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Functional urban ground-cover plants: identifying traits that promote rainwater retention and dissipation

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Abstract
Urban vegetation can influence urban hydrology and reduce the risk of flooding. Urban forestry studies have suggested that tree type and species choice affect the amount of rainwater intercepted and retained. Little information exists, however, for other landscape typologies, and the sorts of ground-cover plants that are best used to retain/detain rainwater during storm events. This is important as many urban spaces are too small to facilitate trees, but can accommodate roadside vegetation, buffer strips, rain gardens, green roofs and stormwater planters. Thus, this research aimed to determine how choice of ground-cover taxa affected rainwater interception and retention. Six model species with contrasting leaf morphologies were used to determine how well rainwater was intercepted, but also dissipated through evapotranspiration (ET). A pot-based system was used to determine how plant water balance changed during late summer in the UK, with the aim to understand how leaf traits affected hydrological processes. Plant choice was important, with fine-leaved taxa, *Festuca glauca* and *Dianthus* 'Haytor White' showing best rainwater interception and *Festuca* demonstrating highest rates of dissipation from the substrate. Overall, compared to non-planted pots, those with plants present were more effective at capturing water (by 2.3–3.0x), and evapo-transpiring water (by 2.5-4.0x). Results indicate that ground cover vegetation has potential to aid urban water management in those localities where space is limited for trees. Plant choice and community-structure should be considered, especially when there is a desire to dry out soil/substrate quickly and restore maximum soil moisture holding capacity.

Keywords Evapotranspiration · Flooding · Green infrastructure · Leaf morphology · Rainfall interception · Urban planting

Introduction

Urban vegetation is increasingly justified for the ecosystem services it provides, as well as for its intrinsic ornamental value (Elmqvist et al. 2015; Cameron and Blanusa, 2016). One key service is to intercept, detain, retain and dissipate rainwater, thus helping to reduce stormwater surface flow and flash flooding (Berland et al. 2017). A problem that is increasing in many tropical and temperate cities around the globe (Hobbie and Grimm 2020). Trees particularly, are gaining popularity as a tool to reduce hydrological flows into rivers, e.g. in upland areas of river catchments (Murphy et al. 2021), but also in towns and cities (Carlyle-Moses et al. 2020). Sustainable drainage systems (SuDS) also employ vegetation to help slow run-off and improve water quality entering rivers. Whilst trees are acknowledged to intercept significant amounts of rainwater (Xiao and McPherson 2016), densification of urban areas and city centres in particular does not always provide enough space for them, or their size and growth characteristics can cause problems (e.g. soil heave and damage to pavements/sidewalks from root growth) (O'Callaghan and Mercer 2019). In light of this, other forms of green infrastructure have been

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investigated for their ability to help mitigate against urban flooding, with green roofs, raingardens, swales and roadside plantings/buffer strips being advocated for providing positive effects at a local level (Yuan 2016; Fairbrass et al. 2018). Whilst some research has identified tree species that are particularly effective at capturing (Xiao and McPherson 2016; Alves et al. 2018) and dissipating (Thom et al. 2020) rainwater, relatively few studies have focussed on what type of 'ground-cover' plants are best at managing rainwater within these small alternative green infrastructure typologies (Sikorska et al. 2017).

Rainfall that falls onto a plant is partitioned into three processes; canopy interception, stemflow and throughfall (canopy dripping) (Rutter et al. 1975; Iida et al. 2005; Guevara-Escobar et al. 2007; Xiao and McPherson 2011). In general, canopy interception refers to a fraction of precipitation that hits the plant surface, and interception loss is the fraction that is retained within the vegetation and does not reach the soil surface. Rainfall interception by the plant canopy is considered one of the most important hydrological processes. This is because it controls rainwater from its source (rainfall), and it affects the rate, depth and spatial distribution of water, which in turn influences processes such as transpiration by the plant, and evaporation from plant and soil surfaces (Gómez et al. 2001). Canopy interception can account for a significant proportion of the rain that falls over a plant, and determines stemflow and throughfall rates (Guevara-Escobar et al. 2007). According to Carlyle-Moses and Gash (2011), canopy interception, or interception losses (retention) account for 10–50% of gross annual precipitation over forest ecosystems and are determined by various hydrological and ecological factors. Interception is strongly driven by three main categorical variables; rainfall magnitudes and patterns, vegetation types and characteristics and meteorological factors (Li et al. 2016). The amount of water retained in a plant's canopy is dependent on vegetation type and varies according to characteristics such as total leaf area, the angle leaves are held with respect to incoming raindrops, leaf texture and leaf shape (Nagase and Dunnett 2012; Cameron and Blanusa, 2016; Holder and Gibbs, 2017). Water that is retained on a plant may either be held on the surface of leaves and branches and eventually evaporate into the atmosphere, or can be absorbed across the leaf cuticle to the internal organs of the plant (as leaf water uptake, although this tends to be minimal) (Liang et al. 2009).

Rainwater, of course may not fall on a plant at all, but discharge via surface run-off or infiltrate through fissures and pores and disperse through the soil (Herwitz 1987). Where plants are present, their roots help rainwater infiltrate the soil (Carbone et al. 2015). Water that is held on the surface or within the soil can be lost back to the atmosphere through evaporation or be used by nearby plants; being absorbed through the roots and transpired back to the atmosphere. Transpiration is affected by plant morphology and stomatal behaviour, with overall plant water use being affected by temperature, humidity, air movement, total leaf area, rate of growth, irradiance, root signalling and eco-physiological traits such as possessing anisohydric behaviour (keeping stomata open even under a certain degree of water stress) (Kemp et al. 2019). High transpiration can help dry out the soil quickly after a storm event, thus recharging the soil's capacity to hold more water, should a subsequent rainfall event take place.

In the case of ground-cover plantings, individual ground-cover plants are likely to intercept and transpire only small volumes of water. They are often used *en masse*, however, within landscape plant communities or within SuDS landscapes, which help alleviate surface water flows and flooding. In addition, smaller plantings can be designed in a more flexible manner, fitting into areas of restricted space, or used to 'soften' areas of pavement or other impermeable surfaces. Ground-cover plants are a component or link into other green infrastructure interventions (Woods-Ballard et al. 2015) such as rain gardens, green roofs or stormwater planters.

Overall, interception studies on smaller plants are less documented compared to trees. Those studies that have been implemented have shown quite wide variation in rainwater interception potential across species. Shrub species (*Diospyrus texana*, *Acacia farnesiana* and *Prosopis laevigata*) were shown to intercept between 22 and 62% of gross rainfall, in a semi-arid environment (Návar and Bryan 1990). Similar findings by Domingo et al. (1998) found interception to be between 21% (*Retama sphaerocarpa*) and 40% (*Anthyllis cytisoides*) of gross rainfall. Zhang et al. (2009) also found interception losses by *Artemisia ordosica* to be 15%, and by *Caragana korshinskii* to be 27% of gross rainfall. Kemp et al. (2019) observed the relationship between canopy properties (e.g. density, small leaf size, hairiness) and retention capacity, and found that *Sedum spurium* canopies retained the most rainwater (17%), followed by *Stachys byzantina* (13%) and *Salvia officinalis* (8%), whilst *Heuchera micrantha* retained the least (2%). Nagase and Dunnett (2012) found grass species (e.g. *Anthoxanthum odoratum*) to have higher retention capabilities, followed by forbs (non-grass herbaceous flowering plants) and *Sedum*. Similar findings were observed by Lundholm et al. (2010), where grass species had higher moisture retention, followed by forbs and succulents. MacIvor and Lundholm (2011) found monoculture graminoids can retain up to 75% of simulated rainfall (10 mm) and outperformed other plants such as tall, creeping forbs and creeping shrubs. Ferns retained the highest amount of water in tropical green roofs, followed by herbs, *Sedum* and grass (Krishnan and Ahmad 2014). Comparisons

within *Sedum* populations (these include water retention in the substrate as well a canopy) were *Sedum spectabile* (91% retention), *Sedum lineare* (91%), mixed *Sedum* community (88%), *Sedum aizoon* (83%) and *Sedum spurium* 'Coccineum' (84%), when rainfall event were light or moderate in intensity (≤25 mm rain) (Gong et al. 2021). Xerophytes that depend on their survival by capturing what limited rainfall is available in arid climates may have higher interception and retention capabilities as well as better water use compared to urban vegetation (Su et al. 2016). A study by Yuan et al. (2017) looked at retention by rain gardens and found forb perennials and mown grasses to retain between 14.6 and 16.8 mm (66–76% of rain). Variation in these retention percentages is likely due to different experimental approaches, how retention was measured (some look at plant canopies alone, others take account of soil holding capacity too, whilst others incorporate moisture losses through ET in the calculations), as well as vary due to different rainfall characteristics and plant size/age. As with trees, Liu and Zhao (2020) suggested that plant morphological traits, especially leaf morphology, should be considered when selecting ground-cover species for managing surface run-off.

The aim of this study was to evaluate a range of ground-cover plant taxa with contrasting leaf morphologies to determine their capacity to intercept rainwater, but also dissipate it via evapotranspiration (ET). The interception factor has implications for reducing stormwater run-off and urban flooding during intense rainfall events, and high evapotranspiration rates will help restore the soil's capacity to hold more stormwater – should there be subsequent heavy or prolonged rain. By focussing on a small number of 'model' taxa the research explored what traits are important for water retention and subsequent dissipation, and to compare these to that found for other vegetation types, e.g. trees. A plant-pot system was used so that plants could be weighed to determine how much water was captured by individual specimens. This included canopy interception, stemflow, and that proportion of throughfall that fell onto the growing media within the pot. Pots without plants (controls) provided information of how much water was held in the substrate itself. This pot 'system' also allowed data on water loss (evapotranspiration) to be collected. Although a pot system rarely reflects the practical use of ground cover plants (where they tend to be grown in natural soils [e.g. on roadside verges] or artificially created substrates [e.g. green roofs], it was an important tool to control for environmental variables that might occur in vivo, and to allow our experimental system to be uniform in terms of growing media volume, media surface area, bulk density of substrate etc., i.e. a standard experimental system). Moreover, our primary research objective was to determine how one plant taxa compared to another in terms of water capture/dissipation, rather than understand how location factors (such as soil/substrate type, substrate structure and depth, degree of surface water flow etc.) affected the dynamics of rainwater interaction/use, thus the pot system provided the best means to compare taxa directly whilst controlling for other abiotic/biotic variables.

We were interested in plant morphology though, and as water management is to some degree controlled by the scale and size of a plant, a component of the research artificially regulated plant canopy size across the species in an attempt to determine how taxa performed when compared on an equal leaf area basis. Finally, by growing plants outdoors, one experiment aimed to determine how changes in water availability affected a plant's capacity to transpire and intercept/retain rainwater from natural precipitation events. Overall, the research posed two key hypotheses:

1. Taxa with narrow, fine leaves will intercept more water than those with broad, large leaves.
2. Taxa with narrow, fine leaves will transpire less water than those with broad, large leaves; and as such the former are less useful for recharging the substrate's capacity to hold water.

Materials and methods

Experiment 1. Plants grown outdoors (14 Aug. – 26 Sept, 2017)

Six landscape plant taxa were chosen to determine their capacity to intercept rainwater and dissipate it back to the atmosphere through evapotranspiration. Common landscape 'ground-cover' taxa were chosen with contrasting leaf morphologies; i.e. narrow linear leaves - *Dianthus* 'Haytor White' and *Festuca glauca*, large broad leaves - *Bergenia cordifolia* and *Hosta sieboldiana* and small, simple leaves *Vinca minor* and *Pachysandra terminalis* (Fig. 1). The plants were potted into John Innes compost No. 2; a 14:3:3:4 mix of sterilised loam, peat, fine bark and sand with 2 g l^{-1} Osmocote Pro controlled release fertiliser (8–9 month) in a 3.5 L square pot (15 × 15 × 20 cm). After establishment, the plants were brought to container (field) water holding capacity, by carefully submerging in buckets of water for 12 h and then draining for 2 h. They were then placed on an open space in a randomised pattern on a low terraced roof (Sir Robert Hadfield Building, University of Sheffield, UK) from 14/08/17 until 26/09/17. Microclimatic conditions (rainfall, temperature, relative humidity, wind speed and direction) were recorded using a weather station (Campbell Scientific, Logan, Utah, USA). A waterproof bench scale (B-100, Marsden, London, UK) was used to monitor pot weight on

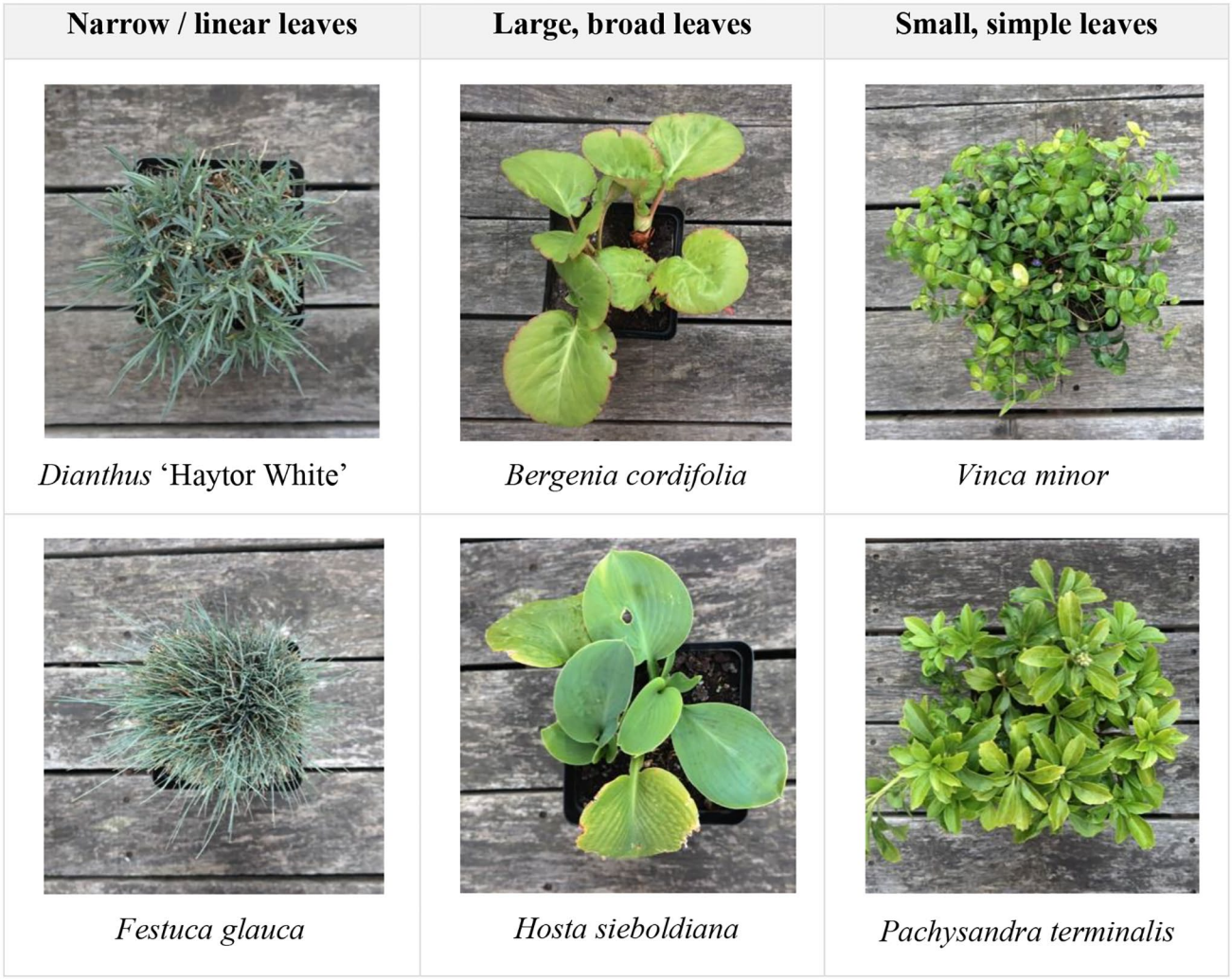


Fig. 1 Leaf shape categories of the six plant taxa

a daily basis and thus estimate water gain through rain or loss through ET. At other specific times, weight data were recorded on a more frequent hourly basis using a subset of plants (n = 2), for example to determine diurnal ET patterns between taxa. For example, this was conducted during a dry weather period between days 11–16 of the experiment. In addition, a moisture sensor (SM150T, Delta-T Devices Ltd., Burwell, Cambridgeshire, UK) was placed in one replicate of each treatment to determine rapid changes in media water content (e.g. during an individual rainfall event) as well as to verify patterns observed from gravimetric data. The sensors were attached to General Purpose (GP) data loggers (Delta-T Devices Ltd., Burwell, Cambridgeshire, UK) and recorded volumetric water content every minute.

One of the objectives was to determine how typical young plants of each taxon intercepted rainwater, or lost it via ET, so plants were allowed to grow naturally after potting. This resulted in leaf canopies of different sizes, densities and dimensions. In an attempt to understand how more equally-sized canopies might affect the water interception/loss processes, a number of specimens of each species were trimmed to standard dimension - effectively covering the same area as the pot surface (Fig. 2); these plants being referred to as the Cropped canopy (compared to the untrimmed Full canopy plants). Water use by the plants in both treatments was recorded gravimetrically by weighing plants on a daily basis and monitoring weight changes with reference to climatic conditions.

Growth data

At various points throughout the experiment, the number of leaves per plant, as well as the length and breadth of each leaf was measured to estimate the total leaf surface area of each plant. For species with numerous fine leaves (*F. glauca* and *D.* 'Haytor White') photographs were used



Fig. 2 Experiment 1. Example of full (left) and cropped (right) canopy size of *V. minor*

instead, with pixel numbers related to leaf colour being used to estimate total leaf area via computer imaging (ImageJ software, Schneider et al. 2012). Both techniques provided broad approximations of leaf area, not accurate replicable data sets (through destructive analyses of additional non-experimental plants we estimate a 10–15% error being typical in these methodologies). Finally, after the experiment was complete, plant leaves of each species were harvested to obtain the total number of fresh leaves, total weight of fresh leaves and total leaf area. The numbers of fresh leaves were obtained by physically counting each leaf, and then weighing to obtain fresh leaf weight. Leaf area values were obtained by taking photographs of the harvested leaves as before.

Chlorophyll fluorescence

At the ends of the experiment chlorophyll fluorescence (Handy PEA, Hansatech, King's Lynn Norfolk, UK) was measured on 3 leaves per plant to assess stress levels (Brestic and Zivcak 2013). Dark adaptation leaf clips were placed onto one leaf for each plant for 20 min, and Fv/Fm data recorded; values < 0.7 tending to indicate greater stress to the photosynthetic apparatus of the plant. Due to the narrow leaves of *F. glauca* and *D.* 'Haytor White', Fv/Fm values were difficult to obtain for these taxa, as the aperture of the dark-adapting clip is wider than the leaf blade. Thus, signs of stress via Fv/Fm were augmented with subjective visual assessment of leaves of all taxa (Lewis et al. 2019). Each treatment combination was represented by 6 plants, with data for water interception/loss and chlorophyll fluorescence being presented as mean values.

Experiment 2. Plants grown under controlled conditions (11 Aug. – 28 Oct. 2017)

Seven RLS010 single-point compression load cells were placed on a bench rig (Poë et al. 2015) that was installed in the Civil Engineering Water Lab, in the Civil and Structural Engineering Department, University of Sheffield. Plants within pots were placed on these cells, with the cells measuring weight continuously during the experimental period. Three high-pressure sodium lamps were placed in the rig and used to artificially illuminate the plants (intensity = 150–160 W m^{-2}) from 10:30 h-18:30 h per day. The load cells were located under the lamps in an attempt to give each plant similar levels of irradiation, but the position of plant species was varied between replicates as an extra safeguard to avoid positional bias. Temperature and humidity within the rig were recorded via an Ultra 2 TinyTag sensor (Gemini Loggers Ltd., Chichester, West Sussex, UK). Plant taxa and pot size/growing media/procedure for gaining container capacity were the same as Experiment 1. As before, a pot with media but without a plant was used as a control to determine 'background' evaporation rates.

Plants of the different taxa (one replicate of each taxon at each time) were randomly placed on load cell platforms at 10:30 h of the first recording day, and weight changes monitors for 12 consecutive days. No additional irrigation was applied during this period. A Modular 600 Multi-Channel data logger (RDP Electronics Ltd., Wolverhampton, West Midlands, UK) recorded weights at 60 s intervals, with weight data being downloaded into Microsoft Excel. The process was repeated four times, consecutively, thus giving four replicates per taxon. The data collection took place between 11 Aug. 2017 and 28 Oct. 2017. After each experiment was complete, photos were taken of each plant canopy to identify any signs of stress. Finally, each plant's leaves were harvested to measure the plant's total leaf area, fresh weight, number of leaves and leaf biomass. As before, chlorophyll fluorescence and subjective notes on plant foliage conditions were carried out at the end of each experimental procedure.

Statistics

Data was presented as mean values. ANOVA was used to determine treatment effects, with Bonferroni post hoc tests being used to determine significant differences between specific treatments.

Results

Experiment 1. Plants grown outdoors from 14 Aug. – 26 Sept. 2017

Water balance over time

Precipitation occurred frequently over the experimental period, with notable rainfall events on day 4, 23 and 29. There was a relatively prolonged dry period between day 7 and 17 (Fig. 3). The water status of plant pots varied as the plants experienced rainfall and warm/windy days that dried the pots out via ET.

Water loss via evapotranspiration (ET)

Periods without rainfall were used to examine water loss via ET across the different taxa and treatments. There was no rainfall between day 10 and 17. Over this period, greatest daily moisture loss was associated with *F. glauca* full-canopy plants, with the exception of days 16 and 17 (Fig. 4). The greatest weight loss during this dry period was by *F. glauca* and *D.* 'Haytor White', with over 1000 g of water being lost from the plant/pot systems (Fig. 5). *Hosta sieboldiana* and *P. terminalis* lost considerably less water over this period (Fig. 5). With the exception of *V. minor*, there was little difference in the water losses between full and cropped-canopy plants in each species. Subsequent rainfall events replenished the pots with water. By day 44 (i.e. the end of the experiment), it was still evident that *F. glauca's* pots were drier than *V. minor, H. sieboldiana, P. terminalis B. cordifolia* (cropped-canopy) and *D.* 'Haytor White' (full-canopy) plants (Fig. 5), indicating that this taxon was still evapo-transpiring more water than others.

Diurnal evapotranspiration (ET) 'patterns

Monitoring water availability using moisture sensors and ET during the day also provided some insight to how plants were dissipating rainwater from their pots. During the relatively dry period of days 11–16, taxa such as *D.* 'Haytor White', *V. minor, F. glauca* and *H. sieboldiana* with full canopies tended to maximise ET in the early afternoon (Fig. 6a). Evapotranspiration for *Pachysandra terminalis*, in contrast, peaked early in the morning, but the plant then reduced its stomatal conductance, with lower levels of moisture loss after 10am (10 h). For cropped-canopy plants, ET was also highest in the afternoon for *D.* 'Haytor White', *B. cordifolia*, *V. minor* and *F. glauca*, but again highest in the morning for *P. terminalis* and to some extent *H. sieboldiana*. The highest

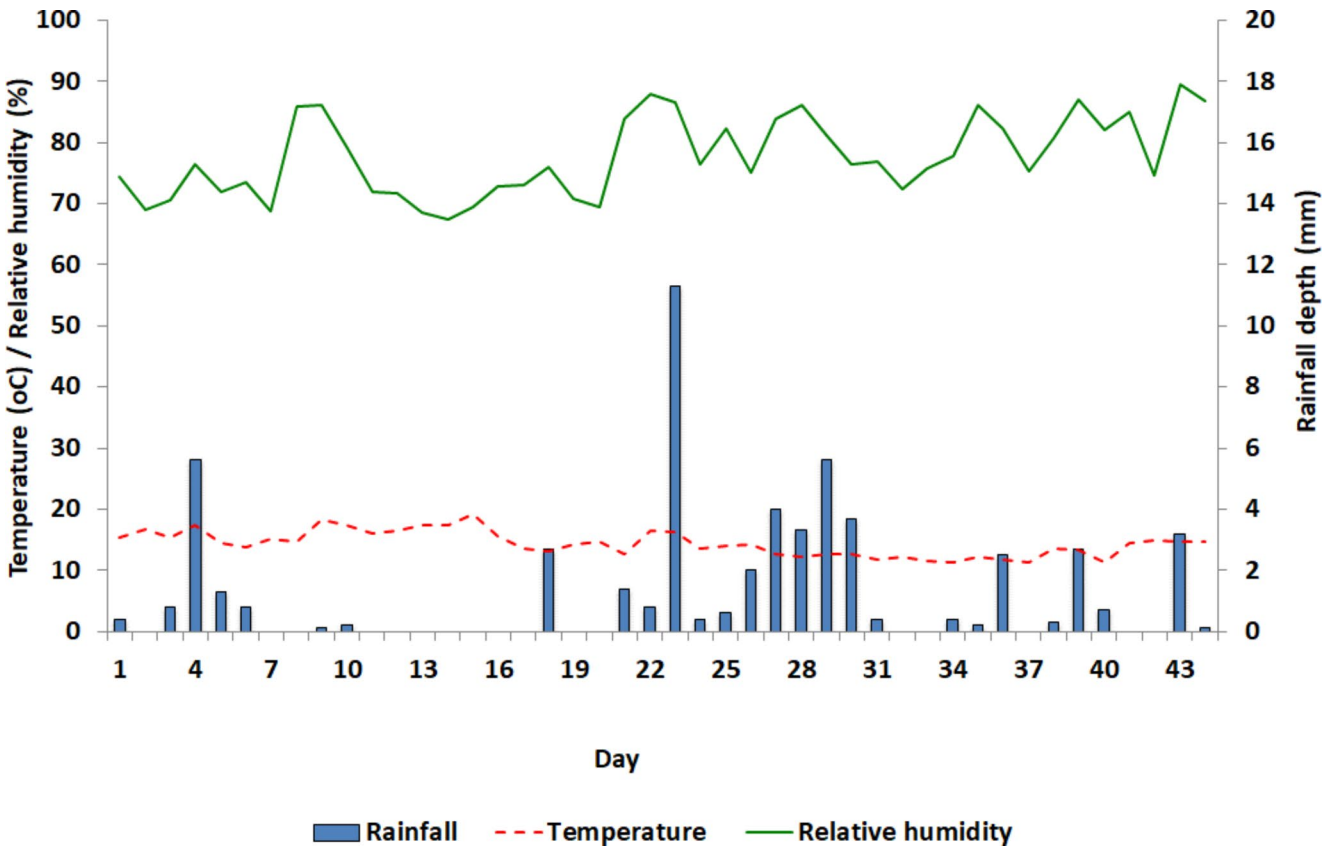


Fig. 3 Experiment 1. Rainfall, temperature and relative humidity over the 44 days of experimentation

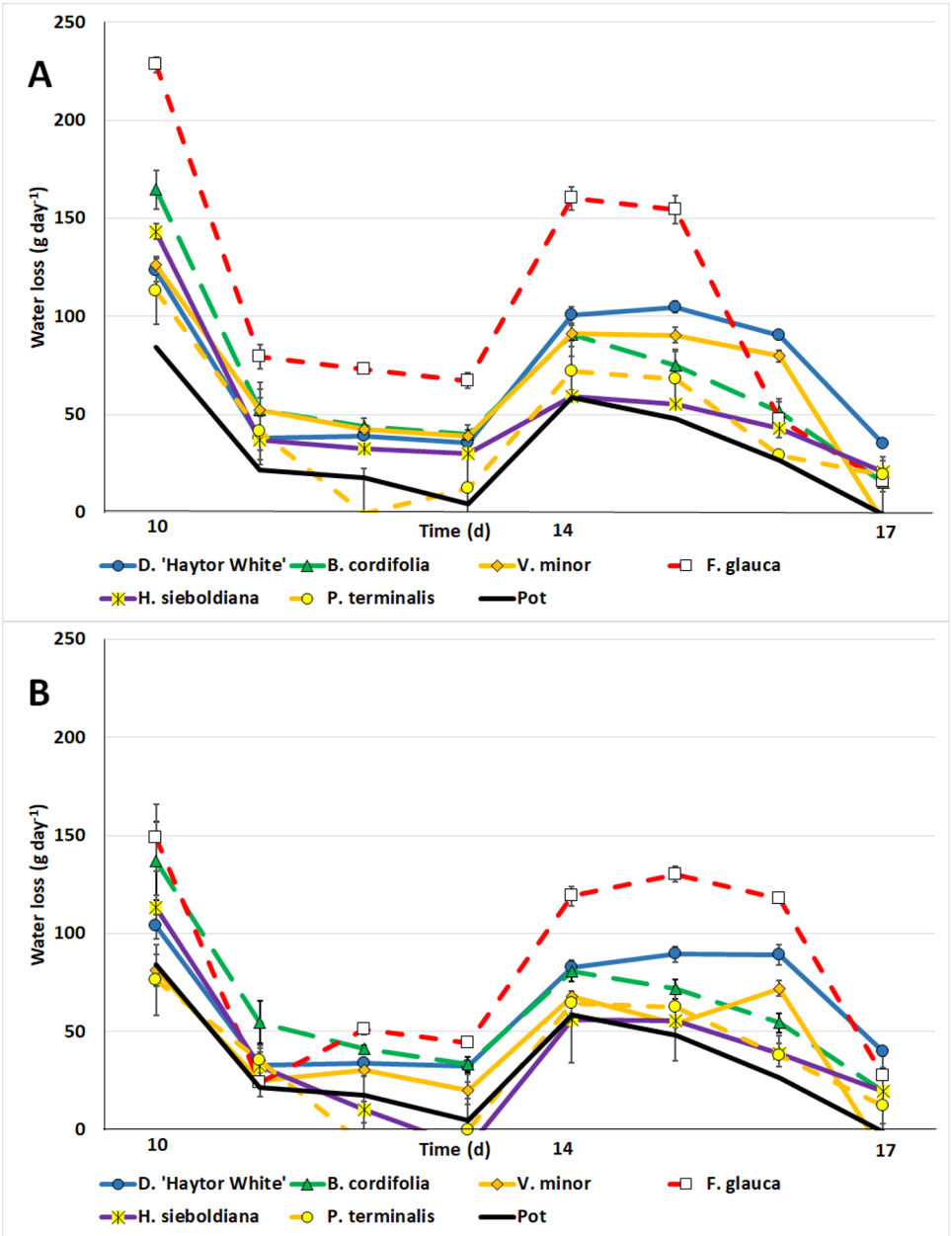


Fig. 4 Experiment 1. Water loss over each day of day 10 to day 17; (A) full-canopy plants; and (B) cropped-canopy plants. Bars = Standard Errors

ET value was associated with the cropped-canopy *Pachysandra* plants when they peaked at 31 g h^{-1} at 10am (10 h) in the morning (Fig. 6b). *Festuca glauca* also transpired a relatively large volume of water in the cropped-canopy specimens, with its ET peaking at 3pm (15 h). This was a higher value than the equivalent full-canopy plants at this time.

Rainwater retention

Data is presented for two separate days (weight gain over 24 h) with contrasting rainfall events; day 18 – a short, discrete 'light' rainfall event (Fig. 7); and for day 23, a more prolonged period of rain, with consistent rain over 5–6 h (Fig. 8). On day 18, *D.* 'Haytor White' showed the greatest rainwater retention capacity, with full-canopy plants outperforming taxa such as *V. minor*, *H. sieboldiana* and *P. terminalis* (Fig. 7). On day 23, however, the greatest amount of rainwater (> 800 g) was retained on full-canopy plants of *F. glauca* (Fig. 8), with even the cropped plants of this taxon outperforming some other (full-canopy) taxa. Full-leaved *B. cordifolia*, also showed better retention than *D.* 'Haytor White', *H. sieboldiana* and *P. terminalis*. The volume of water intercepted within the more persistent rain episode (day 23) is considerably more than that with the short. 'light' rain event (compare Figs. 7 and 8). During other rainfall events, greatest retention was associated with

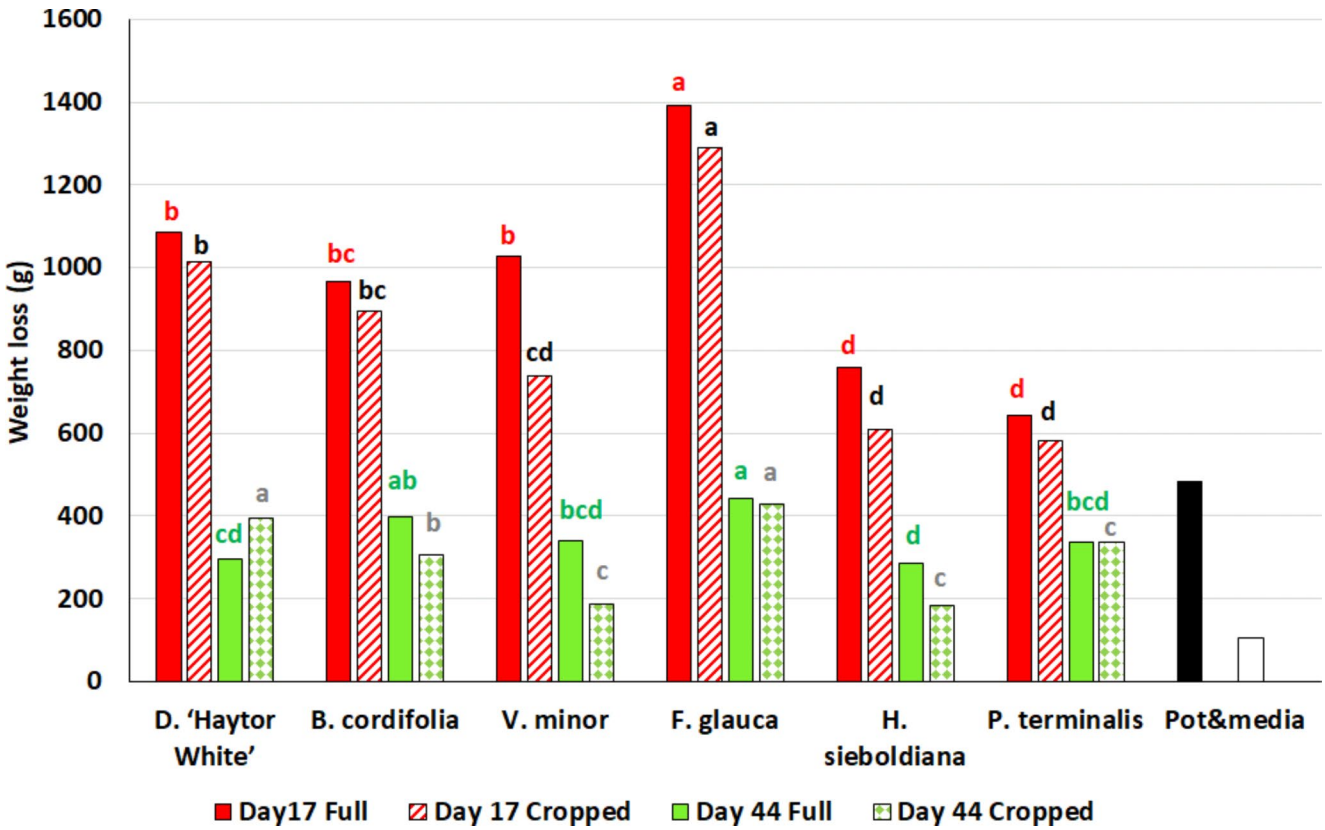


Fig. 5 Experiment 1. Weight changes in pots over the duration of the experiment, with data for day 17 (after dry period) and day 44 (end of experiment) shown. Solid bars represent plants with full canopy and hatched bars represent plants with cropped canopies. Black and white bars represent pots without plants after 17 and 44 days, respectively. Letters denote significant differences between taxa within individual times/treatment only (e.g. compare red letters with other red letters only; 'a' significantly different from 'b' etc.)

either full-canopy plants of *F. glauca* or *D.* 'Haytor White' (data not shown).

Plant hydrological performance in relation to leaf area

Mean total leaf area and number of leaves present were calculated for each taxa (Table 1). As might be expected, the full-canopied plants had higher total leaf area than the cropped-canopied equivalents (Table 1). Similarly, in terms of the number of leaves, the mean numbers of leaves of the full-canopied plants were higher than the cropped, with the exception of *D.* 'Haytor White'. While some species showed great differences between the number of leaves of the full and cropped canopy, others showed less marked differences (i.e. *B. cordifolia* and *H. sieboldiana*). This was due to the trimming not necessarily reducing the number of leaves, but actually cutting parts of individual leaves (so reducing leaf area, but not number).

Dividing the rainwater retention and ET data by the total leaf area, gave a figure for water retention / ET loss per unit of leaf area. This helps account for any effects due to different canopy widths and depths. Results showed no significant difference in rainwater retained per unit of leaf area across the taxa (Table 1), at least when the data is based on the final recorded plant leaf area. Patterns of ET water loss on day 9, per unit of leaf area, indicated cropped-canopy plants of *B. cordifolia* (0.102 g cm^{-2}), *F. glauca* (0.077 g cm^{-2}) and *D.* 'Haytor White' (0.075 g cm^{-2}) showed highest ET losses (Table 1). *Pachysandra terminalis* demonstrated 0 g cm^{-2} of ET. Although not always significantly different, water loss per unit area in general, was greater with cropped canopy plants compared to the full canopy equivalents.

Comparisons with non-planted, control pots

Overall, the best treatments associated with planted pots, were between 2.5x and 4.0x more effective at evapo-transpiring water than the control, non-planted pots; and 2.3–3.0x more effective at capturing rainfall than non-planted pots.

Chlorophyll fluorescence and subjective assessments of leaf health

Of the four broad leaf species that gave Fv/Fm data, *H. sieboldiana* showed some indication of plant stress by the

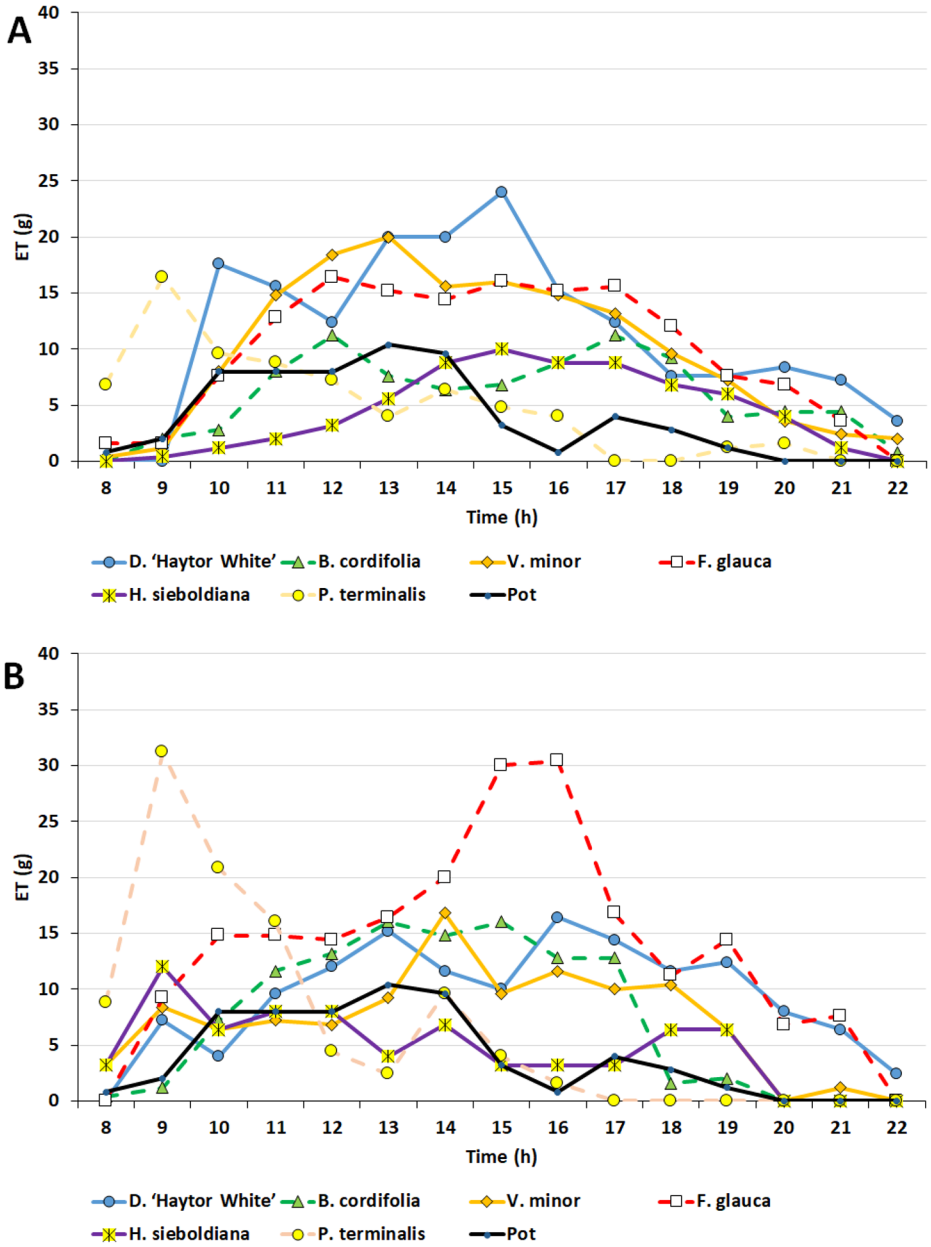


Fig. 6 Experiment 1. Evapotranspiration rates during the day (mean values day 11–16); (**A**) full-canopy plants; (**B**) cropped-canopy plants

end of the experiment, with Fv/Fm values significantly lower than other species (Table 2). This was particularly so with the full canopy plants (Fv/Fm = 0.59). Visual observations indicated some chlorosis in the older leaves of *H. sieboldiana*.

Experiment 2. Plants grown under controlled conditions from 11 Aug. – 28 Oct. 2017

Evapotranspiration under controlled conditions

All taxa showed similar water use over the duration of the entire experiment when kept under controlled conditions, except for *F. glauca*, where water use was about 1/3 more at approximately 1500 g per plant (Fig. 9). This taxon particularly demonstrated high ET rate over the first 3 days of the experiment, although ET rates were lower and comparable to other taxa in the last 2 days (Fig. 10), which suggests that stomatal conductance was being reduced by lower water availability at the end of the experiment.

Chlorophyll fluorescence and subjective assessments of leaf health

There were no significant differences in Fv/Fm between taxa recorded at the end of the individual phases of the load

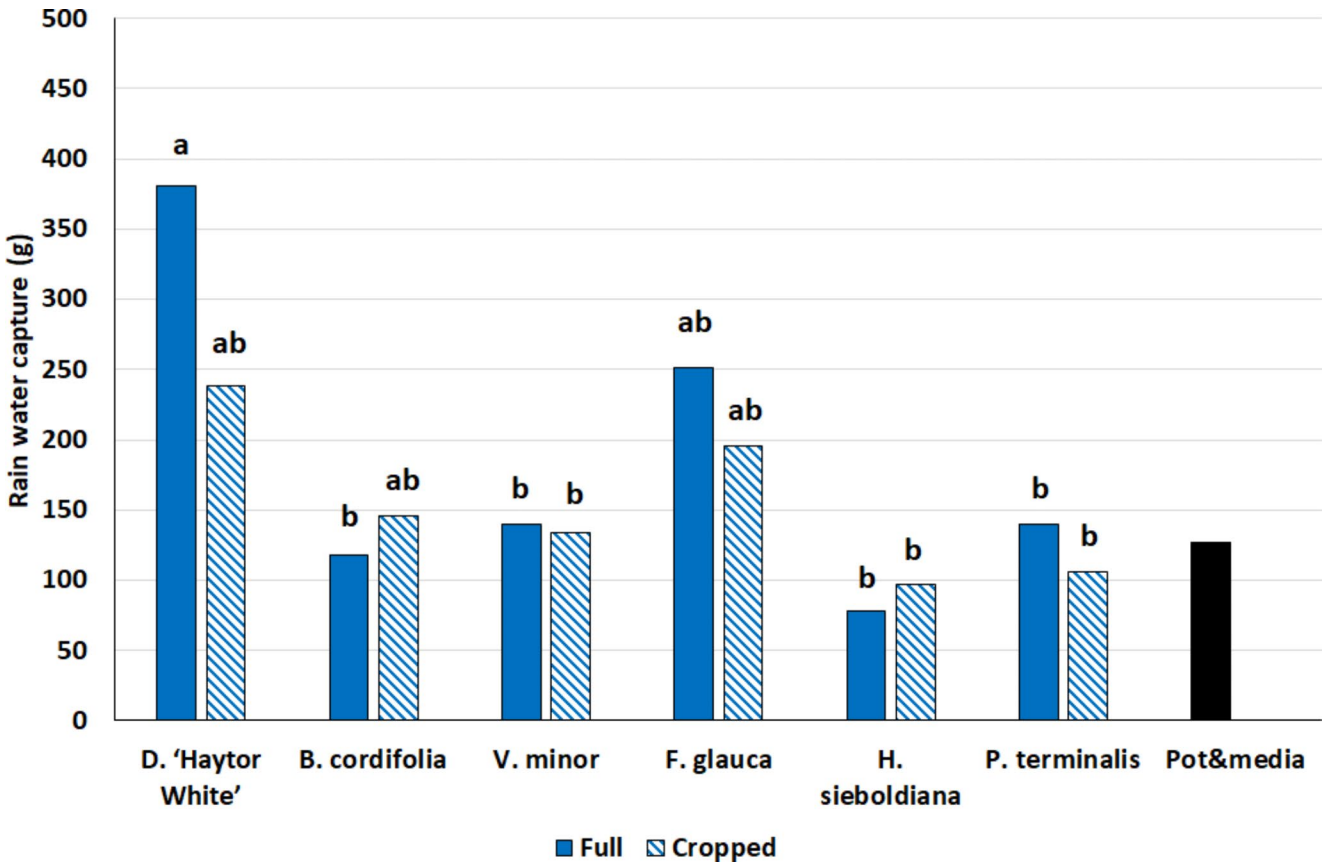


Fig. 7 Experiment 1. Rainwater interception across different taxa on day 18 (24 h period with a total rainfall depth ~ 3 mm). Letters denote significant differences between taxa and treatments

cell experiment. There was some evidence of minor leaf chlorosis in all the broad leaf species in the last phase of this experiment (replicate 4), but this was the phase corresponding with the onset of autumnal conditions outdoors.

Discussion

The capacity of groundcover plants to intercept and dissipate rainwater varied with the taxon chosen. When comparing established plants of a similar age in a 3.5 L pot, it was clearly evident that one taxon, *Festuca glauca* was very effective at both capturing rainwater (Fig. 8) and transpiring water from the substrate (Figs. 4 and 5).

Rainwater interception/retention

Along with *F. glauca*, another fine-leaved species *Dianthus* 'Haytor White' also showed some capacity to intercept rainwater, and indeed during a discrete period of 'light' rainfall (day 18) caught more rain than *F. glauca*, but not by a significant margin. In contrast, during a period of more prolonged, consistent rainfall (day 23), *F. glauca* intercepted significantly more water than *D.* 'Haytor White'. This suggests that there may be interactions between rainfall intensity and the ability of different plant canopies to intercept and retain the raindrops, which needs further evaluation. Within broad-leaved and the simple-leaved species, there was a suggestion that *Bergenia cordifolia* and full canopy *Vinca minor* were more effective at capturing/retaining rainwater than the other species such as *Hosta sieboldiana* and *Pachysandra terminalis* (Fig. 8). During the prolonged rain event (day 23), it was noteworthy that the larger-leaved *Bergenia cordiofolia* plants caught more water than *D.* Haytor White (Fig. 8).

One of the reasons for high water retention capacity by *F. glauca* may relate to the high number of leaves in this species and a high total leaf area (Table 1), however, even cropped specimens of this taxa (with much reduced total leaf area, but still high numbers of leaves) retained relatively good water capturing capabilities (Figs. 7 and 8). This suggests that the number of leaves along with their narrow shape and orientation (mostly upward facing) are helping this taxon hold water and direct any run-off from the leaves to the central basal growing point and roots of the plant. Large numbers of small leaves may also partially explain the relatively

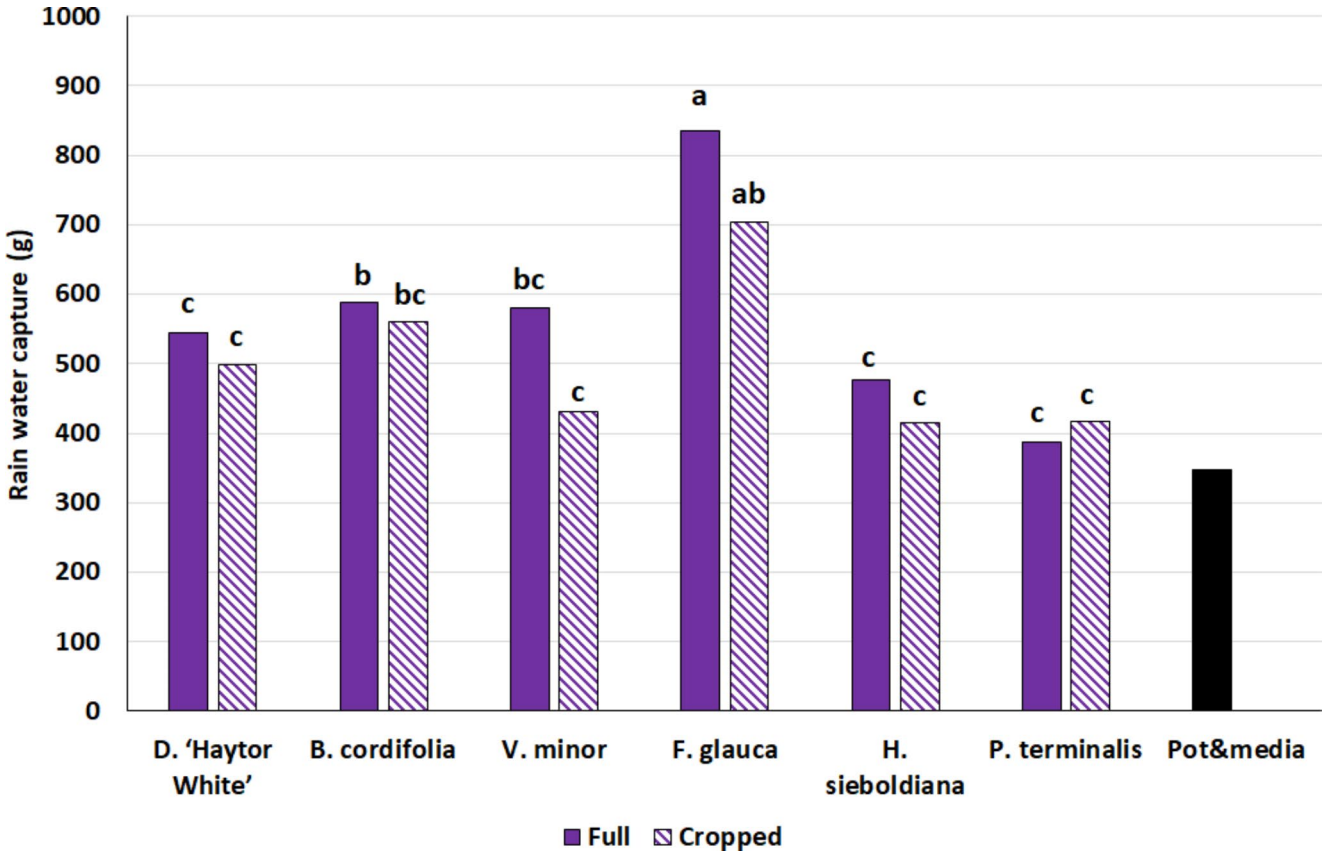


Fig. 8 Experiment 1. Rainwater interception across different taxa on day 23 (24 h periods with rainfall depth ~ 11 mm). Letters denote significant differences between taxa and treatments

Table 1 Experiment 1. Mean total leaf area, number of leaves, water retention and evapotranspiration per unit of leaf area in the six plant taxa. Letters denote significant differences between taxa and treatments

Treatments	Mean total leaf area (m^2)	Mean number of leaves*	Retention (D23) / Unit of leaf area ($g\ cm^{-2}$)†	ET (D9) / Unit of leaf area ($g\ cm^{-2}$)†
Full canopy				
D. 'Haytor White'	0.070b	826a	0.61a	0.058ab
B. cordifolia	0.064b	17 cd	0.82a	0.073ab
V. minor	0.129ab	1028a	0.42a	0.034b
F. glauca	0.200a	977a	0.43a	0.038b
H. sieboldiana	0.055b	4.2e	0.79a	0.061ab
P. terminalis	0.149ab	449ab	0.50a	0.00c
Cropped canopy				
D. 'Haytor White'	0.046c	839a	1.01a	0.075a
B. cordifolia	0.041c	15 cd	1.22a	0.102a
V. minor	0.052c	501ab	0.61a	0.060ab
F. glauca	0.067b	847a	0.70a	0.077a
H. sieboldiana	0.037c	4.4e	0.81a	0.030b
P. terminalis	0.039c	215bc	0.92a	0.00c

*In some taxa, the cropping reduced overall leaf number and in others it made individual leaves smaller but did not change number radically

† Weight gains and losses during experiments were divided by leaf area as recorded at the end of the experiment – thus may include some errors due to relative differences in growth rates between taxa in the intervened periods

Table 2 Experiment 1. Mean chlorophyll fluorescence (Fv/Fm) values. Values below 0.7 indicate plant stress. Letters denote significant differences between taxa and treatments

Treatments	Fv/Fm
Full canopy	
D. 'Haytor White'	NA
B. cordifolia	0.82a
V. minor	0.71b
F. glauca	NA
H. sieboldiana	0.59d
P. terminalis	0.72b
Cropped canopy	
D. 'Haytor White'	NA
B. cordifolia	0.83a
V. minor	0.78b
F. glauca	NA
H. sieboldiana	0.66c
P. terminalis	0.71b

NA – Not applicable due to the leaves being too narrow to fill the chlorophyll fluorescence dark adaption chamber

good water interception/retention traits of *D.* Haytor White and *Vinca minor*. Overall, our data tends to agree with previous studies on both trees (Carlyle-Moses and Gash 2011; Li et al. 2016; Xiao and McPherson 2016) and green roof plants (Lundholm et al. 2010; MacIvor and Lundholm 2011; Nagase and Dunnett 2012) that finer-leaved species, with many small leaves are effective at capturing and holding rainwater in their canopies. We did find an exception to this generalisation, however, in that during day 23, *B. cordifolia* intercepted more water than *D.* 'Haytor White' (as mentioned above), this was despite *B. cordifolia* having a marginally smaller leaf area (Table 1). Thus, although we accept that many fine-leaved taxa, are very effective at intercepting and retaining rainwater, we reject our initial hypothesis that they will *always* outperform broad-leaved species in this capacity.

This data also raises the question why the broad-leaved species *B. cordifolia* could be relatively useful in catching rainwater. In this case, the large leaves may be acting like sails and catching water that otherwise would fall outside the area of the pot itself, and then the leaf orientation helps channel this water to the centre of the plant. There was little evidence of moisture drops adhering to the leaves per se, but water pooling was observed at the leaf petiole. This capacity to intercept water (but not retain it on the main part of the leaf) was advantageous in our pot based experimental methodology, but it's less clear how this would impact surface

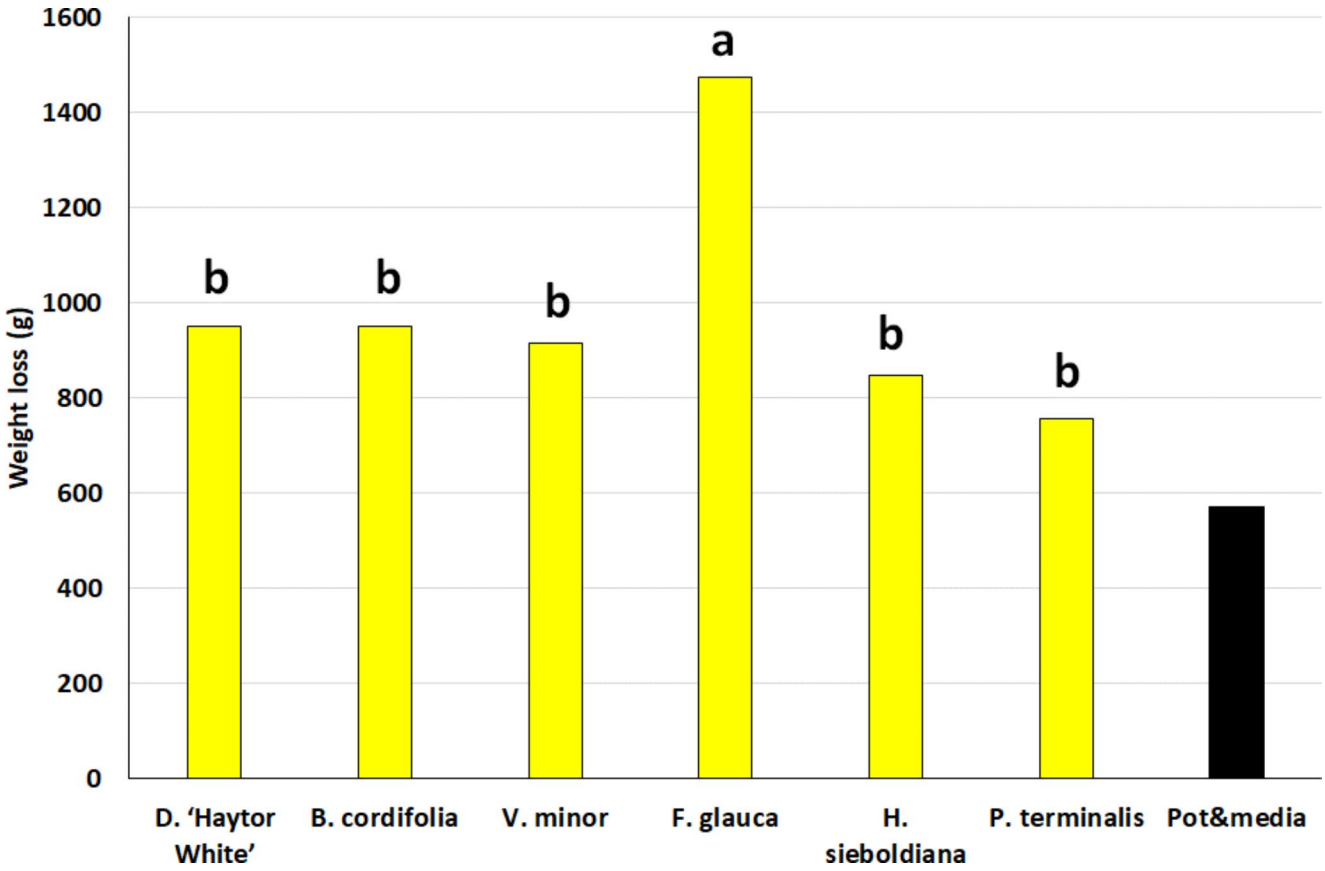


Fig. 9 Experiment 2. Total weight loss over 12 days under controlled environment – uniform conditions. Letters denote significant differences between taxa

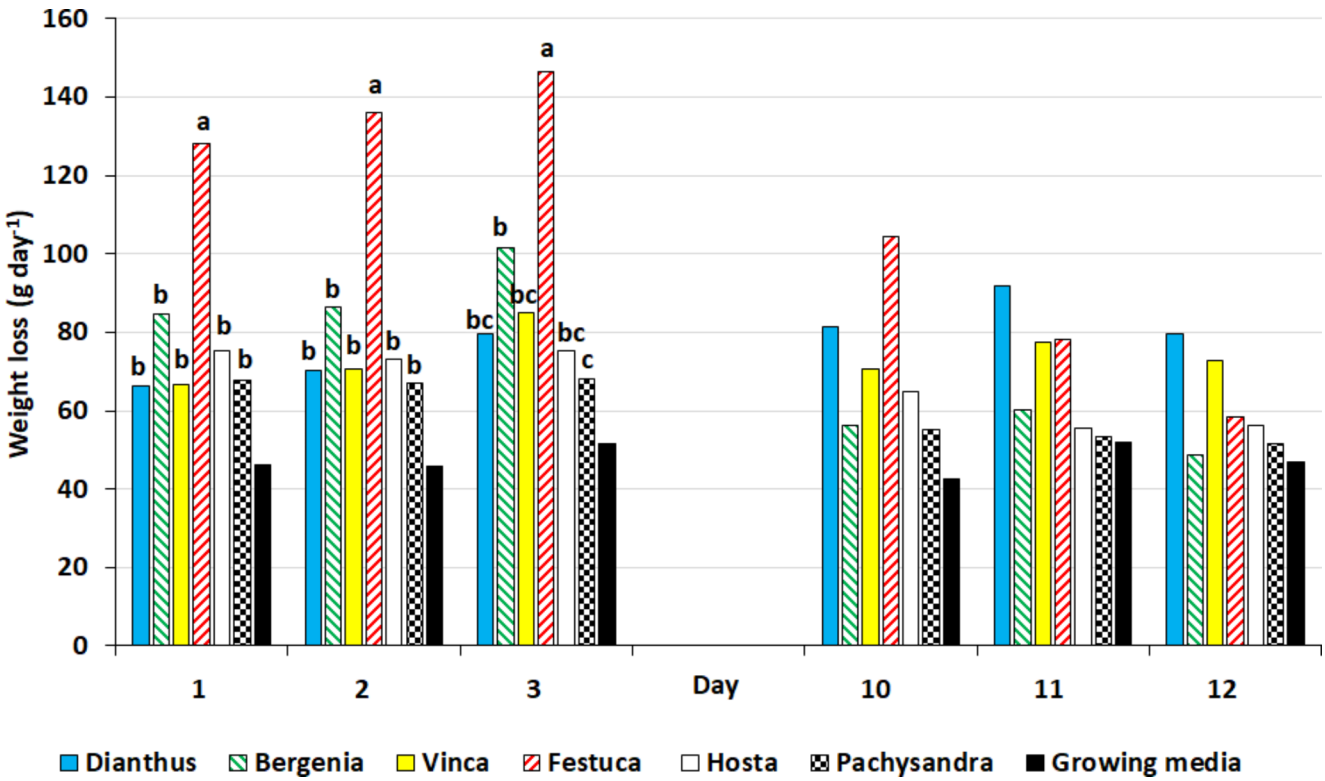


Fig. 10 Experiment 2. The weight of water lost per day within the first three days (D1-D3) and the last three days (D10-12) of the experiment. Statistics are shown for D1-D3 only. Letters denote significant differences between taxa on each day; Comparisons across different days are not valid. No treatments were significantly different from each other on D10-D12

flow in an in vivo landscape situation. Certainly, leaf orientation seemed an important aspect in the broad-leaved taxa within this pot experiment. For example, *P. terminalis* was not effective at capturing/holding water, and this may be due to the orientation of its leaves (shedding water away and over the rim of the pot rather than directing it to the centre) or encouraging raindrops to bounce off the leaves and 'splash' away from the pot. Shedding excess water away from the pot may have also been the case with *H. sieboldiana*, where similarly, observations indicated that droplets did not adhere to leaves but ran-off rapidly. Although such species may catch raindrops (and help dissipate some of their energy), the fact the water runs off readily and quickly is not conducive to good retention characteristics.

Although we identified differences in water retention per unit of leaf area (Table 1), these values were not significantly different across the taxa, suggesting that the micromorphology of leaves associated with any taxon, was not having a large effect on water interception/retention. In contrast, the morphology of plant canopies, the number of leaves present and the complexity of the canopy as an entity seemed to determine rainwater interception more strongly. When leaves were cropped and leaf area was more equitable across taxa (Table 1), there were still some advantages with *F. glauca* and to some extent *B. cordifolia* (Fig. 8). In the former case, perhaps this was due to the number of narrow leaves present and the overall complexity of the canopy; and in the latter case, as mentioned above, a small number of large leaves intercepting the raindrops and then channelling them towards the central crown of the plant.

Evapotranspiration and dissipating water from the substrate

Festuca glauca was superior to other species in terms of evapo-transpiring water in both the outdoor (Fig. 5) and semi-controlled experiment (Figs. 9 and 10). This may partially be due to a large total leaf area, but even when its leaves were cropped, this taxon continued to dissipate water well (note leaf area in Table 1 and water use in Fig. 5). Being a grass, this species may also be adapted to growing fast and exploiting what water is available to maximise cell expansion and photosynthesis, thus also being a useful candidate to dry out soil quickly. Indeed, the data around this species was remarkable, with its ability to dry the soil out 3 times greater on day 17 and 4 times greater on day 44 than non-planted pots (Figs. 4 and 5). Even when this taxon had its leaves cropped, it was still more effective at transpiring water than other species that had retained their full canopy, for example, on Day 10, 150 g of water was lost

in cropped canopy *F. glauca* (Fig. 5b) compared to 110 g in full canopy *Pachysandra terminalis* (Fig. 5a). This clearly demonstrates that plant choice matters when the objective is to restore soil moisture holding capacity. The data also does not support our second hypothesis that narrow-leaved species transpire less than broad-leaved species, at least when being compared at the whole plant level. Even when plant canopies were cropped to give similar dimensions, the evidence that broad leaves were more beneficial for dissipating water vapour is not clear. On day 9, *B. cordifolia* transpired more water per unit leaf area (0.102 g) than other species but was not significantly more than the fine-leaved taxa *F. glauca* (0.077 g) or *D.* 'Haytor White' (0.075 g), but these in turn did transpire more water than other broad leaves such as *H. sieboldiana* and *P. terminalis.*

As well as total leaf area and leaf traits, plant water use may also relate to underlying ecophysiology factors. Plants adapted to dry shade (*Pachysandra*) or damp shade (*Hosta*) may not have the same need to transpire as rapidly and maximise extension growth, compared to open space or meadow species (*Festuca* and *Dianthus*). where these may face more competition for light in mixed plant communities. A relatively high transpiration per unit leaf area in *Bergenia* may relate to this taxon using its large leaves and rapid leaf growth to cover the ground entirely, and thus shade-out competition in the open, alpine woodlands it originates in.

The growing conditions were relatively stable over the experimental period, and further work is warranted across a range of more extreme weather events. It is unclear whether the ranking of evapotranspiration water use across the taxa would remain the same, when conditions got warmer. Certainly, differentiation between the taxa was greatest on those few occasions when temperatures were relatively high, and humidity lower, e.g. day 10 (Fig. 4). Periods of prolonged dryness and warmth, however, will affect water availability at the rootzone, and stomatal sensitivity to this (and other factors such as irradiance levels) can vary between landscape plant taxa (Cameron et al. 2006). Some species may stop transpiring more readily than others. Previous dry periods may also influence the capacity for full evapotranspiration to be restored, once substrate water becomes freely available again (Cameron et al. 2006, 2008).

Plant quality

Physiological stress was observed (lower chlorophyll fluorescence values) in some *H. sieboldiana* plants in the outdoor experiment. This suggests that this damp tolerant, shade-adapted species was exposed to a degree of abiotic stress during the drying out of the substrate phase in late summer. We did not manage to measure physiological stress in the two narrow-leaved taxa, but found little evidence of obvious drought injury from our visual observations. Again, these findings suggest that species choice is important in not only providing ecosystem services, but also surviving and maintaining functionality under the stressful conditions they may encounter within the urban landscape. Good candidates in this respect (at least under our open location, full natural irradiance conditions) were *Festuca glauca*, *Dianthus* 'Haytor White', *Bergenia cordifolia* and *Vinca minor*, with some suggestion of lower functionality with *Pachysandra terminalis* and lower viability with *Hosta sieboldiana* under these conditions.

Limitations to the research

Clearly the capacity of an individual plant to capture and evapo-transpire water will depend on its size. In this taxon comparison study, attempts to standardise size was employed by growing plants in a standard 3.5 L pot and utilising plants of similar age. The pot system helped provide uniformity across taxa and allowed for accurate water determinations through weighing the whole pot/plant system. A plant growing in a pot, however, may interact differently to rainwater to one growing in an in vivo landscape, for example roots can spread further laterally when not confined by a pot and thus help with greater transpiration from the soil. Thus the results reported here need to be viewed with caution with respect to real hydrological interactions and flows across an urban landscape. As stated at the outset though, the pot system was not designed to replicate in vivo scenarios, but rather to provide an effective experimental system to compare taxa in a relativity unbiased manner. There may also be some (relatively small) inaccuracies around the leaf area/number effects on water capture/dissipation as these parameters were measured in detail at the end of the experiment – not after e.g. individual rainfall events. It was noted, however, that growth was generally slow in later summer across all taxa, limiting differences in leaf area/number during the progression of the experiments.

Conclusions

This research confirms that plant choice matters when trying to optimise hydrological management in urban settings and utilising groundcover plant taxa to do so. In general, we deem that rainwater interception is improved by the use of fine-leaved taxa with large numbers of leaves and large overall surface leaf areas. This observation agrees with previous findings (Lundholm et al. 2010; Carlyle-Moses and Gash 2011; MacIvor and Lundholm 2011; Nagase and Dunnett 2012; Li et al. 2016; Xiao and McPherson 2016), but more novel is the illustration that plant choice also strongly

influences the ability to dry out the substrate (soil) after it has rained; thus has value in recharging the soil's capacity to store water should a subsequent heavy rainfall event take place. In essence, plants can help mitigate urban flooding by both slowing down surface water run-off and also by the process of evapotranspiration, which allows more water to subsequently enter and be stored by the soil. This ability to restore water holding capacity through the appropriate choice and design of urban planting has, up to now, been under-researched. The data presented here indicates that species choice is also important when delivering this particular ecosystem service. Ideally, such plants should have a large capacity to remove soil moisture, yet retain the ability to tolerate low water availability themselves, once they have depleted the soil's water supply. In essence, such plants should have the capacity for high transpiration, but also rapid and effective stomatal closure and tolerance of low leaf water potentials, once a threshold of low soil water availability is reached. *Festuca glauca* showed some evidence of being a species that follows this pattern, but further research is required to identify other groundcover (and landscape plants in general) that can dry soils out quickly but without risking their own viability.

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Declarations

Ethics approval NA.

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