Amount of water runoff from different vegetation types on extensive green roofs: Effects of plant species, diversity and plant structure

Ayako Nagase\textsuperscript{a,∗}, Nigel Dunnett\textsuperscript{b,1}

\textsuperscript{a} Chiba University, Graduate School of Horticulture, Environmental Science and Landscape Architecture Course, 648 Matsuo, Matsudo-city 271-8510, Japan
\textsuperscript{b} University of Sheffield, Department of Landscape, Arts Tower, Western Bank, Sheffield S10 2TN, UK

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Increased stormwater runoff from impervious surfaces is a major concern in urban areas and green roofs are increasingly used as an innovative means of stormwater management. However, there are very few studies on how different vegetation types affect the amount of water runoff. This paper describes an experiment that investigates the influence of plant species and plant diversity on the amount of water runoff from a simulated green roof. Twelve species were selected from the three major taxonomic and functional plant groups that are commonly used for extensive green roofs (forbs, sedum and grasses). Four species were chosen from each group and planted in combinations of increasing diversity and complexity: monocultures, four-species mixtures and twelve-species mixtures. The results showed that there was a significant difference in amount of water runoff between vegetation types; grasses were the most effective for reducing water runoff, followed by forbs and sedum. It was also shown that the size and structure of plants significantly influenced the amount of water runoff. Plant species with taller height, larger diameter, and larger shoot and root biomass were more effective in reducing water runoff from simulated green roofs than plant species with shorter height, smaller diameter, and smaller shoot and root biomass. The amount of water runoff from \textit{Sedum} spp. was higher than that from bare ground. Species richness did not affect the amount of water runoff in this study.

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\textbf{1. Introduction}

Increased stormwater runoff from impervious surfaces is a major concern in urban areas (Scholz, 2004) where the sewage systems cannot cope with heavy storms. However, upgrading to a larger system capable of quickly rerouting the water would not only be costly, but would also pose a risk of flooding downstream and reduced efficiency of water treatment installations (White, 2002). Hence, water runoff management has attracted much interest in recent years. In the United States, Stormwater Best Management Practices (BMPs) are primarily designed to lessen the impact of urban development and drainage by increasing stormwater storage areas across a watershed, therefore slowing the flow of water into a receiving water body, and/or replacing impervious surfaces with permeable areas that allow stormwater infiltration (Carter & Jackson, 2007). Effective management practices include stormwater planting (aboveground planting containers that intercept water diverted from a roof), open channels (concave, vegetated conveyance systems), wetlands, and green roofs (vegetated roof surfaces) (Dunnett & Clayden, 2007). Green roofs are one of the most important BMPs given the lack of land in urban areas. A number of large cities have established water management policies to encourage the construction of green roofs. For example, in Portland, Oregon, developers who install impervious surfaces exceeding an area of 46.5 m\textsuperscript{2} must allow for onsite stormwater management. If conditions onsite do not permit full water quality treatment and flow rate control, the developer must either build an offsite facility, or pay an ‘in lieu’ fee for municipal stormwater management. Additionally, in areas where zoning regulations limit a building’s height-to-floor-area ratio, by greening all or part of a roof, a developer can add as many as three additional square metres to the building height for every square metre of green roof (Liptan, 2005).

The management of water runoff is a highly active area of green roof research and many studies have shown that green roofs can significantly reduce the amount of water runoff compared to black roofs (Carter & Jackson, 2007; Getter, Rowe, & Andresen, 2007; Schroll, Lambrinos, Righetti, & Sandrock, 2011; Teemusk & Mander, 2007; VanWoert et al., 2005).Mentens, Raes, and Hermy (2006), summarised German studies from 1987 to 2003 and reported that the estimated annual rainfall-retention capability ranges from 75% for intensive green roofs (median substrate depth: 150 mm) to 45% for extensive green roofs (median substrate depth: 100 mm).
roofs influence runoff water in a number of ways. Water that falls on the roof can be absorbed into pore spaces in the substrate or can be taken up by absorbent materials in the substrate. It can also be taken up by the plants and either stored in plant tissues or transpired back into the atmosphere. Some water may lodge on plant surfaces and subsequently evaporate (Dunnett & Kingsbury, 2008).

During a short storm, water in excess of the field capacity is temporarily stored in the soil and vegetation, which means that the peak runoff is delayed and reduced (Bengtsson, Grahn, & Olsson, 2005).

Green roof vegetation can affect the amount of water runoff depending on each plant’s capacity for water interception, water retention and transpiration. The amount of water runoff from a green roof is given by the following formula (Koehler, 2004): water runoff = precipitation – (water interception + water retention + transpiration from plants + evaporation from soil). Greater water interception by plants may effectively reduce water runoff from green roofs. Clark (1937, 1940) compared the interception of rainfall by different types of plants and concluded that low-growing or mat-forming plants did not intercept as much rain as taller plants because of the smaller surface area that was exposed. In addition, the belowground plant structure is important for water management since water retention in the soil may also be affected by the plant root structure. Maclvor and Lundholm (2011) showed that plant species that formed extremely dense fibrous roots captured the least amount of water runoff from green roofs because they reduced the porosity of the growing medium and the volume of space in which water could be retained. Not only water interception and water retention, but also a higher transpiration rate could lead to a greater reduction of water runoff (Lundholm, Maclvor, MacDougall, & Ranalli, 2010). Species that can evaporate/sprinkle more water from the growing medium will create more space for water capture in subsequent rain events (Maclvor & Lundholm, 2011). Plants are divided into three types in terms of their photosynthetic mechanism: C3 plants (to which the majority of plants belong), C4 plants (mainly grasses) and Crassulacean acid metabolism (CAM) plants (mainly succulents). C4 plants tend to show a high transpiration rate, and their growth rate is higher than that of C3 and CAM plants (Larcher, 2003). On the contrary, CAM plants generally have higher water-use efficiency and retain more water in the substrate than C3 and C4 plants. As the stomata of CAM plants are closed during the day, plant gas exchange occurs at night, thus reducing transpirational water loss (Gravatt & Martin, 1992). It was previously hypothesized that C3 and C4 plants are more effective at reducing water runoff from green roofs compared to CAM plants because C3 and C4 plants use more water than CAM plants.

In addition to the above characteristics of individual plants, vegetation diversity might also influence the hydrological performance of green roofs. The amount of water runoff can be reduced if the vegetation contains many species and a variety of structural types according to the following reasons. Rixen and Mulder (2005) pointed out that the increase in water absorption with greater species richness may be explained by two different mechanisms. Firstly, it may be a sampling effect: there is a greater probability of including at least one species with a very high absorption capacity in high-diversity plots. Secondly, the inclusion of more species results in a greater diversity of architectures. The inclusion of taller species may result in a lower rate of evaporation, while mat species that are in contact with the soil may release more moisture from the soil into the subcanopy space. Lamont and Bergl (1991) pointed out that many species of contrasting growth form behave differently in their use of soil water. Different rooting patterns or phrenologies in these species create a type of belowground niche separation. This facilitates coexistence by allowing differential exploitation of the soil profile either spatially or temporarily.

Although previous studies have shown that the amount of water runoff is influenced by the design of a green roof, such as the roof slope (Getter et al., 2007), substrate depth (VanWoert et al., 2005), and roof structural components (Berntdttson, 2010), as well as the rainfall intensity (MacMillan, 2004), studies on the role of green roof vegetation in the management of runoff water have been limited (Lundholm et al., 2010). Previous green roof studies tended to use Sedum spp. (Monteirussro, Rowe, Rug, & Russell, 2004; VanWoert et al., 2005) or a mixture of perennial plants (Teemusk & Mander, 2007) and different vegetation was not compared. However, some recent papers address the effect of plant species and functional group combinations on green roof ecosystem functions (Bultur & Orians, 2011; Dunnett, Nagase, Booth, & Grime, 2008; Lundholm et al., 2010; Maclvor & Lundholm, 2011; Nagase & Dunnett, 2010; Wolf & Lundholm, 2008). Bulter and Orians (2011) showed that Sedum spp. could facilitate the growth of neighbouring plants during water stress, but acted as a competitor when water was abundant. Lundholm et al. (2010) studied green roof systems planted with monocultures or mixtures containing one, three, or five forms to quantify water capture, and they showed that some mixtures outperformed the best monocultures for water capture and evapotranspiration. Although the above mentioned studies demonstrated that the composition of vegetation affected both the amount of water retained and released from green roofs, detailed information was not explicitly provided on factors such as the role of the plant structure.

In the present study, we investigated how vegetation and plant diversity affect runoff reduction from green roofs. Understanding the hydrological performance of different vegetation makes it possible to choose the appropriate plants to maximize the benefit of reduced water runoff from green roofs. This study followed up on the previous study by Dunnett et al. (2008), who compared two experiments to show the role of vegetation composition on green roof function in relation to rainwater runoff. Their two experiments were (a) an outdoor lysimeter experiment that investigated the quantity of runoff from trays containing 100 mm of growing medium and combinations of grasses and forbs, together with bare substrate, and (b) a greenhouse experiment using simulated rainfall to estimate the amount of rainfall intercepted by different vegetation types. The latter experiment comprises only part of our experiment and it is necessary to show additional information to discuss how vegetation and plant diversity affect water runoff from green roofs. In this study, the results of water runoff from modules planted with species in monocultures and mixtures experiencing simulated rain intensity of 50 mm/h are shown and discussed whereas the same modular setup experienced 100 mm/h simulated rainfall intensity in Dunnett et al. (2008). Our first goal was to examine how different plant species and vegetation in mixtures and in monocultures affect the reduction of water runoff from green roofs. Our second goal was to examine how plant structure affects the amount of water runoff.

2. Methods

The experiment was carried out in a greenhouse in order to maintain a constant volume and intensity of simulated rain. We selected one of the greenhouses of the experimental garden at the University of Sheffield, UK. This greenhouse was heated when the outside temperature fell below 20 °C; the inside temperature was kept at more than 20 °C. Twelve plant species were used to create a vegetation cover of the same plant density but differing species composition. The twelve species were chosen from sedum (Sedum acre ‘Minor’, Sedum album ‘Coral Carpet’, Sedum rupestre, Sedum spurium ‘Coccineum’), grasses (Anthoxanthum odoratum, Festuca ovina, Koeleria macrantha, Trisetum flavescens), and herbaceous plants other than grass and sedum, referred to as forbs in this study.
Table 1
The twelve species and their ecological and morphological characteristics (Brickell, 2003; Hubbard, 1984; Snodgrass & Snodgrass, 2006).

<table>
<thead>
<tr>
<th>Plant name</th>
<th>Family</th>
<th>Plant type</th>
<th>Leaves</th>
<th>Roots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Armeria maritima</td>
<td>Plumbaginaceae</td>
<td>Forb</td>
<td>Dense rosettes of liner to sharp shaped leaves</td>
<td>Shallow roots</td>
</tr>
<tr>
<td>Leontodon hispidus</td>
<td>Asteraceae</td>
<td>Forb</td>
<td>Erect or oblique usually branched premorose stock. Hispid with forked</td>
<td>Root stock with shortly cylindrical</td>
</tr>
<tr>
<td>Prunella vulgaris</td>
<td>Lamiaceae</td>
<td>Forb</td>
<td>Broadly ovate, spreading and vigorous growth</td>
<td>Rooting freely from nods</td>
</tr>
<tr>
<td>Silene uniflora</td>
<td>Caryophyllaceae</td>
<td>Forb</td>
<td>Fleshy, lance shaped leaves, fringed with hairs</td>
<td>Deep rooting</td>
</tr>
<tr>
<td>Sedum acre 'Minor'</td>
<td>Crassulaceae</td>
<td>Sedum</td>
<td>Erect or trailing stems densely clothed in overlapping, triangular</td>
<td>Fibrous roots</td>
</tr>
<tr>
<td>Sedum album 'Coral Carpet'</td>
<td>Crassulaceae</td>
<td>Sedum</td>
<td>Glabrous green, creeping stem forming large mats, small ovoid-globose to</td>
<td>Fibrous roots</td>
</tr>
<tr>
<td>Sedum rupestre</td>
<td>Crassulaceae</td>
<td>Sedum</td>
<td>Alternate, pointed, cylindrical leaves. Upright, leafy woody stems</td>
<td>Fibrous roots</td>
</tr>
<tr>
<td>Sedum spurium 'Coccineum'</td>
<td>Crassulaceae</td>
<td>Sedum</td>
<td>Upright, branching red stems bearing opposite, ovate, toothed leaves</td>
<td>Developed root stocks</td>
</tr>
<tr>
<td>Anthoxanthum odoratum</td>
<td>Poaceae</td>
<td>Grass</td>
<td>A tufted, culms erect or spreading, stout and smooth leaves</td>
<td>Fibrous root. Relatively shallow root</td>
</tr>
<tr>
<td>Festuca ovina</td>
<td>Poaceae</td>
<td>Grass</td>
<td>Densely tufted, culms erect or spreading, very slender, stiff, narrowly</td>
<td>Relatively shallow root system</td>
</tr>
<tr>
<td>Koeleria macrantha</td>
<td>Poaceae</td>
<td>Grass</td>
<td>Densely tufted, forming a compact mound of narrowly linear, hairy leaves</td>
<td>Fibrous root system, when competing with</td>
</tr>
<tr>
<td>Trisetum flavescens</td>
<td>Poaceae</td>
<td>Grass</td>
<td>A loosely tufted, culms erect or spreading, slender, rather weak,</td>
<td>generally shallower</td>
</tr>
</tbody>
</table>

(Armeria maritima, Leontodon hispidus, Prunella vulgaris, Silene uniflora) (see Table 1). From each of these groups, four representative species were chosen and planted in combinations ranging from monocultures through to highly diverse mixtures. Combinations (vegetation types) were as follows: (a) each species grown in monocultures; (b) three mixtures of single taxonomic or functional types: forbs, grasses and sedum; and (c) all twelve species in combination (Fig. 1). As a reference, substrate with no vegetation (bare ground) was also prepared.

The plug plants of each species were transplanted into flats (368 mm \( \times \) 216 mm \( \times \) 57 mm, 0.79 m\(^2\)) in the middle of May 2006. The methodology for plant cultivation in this study is the same as in Nagase and Dunnett (2010) except that L. hispidus was used instead of Origanum vulgare.

The transplanting medium was a mixture of commercial green roof substrates based on crushed tile or brick (Zinco sedum substrate and Zinco semi-intensive substrate 1:1). Details of the substrate characteristics are as follows: granules of <0.063 mm diameter \( \leq \)7–15%, salt content \( \leq \)2.5%, porosity 63–64%, pH 7.8–7.9, dry weight 940–980 kg/m\(^3\), saturated weight 1240–1360 kg/m\(^3\), maximum water capacity 22–38%, and water permeability >0.064–0.1 cm/s (Alumasc Exterior Building Products, 2006). Zinco substrate was obtained from Alumasc (Northamptonshire, UK). This substrate was chosen because it is one of the most commonly used substrates for green roofs in the UK. Each flat was prepared with 3000 g of substrate to a depth of 50 mm. Twelve plants were planted in four rows (75 mm interval) and three lines (55 mm interval). There were three replicates for each vegetation type, resulting in a grand total of 48 flats. The flats were watered every other day until the experiment started.

A rainfall simulator (Department of Civil Engineering, Sheffield University) was used to quantify the exact amount of water falling onto the vegetation surface. A plastic tank (503 mm \( \times \) 675 mm \( \times \) 410 mm outside, 477 mm \( \times \) 650 mm \( \times \) 399 mm inside) was supported 1.5 m above a table. At the base of the tank, seven rows of ten holes 5 mm in diameter were drilled at 48-mm intervals. A needle was attached to the base of each hole: these produced regular drops, similar to real rainfall. To collect the runoff water, a flat (shallow tray 368 mm \( \times \) 216 mm \( \times \) 57 mm, same dimensions as the vegetation flat) without drainage holes was placed on the table surface.

![Monoculture](image1.png)

![Four-species mixture](image2.png)

![Twelve-species mixture](image3.png)

Fig. 1. Combination of plants.
Four plastic tubes (40 mm in diameter and 50 mm in height) were placed in each corner of the flat to collect the water, thus ensuring that the runoff water was separated from the vegetation flat.

Two different intensities of rainfall were simulated: 100 mm/h and 50 mm/h because it was hypothesized that the different plant species and mixtures may affect the amount of water differently in high and low rainfall intensity. We chose two high intensities in view of the studies suggesting that rainfall has become more variable and that rainfall intensity and the frequency of high-intensity rainfall may have increased in some areas, including the UK (Easterling et al., 2000; Osborn, Hulme, Jones, & Basnett, 2000; Robson, 2002). For 100 mm/h, the water tank was filled to 390 mm and allowed to fall to a depth of 374 mm (2000 mL for each flat). For 50 mm/h, the tank was filled to 228 mm and allowed to fall to 220 mm (1000 mL for each flat). Each rainfall event lasted 15 min. The 100 mm/h rain events were alternated with the 50 mm/h rain events over a 12-week period. The water runoff from all vegetation flats was measured every seven days from September 16 to November 19, 2006 (five times in each rainfall and ten times in total), by tipping the water in the collection flats into a 200-mL graduated cylinder after the water runoff had stopped. Two flats were set up at the same time for each rainfall. Each water runoff value was obtained from the mean of 15 measurements (3 replicates × 5 weeks). Vegetation flats received only the above artificial rainfall and no further irrigation was applied.

Plant height (from bottom to highest leaf apex) and diameter (the plants were observed from above and the plant length and width were measured) were measured every two weeks from September 16 to November 12, 2006 (five times in total). For the diameter, the plant length and width were averaged. In this study, the number of plant species for each vegetation type was different; thirty-six plants for monocultures (twelve plants for each flat × 3 replications), nine plants for four-species mixtures (three plants for each flat × 3 replications), and three plants for twelve-species mixtures (one plant for each flat × 3 replications). Therefore, representative plants from each flat were chosen randomly and plant growth was measured to obtain three replicates of each species in total: one plant was measured for monocultures, four plants (one plant from each species) for four-species mixtures, and all plants for twelve-species mixtures. They were marked for identification and the growth of the same plant was measured. In December 2006, all plants were harvested and the roots were carefully washed. The plants were then oven-dried at room temperature for seven days, after which shoot dry weight and root dry weight were measured using two balances: Precisa 2200c and Mettler AE 163. The readability of these balances was 0.01 g and 0.1 mg, respectively. The Mettler AE 163 was used when the plant dry weight was less than 0.01 g.

To test for significant differences in amount of water runoff from different vegetation types, one-way ANOVA was used. When there were significant differences, means were separated by Tukey's test at the probability level P < 0.05. Linear regression was carried out to identify the relationship between four factors (plant height, plant diameter, dry shoot weight and dry root weight) and the amount of water runoff, respectively. Plant height and diameter were compared with the mean water runoff each time they were measured. Dry shoot and dry root weight were compared with the mean water runoff of six measurements. All statistical analysis was carried out using Minitab Release 14 software.

3. Results

Mean water runoff (all five measurements) from seventeen types of vegetation is shown in Fig. 2. The results reveal a highly significant difference between the amount of water runoff and the vegetation type (d.f. = 15,238, F = 12.88, P < 0.01). Overall, the grass species were the most effective at reducing water runoff, followed by the forbs and sedum. In the grass species, A. odoratum showed the least amount of water runoff. Both K. macrantha and F. ovina had more water runoff than A. odoratum, although there was no significant difference among all grass species. Among the forbs, S. uniflora was more effective at reducing the amount of water runoff from flats compared to the other species, whereas A. maritima showed the largest amount of water runoff. Overall, Sedum spp. showed the largest amount of water runoff and was the only species group with more water runoff than the bare ground. Among the Sedum spp., S. rupestrse showed less water runoff compared to the creeping species S. acre 'Minor' and S. album 'Coral Carpet'. However, the difference between them was not statistically significant. For the four-species mixtures, the grass mixture was more effective at reducing water runoff compared to the sedum mixture. The twelve species did not show the smallest amount of water runoff; instead, the water runoff was less in the monocultures of A. odoratum, S. uniflora, T. flavescens, as well as in the four-grass mixture.

![Fig. 2. Mean amount of water runoff from different vegetation types. Error bars represent standard error. Means with the same letter do not differ significantly from each other (d.f. = 15,238, F = 12.88, P < 0.01).](image)

![Fig. 3. The relationship between height (cm) and mean amount of water runoff (mL). The fitted line is y = 613.5 – 13.27x (R² = 46.5%, d.f. = 1,14, F = 12.19, P < 0.01).](image)
The relationship between the amount of water runoff and the plant size (height and diameter) on November 12, 2006 is shown in Figs. 3 and 4, respectively. The relationship was compared at each measurement and showed a significant difference in all six measurements. The results on November 12 (final measurement) were chosen as representative because they were almost the same in five measurements. There was a significant negative relationship between both height (cm) and diameter (cm) and the amount of water runoff (mL) (height: $y = 613.5 - 13.27x$, $R^2 = 46.5\%$, d.f. = 1,14, $F = 12.19$, $P < 0.01$; diameter: $y = 763.3 - 18.57x$, $R^2 = 58.6\%$, d.f. = 1,14, $F = 19.79$, $P < 0.01$). This indicates that the modules of taller species with a larger diameter (most grass species used in this study) retain more water compared to the modules of shorter species with a smaller diameter (most Sedum spp. used in this study).

There was a significant negative relationship between mean dry weight of roots and mean water runoff ($y = 564.9 - 137.7x$, $R^2 = 56.3\%$, d.f. = 1,14, $F = 18.05$, $P < 0.01$) (Fig. 5). This result suggests that grass species and the forbs that had more root growth lead to greater water capture in the soil. Similarly, there was a significant negative relationship between the mean dry weight of shoots and the mean water runoff ($y = 717.0 - 275.0x$, $R^2 = 46.7\%$, d.f. = 1,13, $F = 10.51$, $P < 0.01$) (Fig. 6). Therefore, not only the plant structure, but also the extent of plant growth is important for reduction of water runoff. We regarded the shoot weight of S. acre 'Minor' as an exception and therefore omitted the value from statistical analysis. This species showed a different pattern from the other species; mean water runoff was high although the dry shoot weight was also high. S. acre 'Minor' had very dense foliage and succulent leaves; therefore, its dry shoot weight was high.

4. Discussion

It was shown that different plant species influenced the amount of water runoff. The grass species were the most effective for reducing water runoff, followed by forbs and sedum. This is consistent with previous research on the effect of plant species and functional group combinations on green roof ecosystem functions. Lundholm et al. (2010) showed that the highest water capture was observed in grasses, followed by tall forbs, creeping forbs and succulents. MacIvor and Lundholm (2011) showed how different species affect

![Fig. 4](image1.png)

*Fig. 4.* The relationship between diameter (cm) and mean amount of water runoff (mL). The fitted line is $y = 763.3 - 18.57x$ ($R^2 = 58.6\%$, d.f. = 1,14, $F = 19.79$, $P < 0.01$).

![Fig. 5](image2.png)

*Fig. 5.* The relationship between dry root weight (g) and mean amount of water runoff (mL). The fitted line is $y = 564.9 - 137.7x$ ($R^2 = 56.3\%$, d.f. = 1,14, $F = 18.05$, $P < 0.01$).

![Fig. 6](image3.png)

*Fig. 6.* The relationship between dry shoot weight (g) and mean amount of water runoff (mL). The fitted line is $y = 717.0 - 275.0x$ ($R^2 = 46.7\%$, d.f. = 1,13, $F = 10.51$, $P < 0.01$).
the stormwater capture ability; in their study, three graminoids (Carex argyrantha, C. nigra, and Deschampsia flexuosa) captured more water than other species. All of the above studies found that bare soil (no vegetation) captured more water compared to most species. In this study, the water runoff from most species was lower than that of the bare soil; Sedum spp. was the only exception. This may be due to different experimental design (e.g., green roof vs. greenhouse, different substrate types) and the difference in rainfall duration might be an important factor leading to the different results. In MacIvor and Lundholms study, the rainfall duration was much shorter (10 mm of rain within 30 s and within one min, respectively) than the duration in this study (50 mm/h for 15 min).

The results from this experiment indicate that the structural properties of plants promote rainwater interception. Shorter plants with a smaller diameter shed the greatest amount of water runoff, while taller plants with a bigger diameter intercepted and retained the greatest amount of water runoff. This result agrees with previous hydrology studies; height, canopy size and density have been reported to determine interception fluxes (e.g., Crockford & Richardson, 2000). Low-growing or mat-forming plants do not intercept as much rain as taller plants because of the small surface area that is exposed (Clark, 1940; Park & Cameron, 2008). Not only the plant structure, but also the surface water storage capacity of the plant cover is an essential contribution to the interception process (Garcia-Estringana, Alonso-Blázquez, & Alegre, 2010). The fate of water droplets on leaves is significantly influenced by the fine structures found on the leaf surface as in the case of hairy and waxy leaves (Yu et al., 2005). For example, S. uniflora might be just as effective as the grass species at reducing runoff in part because S. uniflora is covered with an impermeable wax and has dense flat leaves, thus water drops effectively adhere to the leaves (Hull & Bleckmann, 1977). In this study, it was observed that hairy leaves such as in K. macrantha and T. flavescens could catch more water drops than F. ovina, which has needle-like leaves. Similarly, the horizontal leaves of S. rupestre and S. spurium ‘Coccinium’ helped the water to stay on the leaves although water on the sedum leaves fell off quickly because of the small size of the leaves and the gaps between them. In a previous study, plant pubescence was considered the variable that best explains the water storage capacity in some plants (Monson, Grant, Jaeger, & Schettle, 1992). Many drought-tolerant plants, which are appropriate for extensive green roofs, have adapted such morphology as waxy leaves (e.g., Eryngium maritimum) and hairy leaves (e.g., Stachys byzantina) to limit the rate of water loss (Dunnett & Kingsbury, 2008; Jones, 1983).

In this study, the modules of grasses and of forbs that had more root growth led to greater water capture in the substrate. It was observed that the roots connected large aggregates together in the substrate and it was like a sponge in the vegetation flat when the plants were harvested. Therefore, the volume of space in which water could be retained increased because the roots act like a water retaining mat. This result is inconsistent with the previous study, which showed that the species that formed extremely dense fibrous roots captured the least amount of water (MacIvor & Lundholm, 2011). The difference in physical properties of the growing medium might be the reason for the controversial results; however, further research is necessary to confirm this.

Not only water capture, but also the water use of plants might affect the amount of water runoff. Lundholm et al. (2010) showed that water lost due to evaporation and transpiration followed a similar pattern to water capture. In this study, Sedum spp. showed the largest water runoff and most Sedum spp. showed an even larger amount of water runoff than the bare ground. This is consistent with a previous study in which pots planted with Sedum spp. retained more water than pots with substrate alone (Bulter & Orians, 2011; Wolf & Lundholm, 2008). It is estimated that the lower evapotranspiration rate of sedum might diminish the ability of a green roof system to mitigate stormwater retention. Moreover, Sedum spp. covered the bare soil and this can reduce the evaporation from the soil. On the contrary, C3 and C4 plants generally transpire more water per molecule of CO2 fixed; thus they probably exhibited a higher transpiration ratio (Durman, Rowe, & Rugh, 2006). Sedum spp. as well as A. maritima grow slowly resulting in low biomass, whereas grass species grow quickly, resulting in high biomass in this study. These results indicate that the former might be able to use water efficiently and the latter might use a lot of water. Indeed, Sedum spp. and A. maritima resulted in great survivability in three weeks of no watering; on the contrary, grass species were not able to survive at all in three weeks of no watering in a previous drought-tolerance study (Nagase & Dunnett, 2010). Unfortunately, evapotranspiration was not measured in this experiment and further detailed research is necessary to better understand the relationship between evapotranspiration and amount of water runoff.

No consistent relationship was found between species richness and amount of water runoff in this study. Plant species complementarity should manifest itself as overyielding, i.e., species mixtures should be more productive than most productive monocultures of their components if the species complement or facilitate each other (Garnier, Navas, Austin, Lilley, & Gifford, 1997; Špačková & Lepš, 2001). However, the results showed that the water runoff from 12 species was higher than that of some of the monocultures (S. uniflora, T. flavescens, A. odoratum) and four-grass mixtures. This may be due to a sampling effect; the greater the number of high-performance plants planted, the better the water retention would be. However, only three types (sedum, forb, grass) of four-species mixtures were used in this study and it is difficult to determine how each of these species affects green roof performance. Lundholm et al. (2010) pointed out that while the sampling effect may be important in determining the relationship between biodiversity and ecosystem functioning, different species or groups are responsible for the high performance of different functioning, thus further supporting the idea that multifunctionality may be an important benefit of plant diversity in green roof systems.

Previous studies have shown that the depth and type of substrate, not the vegetation type and cover, is the major influence on green roof water retention capacity (Berndtsson, 2010; Monterrusso et al., 2004; VanWoert et al., 2005). On the contrary, the difference in amount of water runoff between vegetation types was very clear in this study. It is important to remember that this study was intensive, carried out under artificial conditions and in a short time. The greenhouse conditions in this study were not identical to green roof conditions; however, the aim of this study was focused on the effect of vegetation and plant diversity on runoff reduction from green roofs only. A green roof environment with wide temperature fluctuations, high exposure to wind and solar radiation may lead to different results. In addition, the simulated extensive green roof used in this study was very simple; it consisted only of vegetation and green roof substrate whereas extensive green roofs usually include water retention layers, drainage layers and root protection layers. In particular, water retention layers may significantly affect the amount of water runoff. For example, thick moisture-retention fabric capable up to 5.92 m² was used in one water runoff study (Getter et al., 2007). Moreover, the hydrology of a green roof tends to show dynamic changes over a year. Water is used by plants at different times of the year, depending upon when they are growing and/or when water is available for use (Humphrey, 1959). According to Mentens, Raes, and Hermy (2006), warm seasons result in higher evapotranspiration; therefore, the water retention capacity regenerates faster and the surface runoff from green roofs is smaller during the following rainstorm. According to a study by Neath, Bailey, Chanasyk, and Pluth (1991), differences in water retention are correlated with differences in vegetation especially...
in areas subject to summer drought. Nagase and Dunnett (2010) showed that a diverse plant mix was more advantageous than a monoculture in terms of greater survivability and higher visual rating under dry conditions. The water runoff from vegetation with greater species richness may be smaller than from some monocultures in a dry environment on roofs when measured over the long term; further detailed research is necessary to confirm this.

5. Conclusion

In this study, it was shown that there was a significant difference in amount of water runoff between vegetation types; grasses were the most effective for reducing water runoff, followed by forbs and sedum. Grasses and forbs, which have a tall height, large diameter, and large shoot and root biomass are recommended if reduction of water runoff is the main purpose of installing a green roof. Large-diameter plants reflect the total green roof coverage; therefore, it is also advisable to cover green roofs as much as possible for effective water management. In the case of green roofs where only the most stress-tolerant plants such as sedum can survive, upright Sedum spp. may reduce water runoff more effectively than creeping and succulent types of leafy species. In this study, it was not clear if species richness affected the amount of water runoff and more detailed research is necessary using various plant combinations. In future research, water runoff experiments should be conducted under artificial conditions and in the field, using both artificial rain based on patterns of real storm events and natural rain, and over the long term and short term. It would also be beneficial to study species-rich meadow roofs, such as a sedum–herbaceous–grass roof, for water management.

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