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The influence of plant type on green roof rainfall retention

S. Kemp¹ · P. Hadley¹ · T. Blanuša^{1,2} 

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Abstract

Green roofs can mitigate the flood risk by reducing the volume of runoff through direct interception and subsequent evapotranspiration (ET), but the planting choices can influence the extent of this service. Glasshouse experiments were carried out in spring/summer using simulated rainfall to compare the rainfall retention capacity of three physiologically active broadleaf species (*Heuchera micrantha*, *Salvia officinalis* and *Stachys byzantina*), which have previously shown to provide improved rooftop cooling, to an industry standard green roof species, *Sedum spurium*. Furthermore, the impact of varying ambient temperature and humidity conditions on the ability of these species to restore the substrate retention capacity through ET was also tested in a series of controlled-environment experiments simulating a range of potential UK summertime scenarios. Canopies alone retained up to 17% (*Sedum*) of the total rainfall in this study, with *Salvia* and *Stachys* also retaining in excess of 10%, and can make a substantial contribution to rainfall retention on a green roof. Rainfall retention was also strongly correlated with total ET in the preceding 72 h ($R^2 = 0.94$; $P < 0.001$). Species with high ET rates (*Salvia* and *Stachys*) were able to provide the greatest stormwater management service (up to 72% retention due to ET component). Furthermore, species ‘rankings’, in terms of ET and thus restoration of substrate retention capacity, were the same in all simulated potential UK summertime temperature and relative humidity scenarios, indicating that ‘superior’ species will be able to provide the greatest stormwater management provision in all climatic conditions.

Keywords Evapotranspiration · Runoff · *Salvia officinalis* · *Sedum* · Simulated rainfall · *Stachys byzantina*

Introduction

In highly urbanised societies such as UK, already nearly 90% of the population reside in urban areas (Anon 2013). Development of cities, where soils and vegetation are replaced with impervious surfaces, leads to increases in incidents of surface flooding in urban areas (Perry and Nawaz 2008; Warhurst et al. 2014). Urban vegetation, including green roofs, can help to mitigate the flood risk by delaying and reducing the volume of runoff (Carter and Rasmussen 2006; Speak et al. 2013), with green roofs being able to retain up to 100% of the rainfall in individual storm events (Stovin et al. 2012).

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✉ T. Blanuša
tijanablanusa@rhs.org.uk

¹ School of Agriculture, Policy and Development, University of Reading, Reading, UK

² Plant Sciences Department, Royal Horticultural Society, Garden Wisley, Woking GU23 6QB, UK

The main mechanisms through which vegetation on green roofs provides stormwater management are direct interception on plant canopies during rainfall, infiltration and storage of water in the substrate, and subsequent evapotranspiration (ET) from the green roof during dry periods (Stovin et al. 2012). Previous studies have identified several key factors influencing the retention performance of a green roof, including properties of the roof itself (e.g. slope; Getter et al. 2007), climatic and weather conditions (air temperature and humidity, net radiation, wind speed; Sims et al. 2016), characteristics of individual rainfall events (intensity, depth, duration; Stovin et al. 2012), and the substrate and vegetation types (Beecham and Razzaghmanesh 2015; Brandão et al. 2017).

The substrate of a green roof has frequently been acknowledged as the most important store of water (VanWoert et al. 2005). Retention of rainfall by a green roof has therefore been shown to depend on substrate characteristics, such as the type, depth and age of substrate (Mentens et al. 2006; Getter et al. 2007), and its properties, including water-holding capacity, porosity and antecedent substrate moisture content (SMC) (Stovin et al. 2015). Based on these factors, the substrate can retain a finite maximum volume of water during a rainfall event (defined as the substrate’s retention capacity), after

which any further water added will become runoff (Sims et al. 2016). Water stored in the substrate is subsequently lost from the green roof through ET, thus restoring the water retention capacity of the green roof following a rainfall event and allowing a greater volume of water to be retained by the roof in subsequent storms (Poë et al. 2015).

Vegetation, however, significantly increases the water retention capacity of a green roof compared to bare substrate alone (Voyde et al. 2010a), mainly as a result of the additional contribution of plant transpiration to total ET. Several studies also investigated differences in rainfall retention between different plant communities on green roofs (Nagase and Dunnett 2012; Whittinghill et al. 2015; Szota et al. 2017; Raimondo et al. 2015), suggesting that vegetation choice can influence the stormwater management capabilities of green roofs. Indeed, plant characteristics such as canopy structure, size and density, leaf morphology and root structure are thought to influence the capacity of particular species for direct interception (Nagase and Dunnett 2012; Lundholm et al. 2010; Aloisio et al. 2016).

The contribution of interception to long-term rainfall retention performance is, however, generally considered minor compared to the role of the vegetation in restoring substrate retention capacity through ET (Stovin et al. 2015). Evapotranspiration significantly influences the stormwater retention capacity, and thus the hydrological performance, of green roofs (Berretta et al. 2014). Due to the harsh environmental conditions typically experienced on green roofs, planting choices have traditionally been based on survival without irrigation, and hence species that are able to withstand substrate moisture deficits (i.e. succulents such as *Sedum*) are frequently used (Rayner et al. 2016). Likewise, the majority of green roof rainfall retention studies use succulent species or those with low water use rates (Starry et al. 2016; Berretta et al. 2014; Poë et al. 2015; Soulis et al. 2017). Using plants with inherently low ET rates will restrict the restoration of substrate retention capacity; *Sedums* have typically been found to provide lower rainfall retention due to their low ET rates (Whittinghill et al. 2015; Dunnett et al. 2008). Some recent research suggests however that drought-avoiding, low water-use plants, can also support rainfall retention on green roofs (Szota et al. 2017; Lundholm et al. 2010) and that *Sedum* species differ up to 20% in the rates of ET (Starry et al. 2016), so the story is clearly more nuanced and will be dependent on the local climatic circumstances. In principle though, species with significantly higher ET rates than *Sedum* will likely restore the substrate's water retention capacity faster and to a greater extent in dry periods between storms, so the rainfall retention is likely to improve in subsequent rainfall events.

In the UK, where average annual rainfall is high (between 600 and 3000 mm; Met Office 2017) and where even summertime rainfall in the warmest south-eastern region can reach

80 mm per month (Met Office 2017), choosing high ET species for green roofs would be plausible and advantageous. The substrate rainfall retention capacity could be restored quickly with these species as a result of their consistently high ET rates. Even if such species were implemented, a question remains whether 'superior' performers (i.e. those able to restore the substrate's rainfall retention capacity fastest and to the greatest extent due to high ET rates) remain 'superior' in a range of possible summertime temperature and humidity conditions (e.g. is there an advantage of having high ET species when the summer is humid and cool?). The main climatic parameters influencing ET are solar radiation, air temperature and humidity, and wind speed (Allen et al. 1998). Only a few studies have examined the influence of these climatic variables on the ET rates of green roof species (Berretta et al. 2014; Poë et al. 2015; Sims et al. 2016), especially whilst keeping all other factors constant (e.g. vegetation type, substrate type and depth, season and duration of study). These studies typically observed greater ET in summer compared to spring conditions (Berretta et al. 2014; Poë et al. 2015; Elliott et al. 2016) and in dry compared to humid climates (Sims et al. 2016), resulting from higher vapour pressure deficit (VPD) in warm and dry conditions driving faster ET. Indeed, in a study with identical green roofs located in different climatic regions in Canada (Sims et al. (2016)) found that, despite similar rainfall totals, overall retention was significantly higher on the green roof in the semi-arid climate (75.2%) compared to the roof in the maritime climate (43.4%). This was largely as a result of higher ET between storms on the roof in a semi-arid climate resulting in greater restoration of substrate retention capacity (Sims et al. 2016).

The objectives of our study were therefore:

- i. To investigate the impact of green roof plant species choice on rainfall retention, through a combination of canopy interception and restoration of substrate retention capacity (via ET);
- ii. To investigate the impact of varying environmental conditions (air temperature and relative humidity in different combinations) on the ET rates of a range of traditional and 'alternative' green roof species, and thus their capacity to retain rainfall.

Since it has traditionally dominated green roof planting choices, *Sedum* sp. was used in this study to represent an industry standard green roof species. Three significantly more physiologically active broadleaf species (*Heuchera micrantha* 'Obsidian', *Salvia officinalis* and *Stachys byzantina*), shown in our previous studies to offer superior cooling benefits in the UK climate context compared to *Sedum* (Vaz Monteiro et al. 2017), were selected for comparison. All these 'alternative' species have inherently high ET rates, large canopies of different densities and with varying leaf traits (presence or

absence of leaf hairs, leaf size and leaf angles) which may aid, or hinder, rainfall retention.

Materials and methods

Experiments were carried out in late spring/early summer of 2015 and 2016 in the glasshouse and controlled environment laboratory at the University of Reading, UK.

Plant material

Three broadleaf species, *Heuchera micrantha* ‘Obsidian’ (large, glossy leaves forming a closed canopy with a relatively sparse understorey), *Salvia officinalis* (dense canopy with many ‘layers’ of leaves, which have rough surfaces and short hairs) and *Stachys byzantina* (full, dense canopy and long leaf hairs), were compared to *Sedum spurium* (small succulent leaves forming a dense, low-growing canopy) in all experiments. *Heuchera* plants were purchased as two-year-old plants in 2 L containers from Coblands Nursery (Tonbridge, UK), whilst all other species were propagated in-house.

Experiment 1: The effect of vegetation type on green roofs’ capacity to capture rainfall

Experiments were carried out to quantify the volume of water that could be retained by plants with varying canopy characteristics and ET rates, using simulated rainfall to ensure consistency in the rainfall depth and intensity applied to each species. Experiments took place inside a ventilated glasshouse to avoid interference from natural precipitation in April 2016.

Experimental set-up

In February – March 2016, six replicates of each species were prepared, each planted in a 32 L plastic tray (40 × 60 × 19 cm, with drainage holes in the bottom) filled with 15 cm of peat-based compost (Vitax Ltd., Leicestershire, UK), the same substrate in which the plants were individually grown. The substrate had the following properties: pH 6; air-filled porosity 55%; substrate organic matter 75%, and water-holding capacity 60%. Six control trays of bare, unvegetated substrate were also prepared. As the purpose of the experiment was to compare plant species irrespective of the growing medium, and the experiment involved lifting and moving of large trays, a decision was made to use this lighter compost, rather than a conventional green roof one. To achieve full canopy cover over the tray, 3–4 two-year-old plants of *Stachys*, *Sedum* and *Heuchera* were planted per tray and six *Salvia* (propagated in autumn 2015) were planted per tray. The intention was to achieve a scenario of an aspirational green roof with 90–100% vegetation cover over the substrate (Fig. 1).



Fig. 1 The extent of vegetation cover for the studied species in trays – clockwise from top left - *Heuchera*, *Sedum*, *Stachys* and *Salvia*

Two rainfall events were simulated for each tray, with varying antecedent substrate moisture conditions: ‘saturated’ and ‘unsaturated’. ‘Saturated’ conditions were used to determine the *contribution of canopy retention* to overall rainfall retention by plants and substrate. ‘Unsaturated’ conditions were used to determine the *contribution of ET* to overall rainfall retention. To determine the volume of rainfall directly captured on the canopy, the substrate of all trays was watered to container capacity prior to rainfall application by submerging trays in water for 30 min and then leaving to drain for 2 h. Thus, antecedent substrate moisture content (SMC) was high ($> 0.550 \text{ m}^3 \text{ m}^{-3}$) and no further storage capacity was available in the substrate when rainfall was applied in these ‘saturated’ conditions. The second rainfall event was simulated three days after the first rainfall application, to quantify impact of ET on rainfall retention. The volume of water retained on the whole ‘canopy/substrate complex’ in ‘unsaturated’ conditions following a 72-h antecedent dry period was used as an indicator of the ET contribution to the retention process. ET rates of the chosen species differ, resulting in differing antecedent SMCs for each treatment at the onset of rainfall.

Mean environmental conditions in the glasshouse during the experiment were: day-time (07.00–21.00) $T = 22 \text{ }^\circ\text{C}$, RH 56%, mean radiation 256 W m^{-2} ; night-time (21.00–07.00) $T = 19 \text{ }^\circ\text{C}$, RH 68%.

Rainfall simulation

To ensure that the characteristics of the simulated rainfall were consistent and similar to those of natural rainfall, a sprinkler system based on the design described by Iserloh et al. (2012) and designed in-house by an irrigation specialist at RHS Garden, Wisley, was used to simulate rainfall. Full details of the system, and how it was tested prior to the start of the experiments, are provided in Supplementary Material. Briefly, the system consisted of a Lechler 460,608 nozzle

attached by a 2 m length of hosing to a flow control, consisting of a series of pressure gauges and filters, which was connected to the mains water supply by hosepipe. The nozzle, hosing and simulator were fastened to an L-shaped timber support 2.4 m high and 1 m across which was then secured to a metal pole in the glasshouse. During the experiments, trays were placed on a trolley 1.6 m below the nozzle for rainfall application and flow pressure was maintained at 15 kPa to ensure consistent droplet production.

The simulator was tested extensively prior to the start of the experiments in order to determine suitable rainfall volumes and intensities and establish experimental procedures (Kemp 2018); also see Supplementary Material. The area below the nozzle was found to have the most consistent rainfall characteristics, with an intensity of 28 mm hr^{-1} , and was therefore chosen as the position for test trays during the experiments (Fig. 2). Mean rainfall applied was $9.3 \pm 0.3 \text{ mm}$.

Experimental procedure

Trays were tested one at a time, with one tray of each treatment tested in turn to account for any possible changes in environmental conditions. Each tray was exposed to rainfall for 20 min to simulate a rainfall event of 9.3 mm, considered medium-heavy in the classification system proposed by (Getter et al. 2007), and with a return period of $T = 1.6$ years (Butler and Davies 2003). To measure runoff, each tray was placed inside a second, empty tray of the same dimensions before rainfall application (Fig. 2b), thus ensuring that no rainfall fell directly into the second tray and only runoff was collected.

Before rainfall application, each tray was weighed and antecedent SMC was measured using a WET sensor connected to a HH2 Moisture Meter (Delta-T Devices, Cambridge, UK), with five measurements per tray. After each simulated rainfall, trays were left to drain for 30 min (until runoff stopped) and then weighed again. The volume of water captured on the canopy or 'canopy/substrate complex' was taken to be the weight gain of each tray after rainfall application. The volume of water captured in the runoff tray was measured using measuring cylinders.

For three days following both rainfall applications, each tray was weighed and SMC was measured every 24 h to determine daily ET and thus the rate of restoration of substrate retention capacity. Trays remained in the glasshouse during this time and received no further irrigation. At the end of the experiments, a $15 \times 36 \text{ cm}$ representative section of each planted tray was harvested for leaf area and biomass measurement. Shoots and roots were separated and roots were carefully washed, removing as much substrate as possible, before being dried in an oven at $70 \text{ }^\circ\text{C}$ for 72 h and weighed. Leaf area was measured using a leaf area meter with associated WinDIAS 3 Image Analysis System (Delta-T Devices, Cambridge, UK), and leaf area density (i.e. cm^2 leaf area per cm^3 of canopy volume) was calculated, as this parameter proved to be most descriptive of the canopy in our previous studies (data not shown).

Experiment 2: The impact of varying temperature and humidity on plants' water use

To examine how the ET rate of each species, and thus the rate of restoration of substrate retention capacity, varies in different

Fig. 2 The sprinkler rainfall simulator used in Experiment 1, showing the pressure regulators and filters connected to the nozzle (a) and the experimental setup of the simulator secured to an L-shaped timber support with a tray positioned below the nozzle on a trolley for testing (b)



climatic conditions, a series of five consecutive trials, each with different temperature (T) and relative humidity (RH) conditions, took place between 9th March and 30th April 2015 in controlled environment (CE) cabinets.

Experimental set-up

In February 2015, individual two-year old plants of all species were planted into 2 L containers filled to a depth of 11 cm with an industry standard green roof substrate, Meadow Roof Medium (Vital Earth GB Ltd., Ashbourne, Derbyshire, UK), to replicate green roof conditions. The substrate had the following properties: pH 7.7; air-filled porosity 48%; soil organic matter 3.5%; and water-holding capacity 26% (as defined by Vital Earth GB Ltd.). There were six replicates of each species and an additional six control containers with bare, unvegetated substrate.

Temperature (T) and relative humidity (RH) treatments

Five potential UK summertime T/RH scenarios were simulated using two Fisons 600G3/TL controlled environment growth cabinets (Fisons Scientific Apparatus, Loughborough, UK). A 16-h photoperiod (05:00–21:00 h) was supplied by Phillips 40 W warm white fluorescent tubes, which provided a light intensity of $200 \mu\text{mol m}^{-2} \text{s}^{-1}$. While this is a maximum light intensity which can be generated in the cabinets, it is lower compared to the typical outdoor intensities. The intention was therefore to carry out relative comparisons of the species under the same conditions, rather than extrapolate directly to field conditions. There was no function for the growth cabinets to generate wind, but a vertical air flow of 0.2 m s^{-1} within the cabinet was provided by the air circulation system. Internal T and RH were recorded every minute by the cabinets' inbuilt logging systems.

T and RH settings for each of the trials (hereafter referred to as 'warm', 'hot', 'cool', 'dry' and 'humid') were chosen to represent a range of potential summertime T/RH conditions that could be experienced in the southern UK. Actual T and RH recorded in the cabinets during each trial are presented in Table 1.

Experimental procedure

At the start of each trial, all containers were watered to container capacity by submerging in water for 15 min and then leaving to drain for 1 h. Each container was then weighed and two SMC measurements per container were made before randomly placing all containers inside the CE cabinets. 'Saturated' SMCs of *Salvia* and *Stachys* were somewhat higher than other species in all trials, likely as a result of differing root densities affecting the water-holding capacity of the substrate; however, all

Table 1 Average temperature (T) and relative humidity (RH) settings for each of the potential UK summertime scenarios measured inside the controlled environment cabinets during each trial, with calculated vapour pressure deficit (VPD)

Trial	Temperature (°C)		Relative Humidity (%)	Vapour Pressure Deficit (kPa)
	Day	Night		
'Warm'	22	15	63	0.94
'Hot'	26	17	58	1.34
'Cool'	16	10	75	0.53
'Dry'	22	15	42	1.33
'Humid'	21	14	79	0.55

containers were watered to container capacity and SMCs were all within the well-watered range previously identified for this substrate ($> 0.250 \text{ m}^3 \text{ m}^{-3}$). Three containers of each species/control were placed in each CE cabinet. Containers remained in the cabinets for the remainder of the trial, and were removed every 24 h for weighing and SMC measurement. Daily ET was taken to be the weight loss per container in each 24-h period, and the proportion of total ET accounted for by plant transpiration (i.e. if $\text{ET} = 100\%$ and evaporation from bare substrate = 40% of ET, then plant transpiration = 60% of total ET) was calculated for each species.

To ensure survival of all plants and avoid irreversible damage, trials were ended when the SMC of any species fell below $0.100 \text{ m}^3 \text{ m}^{-3}$ (i.e. after 4–5 days). Containers were then removed from the cabinets and placed in a glasshouse where they were watered daily and allowed to recover for at least three days before the start of the next trial. Plant size (height and diameter) was also measured at the start of every trial, and, once all trials were complete, four plants per species were harvested for leaf area measurement.

Statistical analysis

All statistical analysis was carried out using GenStat 16th edition software (VSN International Ltd., Hemel Hempstead, UK). Analysis of variance (ANOVA) was used in both experiments to assess the effect of species choice on various parameters. Normality assumptions and variance levels were checked for homogeneity and variables were reported as a mean for each treatment with associated Least Significant Difference (LSD), which was used to assess significant differences between treatments at 5% significance level. In Experiment 1, linear regressions were also carried out to test the relationship between the amount of water retained on the 'canopy/substrate complex' and antecedent SMC, ET prior to rainfall application, and various plant/canopy parameters.

Results

Experiment 1: The effect of vegetation type on green roofs' capacity to capture rainfall

The proportion of rainfall retained on the plant canopy in 'saturated' conditions varied significantly between species (Fig. 3). *Sedum* and *Stachys* retained the most water (17.1 and 13.1% of the total rainfall respectively) whilst *Heuchera* retained the least rainfall (2.2%) and was similar to the unvegetated control. Even when retention was expressed relative to leaf area to account for varying canopy size, *Sedum* retained most rainfall on the canopy and both *Sedum* and *Stachys* retained more than *Heuchera* (data not shown). Retention on the canopy correlated significantly with leaf area density ($R^2 = 0.54$; $P < 0.001$), shoot dry weight ($R^2 = 0.72$; $P < 0.001$) and canopy height ($R^2 = 0.48$; $P < 0.001$) (data not shown).

Total ET in the 72-h dry period between rainfall applications varied significantly between species/control (Fig. 4A), with *Salvia* and *Stachys* trays losing significantly more water than *Sedum* and the bare substrate. In this experiment, *Heuchera* trays had very low ET, similar to the bare substrate, with a loss of just 5.9 mm in 72 h. However, when expressed per unit leaf area to account for differing canopy sizes, ET with *Heuchera* was similar to *Salvia* and *Stachys*, whilst water uptake by *Sedum* was significantly lower (data not shown).

Rainfall retention on the whole 'canopy/substrate complex' was much higher in 'unsaturated' conditions (i.e. following a 72-h antecedent dry period; Fig. 4B), and was strongly correlated with total ET in the preceding 72 h ($R^2 = 0.94$; $P < 0.001$; data not shown). Retention varied significantly between treatments, with *Stachys* (72.9%) and *Salvia* (63.6%) retaining significantly more rainfall than all other species and over 3 times more than the bare substrate (20.5%). Retention with *Stachys* was also 2.5 times greater than with *Heuchera*, which

retained a relatively small proportion of the rainfall (28.5%), similar to the bare substrate.

Experiment 2: The impact of varying temperature and humidity on plants' water use

Daily ET rates varied significantly between treatments, and differences in cumulative ET between treatments became greater over time. Cumulative ET in 96 h was significantly different between treatments in all T/RH conditions (Fig. 5), with the same pattern evident in all simulated scenarios: *Stachys* and *Salvia* had the highest ET, followed by *Heuchera* and then *Sedum*, whilst the bare substrate had the lowest ET in all trials. Accounting for plant size, relative water loss per unit leaf area was similar for the three broadleaf species, whilst *Sedum* was always lower (data not shown).

For every species, there were also significant differences in ET among T/RH treatments. Cumulative ET in the 'hot' and 'dry' treatments (i.e. high VPD) was always significantly greater than in the 'cool' and 'humid' treatments (i.e. low VPD) with all species. ET from the bare substrate was particularly low in the 'cool' and 'humid' treatments, around 3.5 times lower than with *Stachys* compared to 2.5 times lower in the 'warm', 'hot' and 'dry' treatments. This was also evident from the proportion of total ET in 96 h accounted for by plant transpiration, which was highest in the 'cool' and 'humid' treatments for all species (Table 2).

Daily ET of all species declined after Day 1 in all T/RH treatments, concurrently with a decline in SMC. Similar patterns of decline were observed in all trials, but were typically greater in the 'hot' and 'dry' treatments and slower in the 'cool' and 'humid' treatments for all species/control. Daily ET in the 'warm' treatment, with associated SMCs (Fig. 6), is shown here as a representative of the average ET decline

Fig. 3 Mean rainfall retention on the canopy in 'saturated' conditions. Data (bars) are means of 6 replicate trays per treatment, with associated standard error of the mean (SEM) and least significant difference between means (LSD, 5%, shown as a vertical line in the upper left of the Figure); different letters indicate statistically significant differences between treatments

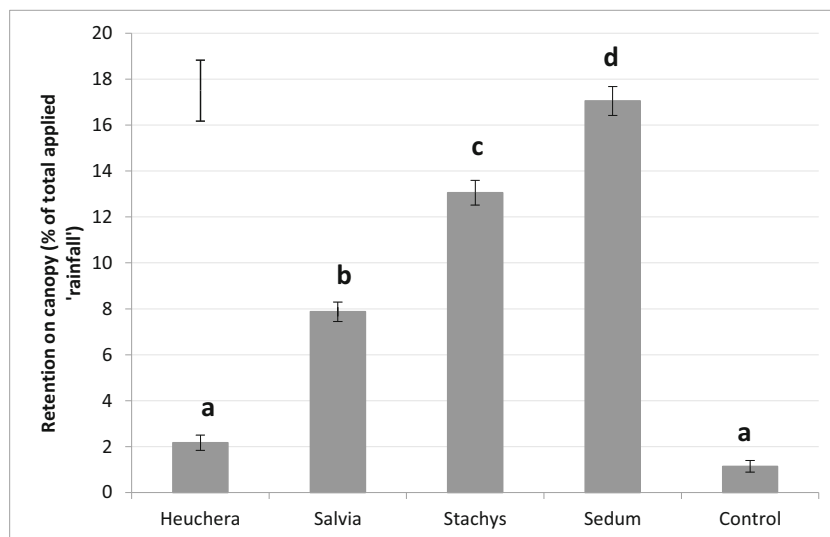


Fig. 4 Mean cumulative evapotranspiration (ET) from each tray for 72 h following saturation (A) and mean rainfall retention on the ‘canopy/substrate complex’ in ‘unsaturated’ conditions (i.e. following the 72-h antecedent dry period) (B). Data are means of 6 replicate trays per treatment, with associated standard error of the mean (SEM) and least significant differences between means (LSD, 5%, shown as vertical lines above the line graph); different letters on Fig. 4B indicate statistically significant differences between treatments

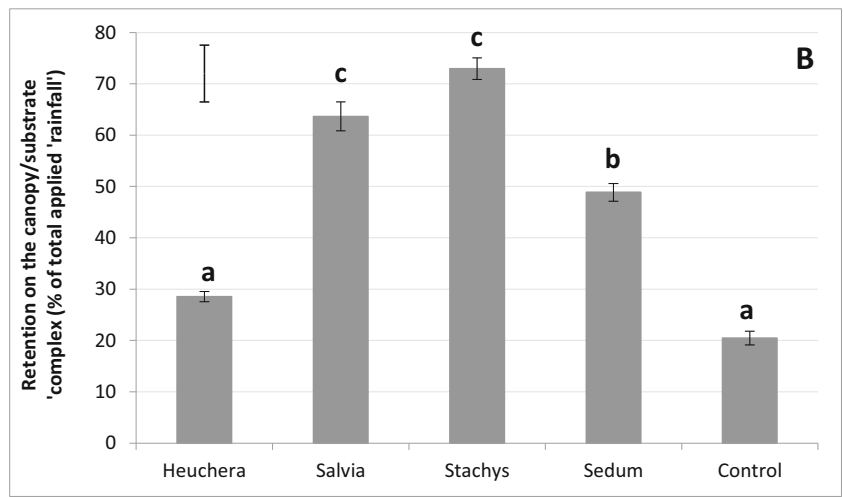
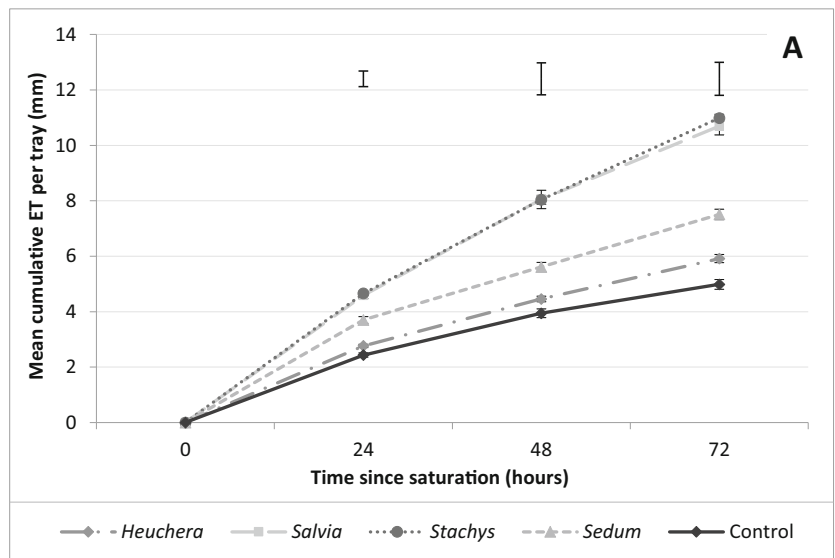


Fig. 5 Mean cumulative evapotranspiration (ET) per container in 96 h in each temperature/relative humidity (T/RH) treatment. Data are means of 6 replicates per species/control with associated standard error of the mean (SEM) and least significant difference between means (LSD, 5%, shown as vertical lines above the bars)

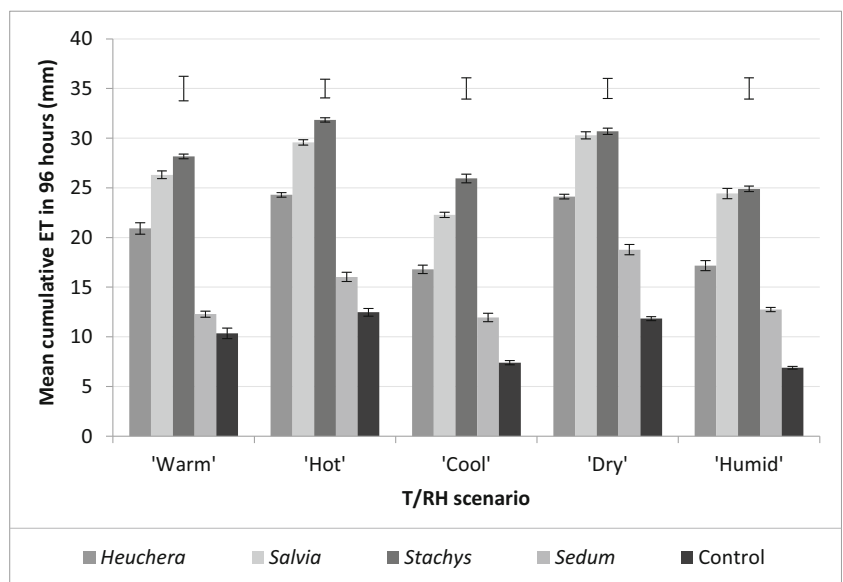


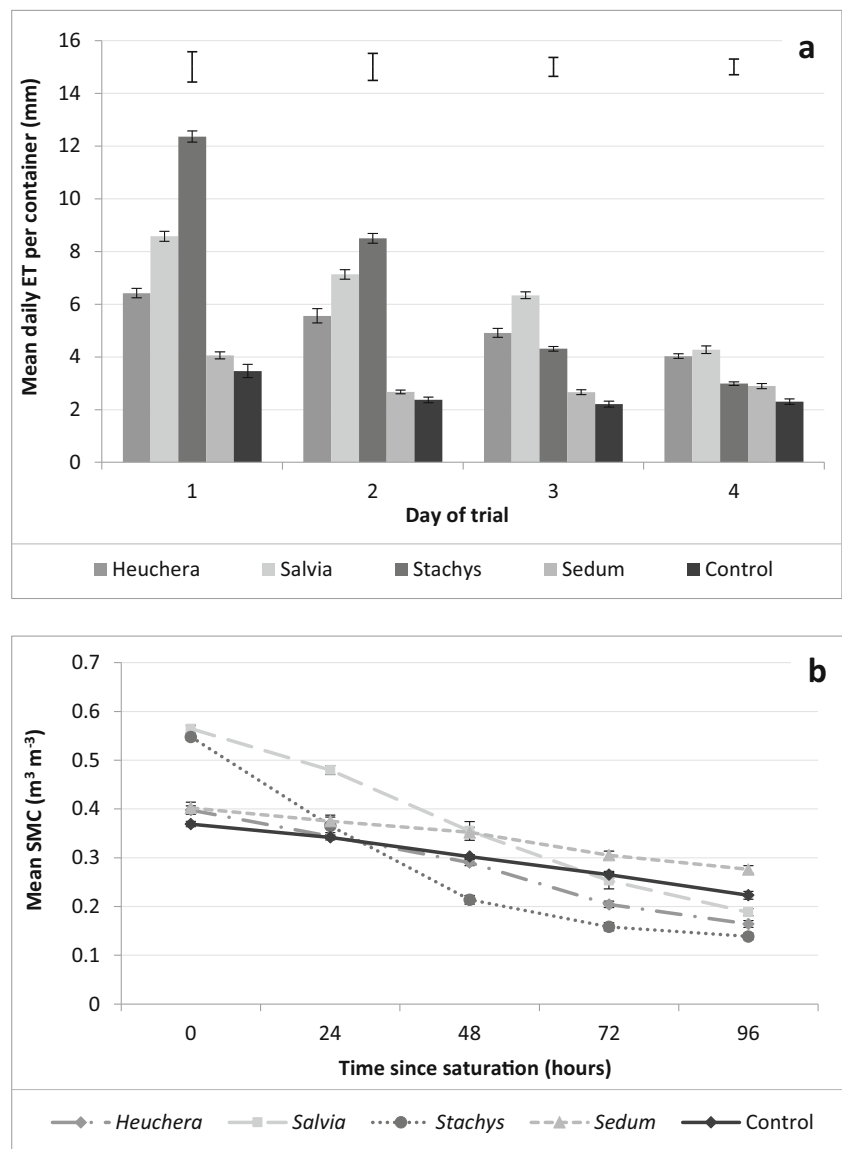
Table 2 Contribution of transpiration (%) to total ET after 96 h in each of the T/RH treatments. Data are means of 6 replicates per treatment

Species	Contribution of transpiration to total ET in each T/RH treatment (%)				
	'Warm'	'Hot'	'Cool'	'Dry'	'Humid'
<i>Heuchera</i>	51	49	56	51	60
<i>Salvia</i>	61	58	67	61	72
<i>Stachys</i>	63	61	72	61	72
<i>Sedum</i>	16	22	38	37	46

observed among all studied treatments. With *Stachys*, the decline in daily ET was initially rapid, reducing by around 4 mm day^{-1} each day in the 'warm' treatment (from $12.36 \text{ mm day}^{-1}$ on Day 1 to 4.31 mm day^{-1} on Day 3; Fig. 6a), before appearing to slow, decreasing by only 1.32 mm day^{-1} on Day 4. *Stachys* SMC also declined rapidly in the first 3 days, from $0.548 \text{ m}^3 \text{ m}^{-3}$ when 'saturated' to

$0.158 \text{ m}^3 \text{ m}^{-3}$ after 3 days of drying (Fig. 6b). *Stachys* ET was initially significantly higher than all other species but declined to such an extent that by Day 3 it was significantly lower than *Salvia* and by Day 4 it was similar to *Sedum*. The declines in both daily ET and SMC were much slower with *Sedum* and the bare substrate, with daily ET for both reducing by only 1.17 mm day^{-1} from Day 1 to Day 4.

Fig. 6 Average daily ET per container in the 'warm' treatment (a) and associated average substrate moisture content (SMC) of each treatment at the start of each 24-h period (b). Data are means of 6 replicates per treatment with associated standard error of the mean (SEM) and least significant differences between means (LSD, 5%, shown as vertical lines above the bars in 6A)



Discussion

Our paper approaches the question of runoff reduction from a biological perspective. In the literature thus far, there is no detailed experimental assessment of the *plant/biological mechanisms* which underlie better performance (or otherwise) of some plants over others. Our aim was therefore to establish what are the driving factors linked with good rainfall retention performance of plants and consequent runoff reduction. We acknowledge that differences in local environmental and edaphic conditions (most importantly temperature, wind, substrate depth and type) will also impact on the extent of runoff reduction. We therefore focus on relative comparisons between plant species to give us a generalised idea of order of magnitude of difference between species in the capacity for runoff reduction.

Contribution of canopy interception to rainfall retention

We observed significant species differences in rainfall retention on the canopy in ‘saturated’ conditions, with *Sedum* retaining the most rain (17.1%), followed by *Stachys* (13.1%) and *Salvia* (7.9%), whilst *Heuchera* retained the least (2.2%). In an earlier study, Nagase and Dunnett (2012) identified plant characteristics such as canopy height, diameter and density, and waxy or hairy leaves as factors that may affect the amount of rainfall retained on vegetation. In our experiment, rainfall retention on the canopy was significantly correlated with shoot dry weight and leaf area density, confirming that species with large and/or dense canopies are able to retain the most rainfall and thus maximise stormwater management provision. *Sedum* in particular formed a very dense canopy, despite having one of the smallest canopies in terms of leaf area, height and diameter, with stems accounting for up to 20% of the total canopy area in addition to leaf area. As well as having full, dense canopies, the hairy leaves of *Salvia* and especially *Stachys* were able to efficiently retain water droplets on their surfaces, even when droplets coalesced and became large, resulting in high rainfall retention on the canopy. In contrast, rainfall retention on the *Heuchera* canopy was low; the smooth, horizontally-aligned *Heuchera* leaves tended to form an almost continual canopy layer that ‘raindrops’ bounced off and dripped, preventing water from infiltrating through the canopy to the substrate or being retained on the leaves. Indeed, up to 20% of the total applied rainfall dripped off the *Heuchera* canopy in a preliminary study with individual plants (Kemp 2018). A large proportion of rainfall dripping off from the vegetation onto surrounding surfaces in this way would result in lower retention on a green roof (due to quicker substrate saturation and less canopy retention), thus potentially limiting the ability of a roof planted with *Heuchera* to provide effective stormwater management. It would also be

more of an issue on roofs where the substrate is already saturated after a rainfall. Obviously though, as canopy grows over time, the capacity for retention will change, and possibly at different rates in different species depending on their growth rates. Our intention here was predominantly to highlight the canopy properties (density, small leaf size, hairiness) which appear to correlate with better canopy retention.

Overall however, contribution of the canopy to rainfall retention was smaller compared to the contribution of ET and substrate water storage. MacIvor and Lundholm (2011) found that vegetated treatments only retained up to 4% more than bare substrate, depending on species. Although relatively small, this additional retention provided by the canopy would be important at times when antecedent SMC is high at the onset of rainfall, for example, when storms occur close together and there is little time for restoration of substrate retention capacity between rainfall events, or during cooler and wetter weather or seasons when ET is limited. In these situations, canopy interception may be the sole mechanism for retention, and so having a species capable of high canopy retention is essential. In our experiment, canopy characteristics were particularly important in ‘cool’ and ‘humid’ weather scenarios when antecedent substrate moisture was high, with large, dense canopies (*Sedum*) providing the greatest rainfall retention. However, restoration of the canopy’s capacity (via evaporation) to retain further rainfall would be influenced by microclimatic conditions (wind speed, temperature, RH), and by the structure/configuration of the canopy.

Contribution of ET to rainfall retention

Removal of moisture from the substrate through ET between storms restores the retention capacity of the substrate for rainfall retention in subsequent storms. This is generally considered to be a more important mechanism than canopy interception for stormwater management provision (Stovin et al. 2015) since it is clear that the substrate itself represents the majority of a green roof’s water storage (Dunnett et al. 2008; VanWoert et al. 2005). Varying ET rates of different species could therefore determine the extent and speed of substrate retention capacity recharge, and thus overall rainfall retention performance. Indeed, rainfall retention was strongly correlated with ET in the preceding 72-h dry period ($R^2 = 0.94$; $P < 0.001$), thus confirming the importance of ET as a key factor determining a green roof’s retention performance (Stovin et al. 2012). The different ET rates of each species and bare substrate in the 72-h dry period preceding rainfall application in ‘unsaturated’ conditions resulted in significantly different antecedent SMCs at the onset of rainfall. Greater substrate storage was therefore available with the species with high ET rates (and thus low antecedent SMCs), and rainfall retention was consequently greater with these species (72.9 and 63.6% for the high-performing *Stachys* and *Salvia* respectively)

compared to those with low ET rates (48.9 and 20.5% for lower performing *Sedum* and bare substrate, respectively). These results clearly demonstrate the impact of varying ET rates between species on their ability to restore the substrate's water retention capacity and thus retain rainfall. This highlights the potential to maximise stormwater management provision on a green roof by selecting species with high ET rates, such as *Stachys* and *Salvia*, particularly in the context of mild, temperate climates such as UK. Some recent research suggests however that drought-avoiding, low water-use plants, can also support rainfall retention on green roofs (Szota et al. 2017; Lundholm et al. 2010) and they have a role in climates with lower summer rainfall and higher temperatures.

The ability of succulent species such as *Sedum* to provide stormwater management is often considered to be limited by their low ET rates (Nagase and Dunnett 2012), resulting in slow restoration of substrate retention capacity. In our study, however, the ET rates of all vegetated treatments, including *Sedum*, were significantly higher than from bare substrate, in all T/RH treatments. The proportion of total cumulative ET in 96 h provided by plant transpiration was large, particularly for the broadleaf species (e.g. up to 72% for *Salvia* and *Stachys* and 60% for *Heuchera*) and even for *Sedum* - up to 46%. This clearly demonstrates that the presence of any vegetation on a green roof enables greater restoration of substrate retention capacity, and thus greater rainfall retention, than bare substrate alone. Indeed, several other studies have reported significantly greater rainfall retention with vegetated treatments compared to bare substrate (e.g. Volder and Dvorak 2014; Beecham and Razzaghmanesh 2015; Stovin et al. 2015).

Rainfall retention in various summertime temperature and relative humidity scenarios

The 'ranking' of plant species in terms of both daily and cumulative ET (and thus their potential to reduce runoff), was always the same in all T/RH scenarios, with *Stachys* and *Salvia* always having significantly higher ET than all other species/control, *Heuchera* ET significantly greater than *Sedum*, and bare substrate ET significantly lower than all species. These results suggest that maximum stormwater management provision would therefore always be achieved with high ET species *Stachys* and *Salvia*, regardless of the predominant summertime weather conditions. Indeed, the same 'ranking' of species was identified in one of our earlier outdoor experiments when stomatal conductance (g_s) was measured as an indicator of ET and cooling capacity, with *Stachys* and *Salvia* having the greatest g_s and *Sedum* the lowest (Vaz Monteiro et al. 2017). Poë et al. (2015) also observed lower ET rates with *Sedum* compared to herbaceous species in a controlled environment study. In our study, *Stachys* and *Salvia* took up approximately twice as much water from the substrate

in 72 h than all other species/control, thus theoretically doubling the available substrate retention capacity for a subsequent rainfall event.

As well as varying between species, ET rates of all species/control were significantly higher in treatments with high VPD ('hot' and 'dry') compared to low VPD treatments ('cool' and 'humid'). Indeed, total cumulative ET in 96 h ranged from 6.89 mm (bare substrate; 'humid' treatment) to 31.83 mm (*Stachys*; 'hot' treatment), meaning that more substrate storage capacity could be created on hot, dry days. Moreover, for all species, the contribution of plant transpiration to total ET was particularly large in the T/RH treatments with low VPD ('cool' and 'humid'), likely due to limited evaporation from the bare substrate and a more abundant water supply (i.e. higher SMC) in vegetated treatments in these conditions (Voyde et al. 2010b).

For ET to continue at its maximum potential rate, water must be continually supplied to the evaporating surfaces (i.e. the substrate or leaf surfaces; Verhoef and Egea 2013). As SMC declines over time after wetting, the water supply to the evaporating surfaces becomes increasingly restricted, causing ET rates to fall (Stovin et al. 2013). This was clearly observed in all T/RH treatments in Experiment 2, with daily ET declining concurrently with SMC. This decline was particularly rapid in high VPD treatments ('hot' and 'dry') and for the species with high ET rates (i.e. *Stachys* and *Salvia*), which quickly depleted substrate moisture. Indeed, daily ET with *Stachys* declined rapidly in the first 3 days after saturation, (e.g. from 12.36 day^{-1} on Day 1 to 4.31 mm day^{-1} on Day 3 in the 'warm' trial), likely as a result of reduced availability of substrate moisture (SMC declined from 0.548 to $0.158 \text{ m}^3 \text{ m}^{-3}$ over the same period). Consequently, by Day 3 *Stachys* ET was significantly lower than *Heuchera* and *Salvia* ET and similar to *Sedum* ET, and by the end of all T/RH trials, the daily ET of *Stachys* was approaching that of the bare substrate. These results imply that the advantage of species with high ET rates (e.g. *Stachys*) over species with lower ET rates (e.g. *Sedum*), in terms of rate of restoration of substrate retention capacity, would be greatest in the first 2–3 days following rainfall. In our experience, in previous field experiments on the same plant species carried over several years in the temperate climate of the UK's south-east (Vaz Monteiro et al. 2017; Blanusa et al. 2013), substrate depth of 10 cm was sufficient to sustain the plants chosen in this study without the frequent need for supplementary irrigation. In the prolonged absence of natural rainfall, supplementary irrigation should be applied to prevent substrate moisture deficit. Since ET has previously been shown to be the primary mechanism by which these species provide cooling (Vaz Monteiro et al. 2017), maintaining high ET rates with supplementary irrigation will also ensure that cooling provision is not compromised, so a green roof will be in a position to provide more efficiently two services (cooling and runoff reduction). Provision of supplementary irrigation obviously adds another

layer of complexity and cost to green roof projects, and requires the support of horticultural specialists in reaching the right balance of most effective planting vs irrigation costs.

Conclusions

Plant canopies alone retained up to 17% (e.g. in most effective *Sedum*) of the total rainfall in this study, with *Salvia* and *Stachys* also retaining in excess of 10%, and can make a substantial contribution to rainfall retention on a green roof. Rainfall retention was also strongly correlated with total ET in the preceding 72 h ($R^2 = 0.94$; $P < 0.001$). Therefore, species with high ET rates (*Salvia* and *Stachys*) were able to provide the greatest stormwater management service (up to 72% retention due to ET component vs 46% in low-ET *Sedum*). Furthermore, species ‘rankings’, in terms of ET and thus restoration of substrate retention capacity, were the same in all simulated potential UK summertime temperature and relative humidity scenarios, indicating that ‘superior’ species would be able to provide the greatest stormwater management provision in all climatic conditions. Although the ET rates are greatest in ‘warm’ and ‘hot’ conditions, the contribution of the plant transpirational component became particularly important in ‘cool’ and ‘humid’ conditions (with $T = 16$ °C and $RH = 80\%$). This is because the evaporation alone from the substrate was low in these circumstances, and transpiration by vegetation increased the substrate’s storage capacity.

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Compliance with ethical standards

Conflict of interest The authors have no conflicts of interest to declare.

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