by the ordination analysis (Fig. 5). A significant separation in the assemblages was found ($r = 0.224$, $P < 0.001$), with yellow brick and

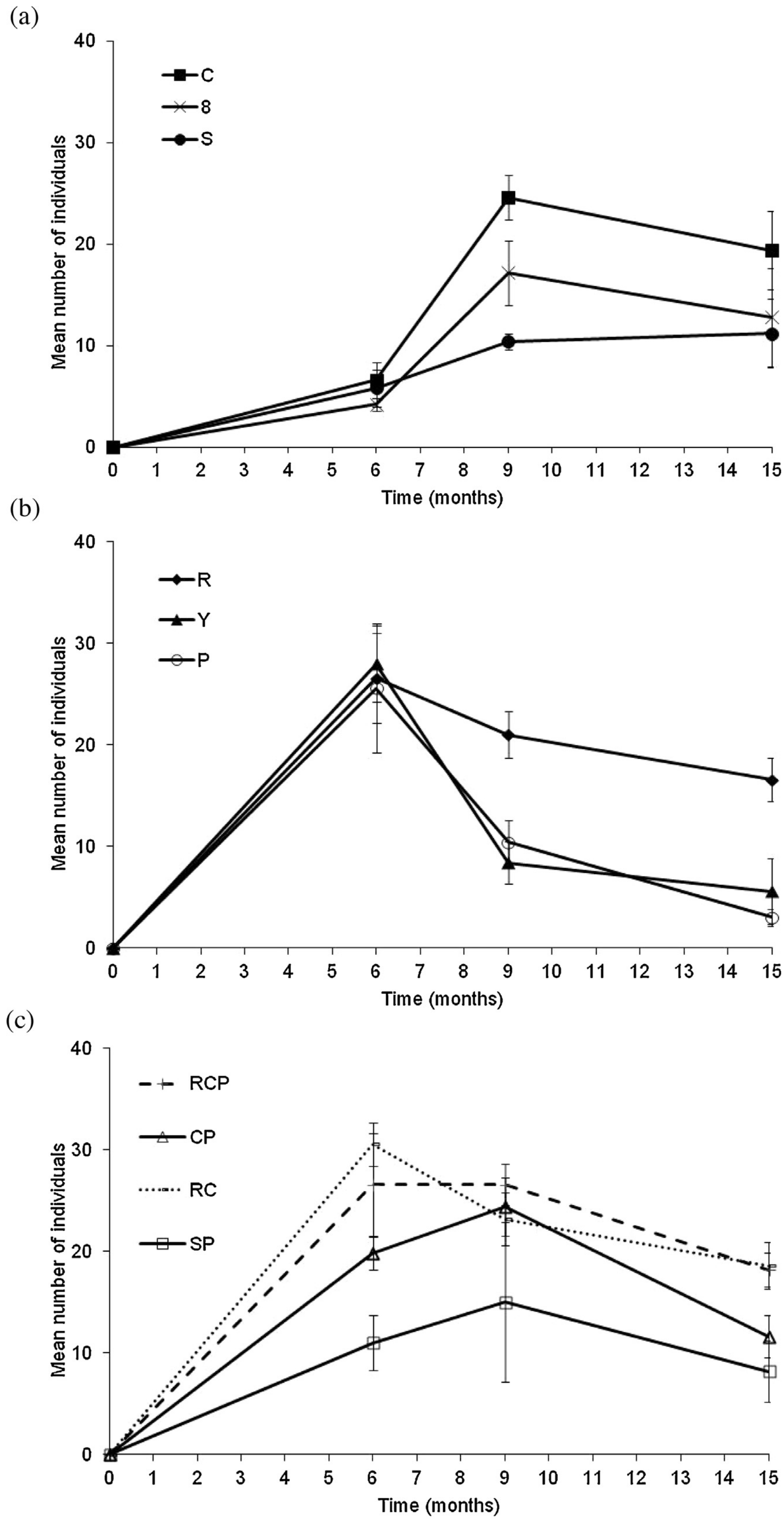

Fig. 2. Average plant/seedling numbers in each of the 10 treatments in test plot I (described in Table 1*), recorded from three surveys conducted: 6, 9 and 15 months after tray seeding, where (a) numbers increased for 3 single blends, (b) numbers decreased for 3 single blends and (c) for the 4 substrate mixes. Bars represent mean ± one standard error. *C = clay pellets, 8 = Carbon8 pellets, S = Superlite, R = red brick, Y = yellow brick and P = paper ash pellets.

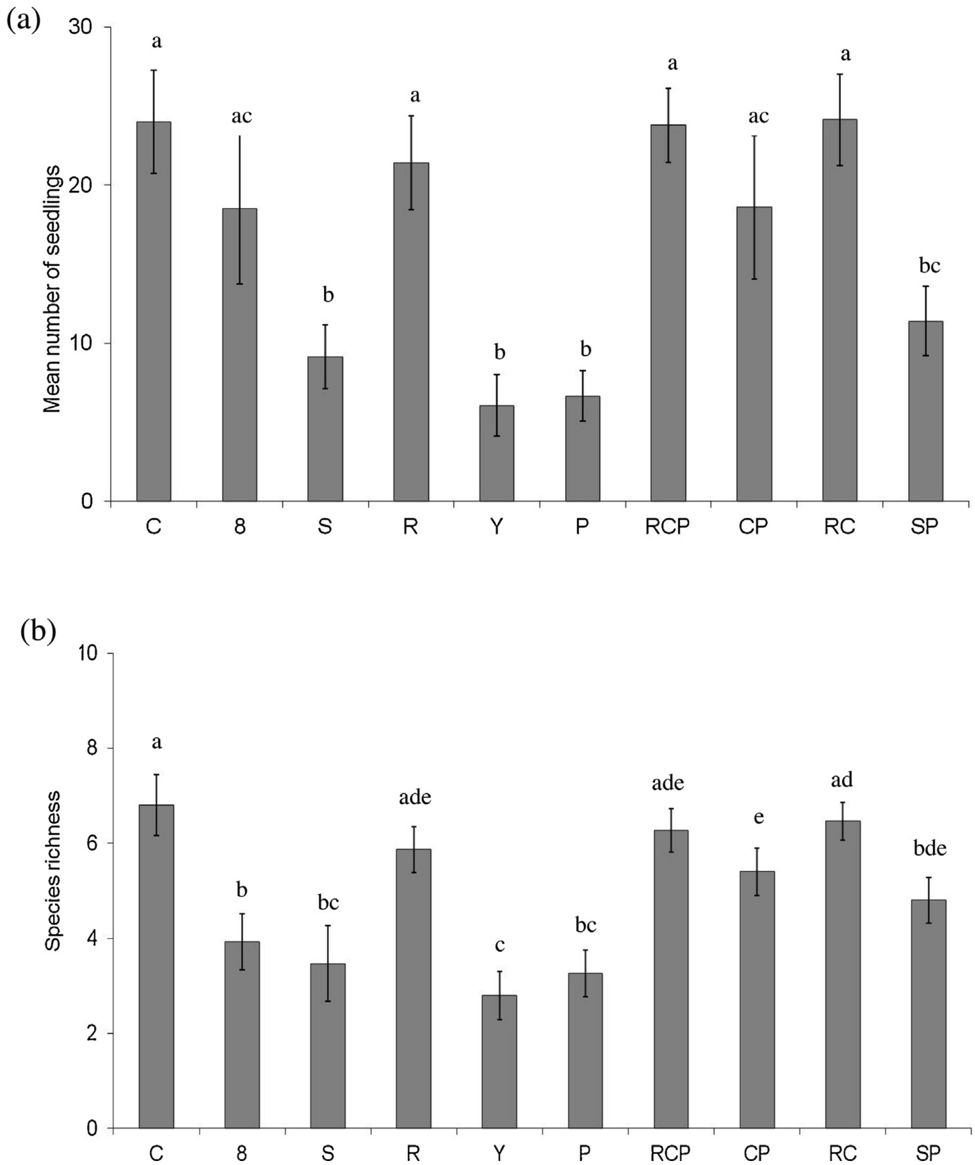

Fig. 3. Average (a) plant numbers and (b) species richness in each of the 10 treatments in test plot I (described in Table 1*), at the end of the study (August 2009). Means analysed with ANOVA and differences separated with Tukey HSD. Values not sharing the same letter indicate a significant difference ($P < 0.05$). Bars represent mean ± one standard error. *C = clay pellets, 8 = Carbon8 pellets, S = Superlite, R = red brick, Y = yellow brick and P = paper ash pellets.

paper ash supporting assemblages that were very different from all other substrates.

3.2. Aggregate type: plant species analysis

At the end of the study in August 2010, *E. vulgare* was the most abundant plant species and seemed suited to most substrates and blends. Mean numbers of plants varied slightly between substrates ($F_{9,40} = 2.2$, $P < 0.05$), with fewer plants established in paper ash pellets and yellow brick. Other plant species followed similar patterns of abundance, though no statistical differences were found between substrates, with the exception of *L. hispidus*, where numbers were extremely low in the Superlite, paper ash pellets and yellow brick substrates.

3.3. Aggregate depth

Overall, both plant number ($F_{1,23} = 11.92$, $P < 0.01$) and species richness ($F_{1,23} = 7.88$, $P < 0.01$) were higher in 8 cm deep substrates than 5.5 cm (Fig. 6). However, this pattern was only seen in substrates that contained paper ash or Superlite, and was not true for yellow brick. For species richness, this resulted in a significant interaction term between aggregate type and depth ($F_{2,23} = 5.16$, $P < 0.05$) implying that the effectiveness of a particular aggregate type very much depends on its depth.

4. Discussion

This study has shown that it is possible on a green roof to establish an assemblage composed of herbaceous perennial plants in varying admixtures of recycled inorganic substrates. Certain plant species such as *E. vulgare*, *L. corniculatus*, *T pratense* and *B. erectus* established well, but their persistence also differed between substrates.

In all substrates, there was good seedling germination, but establishment in clay pellets, Carbon8 and Superlite seemed to be particularly slow. Once established, however clay pellets appeared to provide a good medium for plant growth and resulted in one of

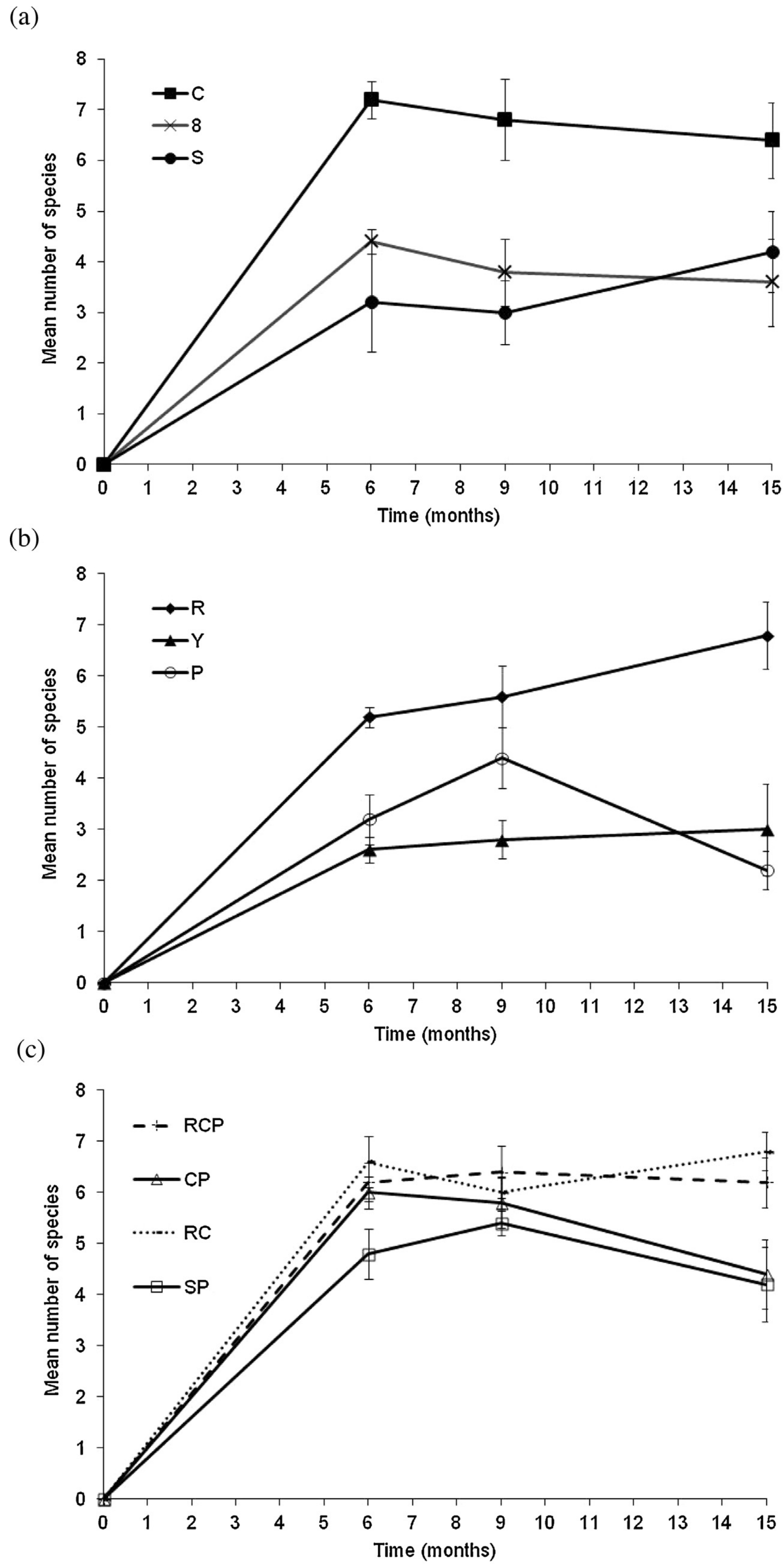

Fig. 4. Plant species richness in each of the 10 treatments in test plot I (described in Table 1*), recorded from three surveys conducted: 6, 9 and 15 months after tray seeding, where (a) numbers decreased for 3 single blends, (b) numbers increased for 3 single blends and (c) for the 4 substrate mixes. Bars represent mean ± one standard error. *C = clay pellets, 8 = Carbon8 pellets, S = Superlite, R = red brick, Y = yellow brick and P = paper ash pellets.

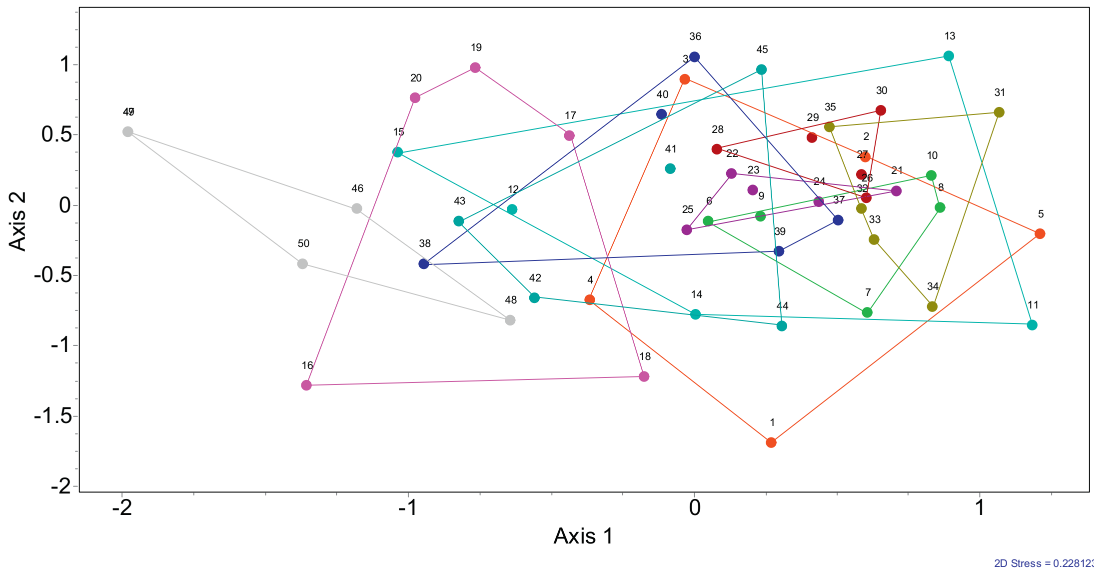

Fig. 5. Results of non-metric multidimensional scaling analysis of communities in the different substrates. Key to points: 1–5: Carbon8 pellets; 6–10: clay; 11–15: clay + paper ash; 16–20: paper ash; 21–25: red brick; 26–30: red brick + clay; 31–35: red brick + clay + paper ash; 36–40: Superlite; 41–45: Superlite + paper ash; 46–50: yellow brick.

the most diverse communities. On average, the rate of emergence was around 70–75 plants m^{-2}, even with a higher sowing rate (approximately 10 g m^{-2}) compared to other studies which recorded between 90–300 plants m^{-2} (Benvenuti, 2014). Indeed Benvenuti (2014) suggests that this may be due to the

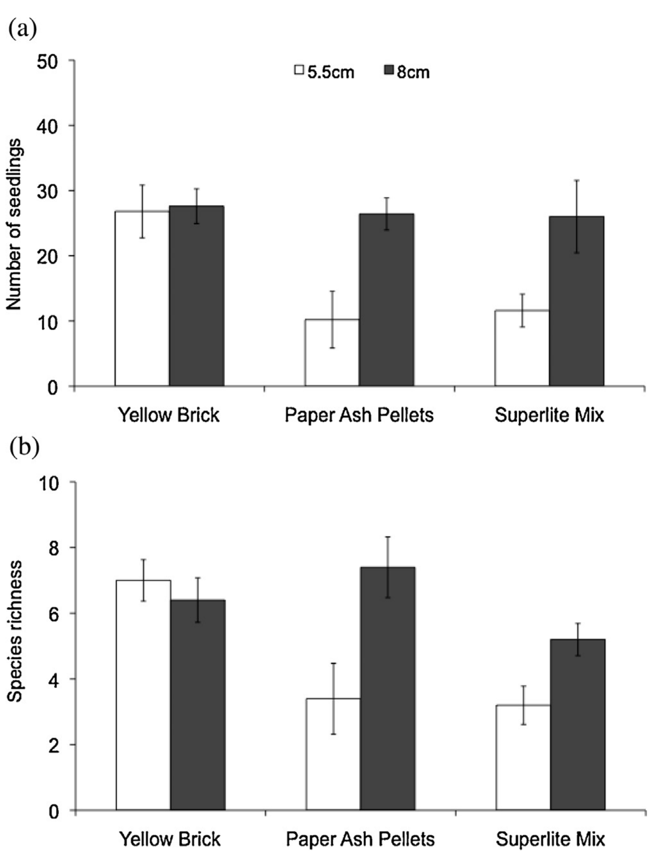

Fig. 6. (a) Plant/seedling numbers and (b) species richness, in each of the six treatments in test plot II; including 3 substrates at 2 depths. Bars represent mean ± one standard error.

characteristic dormancy of wild flower seeds and the faster growth of flora due to warmer conditions at roof level. Findings from this investigation seemed to suggest that for the first couple of years on a new green roof there is an initial surge of plant life, which becomes less over time as competition between larger plants arises (Nagase and Dunnett, 2013), nutrients are reduced and certain individuals struggle to survive in the harsh conditions. Once this phase has passed, seeds that were not in the original mix (such as *Chenopodium album*, as found in this study) were able to colonise the substrates (Madre et al., 2014). However some invaders may be of the same species—possibly with a more hardy advantage over the commercially bought seeds (Vander Mijnsbrugge et al., 2010)—resulting in reduced individual plant numbers over time but a constant number of species maintained within the substrates. It should be noted that this was a short-term study and that the number of species may be reduced in subsequent years, as found by Dunnett and Kingsbury et al. (2008), Nagase and Dunnett (2010) and Benvenuti (2014) as some species become more dominant.

One third of the species in the seed mix were never observed in the experimental units. This may have been due to the time of seeding and perhaps the need for certain species to undergo scarification or more favourable environmental conditions before germination (Hull, 1974). It may also have been due to the harsh conditions on the green roof, such as the thin substrate layers (Madre et al., 2014), severe drought stress during hot, dry months (Bousselot et al., 2011) and the limited nutrients available (Emilsson et al., 2007). The biological, physical and chemical properties of the various growing substrate may also have affected plant germination and survival (Molineux et al., 2009, 2014).

The substrates containing clay pellets were overall the most effective for plant diversity and supported the most individuals at the time of the 9 months survey. This is likely due to the good water holding capacity of these pellets and that in their 'raw' state, pH is not high, and can be reduced to neutral with addition of organic matter (Molineux et al., 2009). For similar reasons, red brick was also a good aggregate to use in the blends for several plant species, especially *E. vulgare*, *L. corniculatus* and *T. pratense*. Not only did these substrates support higher diversity, they also tended to provide a more even establishment of plants, suggesting that they would be of greater value for use in green roof designs. If there is less variation from roof to roof, then the process of installing species-rich green roofs in different locations will become more predictable. Substrates with the combination of these two aggregates (RC) supported the highest numbers of both species and individuals by the end of the study. Meanwhile, paper ash pellets were particularly poor at supporting plant establishment and growth, most probably due to their limited water holding capacity and that organic matter addition has less of an effect on reducing their high pH (Molineux et al., 2009). Only when these pellets were mixed with clay and red brick was the performance acceptable. This suggests that over time substrates are more successful if they comprise of a blend of different materials. The differences in physical characteristics of these aggregates probably contribute to this success on both a particle and chemical level, indeed previous research by Molineux et al., 2009 and more recently Graceson et al., 2013 show that the combination of aggregates with organics changes the original properties of the materials making some substrates more effective at storing water and releasing it to plants when needed than others. Thus, there are often interactions between the substrate components that are hard to predict or calculate from just laboratory-based experiments; this highlights the importance of carrying out rooftop level research.

The ordination analysis showed that the paper ash pellets and yellow brick supported assemblages that were very different to the other substrates, specifically being impoverished in numbers and diversity. This is likely due to the physical and chemical properties, such as water holding capacity and pH of these substrates (Molineux et al., 2009). Other substrates produced assemblages that was persistent over two summer growing seasons, an important factor in creating sustainable communities. It has long been known that communities composed of perennial plants support greater numbers of insects and associated organisms than do the ruderal communities characteristic of early succession, dominated by annual plants (Southwood et al., 1986; Brown et al., 1987). It is thus desirable to attempt to establish such perennial assemblages on green roofs, for the purposes of biodiversity enhancement in urban environments. This study has shown that establishment of the community is certainly feasible. The fact that the highest levels of associated faunal diversity can be achieved with the creation of mosaic habitat is a concept that could be achieved with areas of varying substrate types and depths on green roofs (Gedge et al., 2012). It is important now to conduct experiments that involve the most promising mixtures of aggregates and to monitor the establishment of the associated insect communities.

The establishment and persistence differences between the same substrates at different depths in test plot II showed that the paper ash pellets and Superlite mix were significantly improved. For example, increasing depths from 5.5 cm to 8 cm, vastly improved both abundance and species richness. This indicates that it is not some chemical property such as pH that resulted in poor performance, instead it is more likely to be water holding capacity, which would be increased by depth (Durhman et al., 2007). These results also support early work by Brenneisen (2006) and Kadas (2007) and more recent research by Köhler and Poll (2010) and Madre et al. (2014), where they all show depth to be the most important factor for plant species richness. However in this study, the one exception was yellow brick, which did not improve species richness and, in fact, showed a small though statistically insignificant decrease in species numbers when the depth was increased. It is not known what property of yellow brick made it so unsupportive of plants in plot I and plot II, but it may be a physical attribute rather than a chemical one. Graceson et al. (2013) suggest that increasing substrate depth may not increase water retention capabilities of certain substrate types because of the intra-particle and inter-particle pore spaces available for water holding. As a general rule, increased depth would be beneficial for plant growth in most cases but substrate type also plays a vital role in green roof design. Importantly adding 2.5 cm to the depth of a roof will increase its weight and would not be structurally desirable in some instances.

5. Conclusions

This study has shown that the establishment of perennial plants on green roofs is possible and that these plants can survive over two growing seasons. The most effective substrate for plant biodiversity varied over time, but admixes (blends of two or more different aggregates) performed particularly well in terms of both coverage and plant species richness. In particular, red brick, clay pellets and a combination of the two offer very promising substrates for the maximization of plant diversity and a more even establishment of plants. For poorer performing substrates, coverage and species richness is enhanced (in most cases) with greater substrate depth, and depth alone can vastly improve the performance of a particular aggregate that may not be very successful if used at shallow depths of 5.5 cm. It would be interesting to see if this trend changes in subsequent years, particularly with regards to different weather patterns. Therefore the hope for future research is long-term monitoring of extensive green roofs using a range of novel recycled substrates, to determine just how resilient these urban habitats could be. Furthermore, their abilities to support communities of associated insects and birds need to be tested over extended periods of time.

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