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Impact of plant choice on rainfall runoff delay and reduction by hedge species

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Abstract

Soil sealing and a decrease in vegetation cover in urban areas increase the likelihood and frequency of localised flooding. Populating the remaining green areas with vegetation, which can efficiently capture excess rainfall, is therefore important. We argue that urban hedges can be a useful tool in mitigating rainfall, so the understanding of optimal plant choice, and underlying traits which enable most rain attenuation, is needed.

We tested the hypothesis that higher plant evapo-transpiration rates and larger canopy size can be linked with reduced rainfall runoff in urban hedge species. We first characterised seven hedge species grown in individual containers. These were both deciduous and evergreen species, with a range of inherent canopy sizes and water requirements. We assessed their plant water use, leaf stomatal conductance, canopy rainfall retention, and runoff delay and reduction capacity. The species showing highest and lowest potential for runoff reduction were then investigated for their outdoor performance, when planted in a hedge-like form. Our findings suggest that – after three days between rainfall events - species such as *Cotoneaste*r and *Crataegus* with larger and wide canopies, and with high evapo-transpiration / water use rates, delayed the start of runoff (by as much to 10-15 minutes compared to bare substrate) as well reduced the volume of rainfall runoff. For example, <5% of the applied rainfall had runoff with *Cotoneaste*r and *Crataegus,* compared with >40% in bare substrate. Substrate moisture content at the time of rainfall (which is linked to plants' ET rate) was the key explanatory variable.

Additional keywords: *Cotoneaster*, *Crataegus*, flood mitigation, hawthorn, *Thuja*

Introduction

Rapid urbanisation and an increase in sealed surfaces due to paving over (Smith 2010; Verbeeck et al. 2011) can be linked to higher incidences of localised flooding in urban areas (Perry and Nawaz 2008; Warhurst et al. 2014). However, appropriately chosen and well managed vegetation in different forms of green infrastructure (GI) can play a role in reducing flood risks. This includes domestic gardens (Cameron et al. 2012; Kelly 2016; Warhurst et al. 2014), street trees (Xiao and McPherson 2002), vegetation strips such as grass verges (Charlesworth 2010), as well as urban hedgerows and garden hedges (O'Sullivan et al. 2017). All these green areas help rainfall management chiefly through maintaining soil, as the main natural water store in urban areas (Pit et al. 1999). Presence of vegetation also increases the soil’s ability to receive subsequent rainfall through increasing soil’s water-storage capacity by water loss via evapo-transpiration (Stovin et al. 2012). Additionally, plant roots can improve soil structure and increase porosity, increasing drainage and soil’s water-holding capacity (Bartens et al. 2008; Mueller and Thompson 2009). There is also an element of rainfall interception and retention in the canopy, thus delaying runoff (Crockford and Richardson 2000).

In the UK, domestic gardens in urban areas take up a significant proportion of urban footprint (15-25%, Cameron et al. 2012; Gaston et al. 2005). Garden hedges are a ubiquitous feature of UK front gardens and can thus provide a number of frontline services including rainwater capture and localised flood protection. A recent survey by the Royal Horticultural Society (RHS) suggested that the vegetated area of front gardens across the UK has decreased by as much as 15% in the period 2005-2015. Additionally, one in four UK front gardens are paved-over and nearly one in three front gardens have no plants (Anon 2016). We argue therefore, that maintaining unsealed surfaces in domestic gardens, including features such as garden hedges, can reduce the flooding risks for domestic households and streets/neighbourhoods. The question, however, is to what extent can we maximise canopy capture and runoff reduction by careful plant species choice, with traits to maximise this service?

Previous work in our group (Blanusa et al. 2015; Blanusa et al. 2013; Cameron and Blanuša 2016; Vaz Monteiro et al. 2017; Kemp et al. 2017) provides evidence for the notion that differences in plant structure and the rate/mode of physiological function lead to differences in the provision of various ecosystem services by urban vegetation. E.g. plants with larger leaf areas, lighter leaf colour and greater rates of evapo-transpiration (ET) provide greater extent of building and ambient cooling by green roofs, by reducing soil heat flux and increasing latent heat fluxes (Vaz Monteiro et al. 2017). Larger leaf areas and greater ET rates of vegetation on green roofs have also been linked to reduced rainfall runoff rates (Kemp 2018).

Recent work on urban hedgerows (O'Sullivan et al. 2017) suggested that species with high water use are more efficient at reducing flooding risks. Ranking of species in that study is based on Roloff et al. (2009) work on drought tolerant trees (i.e. O’Sullivan et al. (2017) assume that less drought tolerant species have higher water use and thus offer greater flood protection). While this is a logical principle, no practical testing of hedge species had been carried out to explore this in practice. In the urban setting, other green infrastructure installations such as rain gardens or bioswales, and green roofs have been extensively studied for their capacity to reduce rainfall runoff (Berretta et al. 2014; Cameron and Hitchmough 2016; Scharenbroch et al. 2016), but the role of hedgerows in rainfall mitigation has been understudied.

A small body of existing work investigating rainfall management and runoff reduction by hedgerows was focused on rural / agricultural landscapes, rather than urban areas (e.g. Ghazavi et al. 2008; Herbst et al. 2006). Study by Herbst et al. (2006) quantified the rainfall interception loss of agricultural hedgerows per unit ground area, and determined the horizontal extension of the zone which is being influenced by the presence of a hedgerow. Two hedgerows in this study were composed predominantly of *Crataegus monogyna* (hawthorn), with some *Acer campestre* (field maple) sections, so the emphasis was on determining a general hedge effect rather than distinguishing the contribution of two species. Over the course of nearly a year these hedgerows intercepted >50% of the rainfall falling on the projected canopy area (Herbst et al. 2006). The width of the zone where hedges reduced runoff was equivalent to approximately two hedgerow heights and runoff reduction, during the period of full leaf cover, was 24% (Herbst et al. 2006). This is comparable to the highest observed values for a similar area of broadleaf tree stands and just slightly lower than coniferous woods (Herbst et al. 2006).

In addition to work on hedges' rainfall mitigation in agricultural context, a number of studies focus on individual tree specimens of species which could also be utilised as hedges (Keim et al. 2006; Nordén 1991; Asadian and Weiler 2009). Even so, very few potential hedge species have been studied in terms of the rainfall interception / retention e.g. *Thuja plicata* (Keim et al. 2006), *Fagus sylvatica* and *Carpinus betula* (Nordén 1991). These studies found *Thuja* had low capacity for water storage within the canopy compared to broad-leaved tree species (e.g. *Acer sp., Rubus sp*. etc), but similar to other coniferous trees (e.g. *Tsuga heterophylla*, Keim et al., 2006). As a general guide, branches of all tree species tested in that study retained more water at higher, rather than lower rainfall intensities; leaf area was the best predictor of canopy water storage, but more strongly for broadleaved than for needle-leaved species (Keim et al. 2006).

The aim of our study was therefore to test a range of urban hedge species (both deciduous and evergreen) differing in inherent vigour and canopy sizes, and with varying water use requirements and evapo-transpiration rates. We hypothesised that species exhibiting higher evapo-transpiration rates, which lead to a reduction in soil moisture content, can be linked with reduced rainfall runoff. We also hypothesized that species with larger canopy would exhibit greater runoff reduction. Our approach was two-pronged. We first characterised individual plant specimens of the selected species: their plant water use, leaf stomatal conductance, canopy rainfall retention, and runoff delay and reduction capacity. We have then selected the species showing highest and lowest runoff reduction and investigated their outdoor performance, when planted in a hedge-like form. Our findings suggest that the species with high water use rates, which reduced substrate moisture more before the rainfall was applied, better delayed the start of runoff as well reduced the volume of runoff.

Materials and methods

Rainfall application setup

To simulate natural rainfall in a controlled and repeatable manner, a sprinkler system based on the design described by Iserloh et al. (2012), produced ‘in house’ by an irrigation specialist at RHS Garden, Wisley, was used. The system consisted of a Lechler 460 608 nozzle attached to a 2 m length of hosing (Tricoflex, Hozelock Ltd., Birmingham, UK) to a flow control, which was a series of pressure gauges and filters that ensured that the water flow and the characteristics of the droplets produced were constant. The system was connected to the mains water supply by hosepipe, and rainfall could be turned on and off directly on the simulator (Figure 1). The optimum flow pressure to achieve consistent rainfall in terms of droplet size and distribution was found to be 0.15 bars (15 kPa), and so this pressure setting was used for all rainfall simulations. The nozzle, hosing and simulator were fastened to an L-shaped timber support structure 2.4 m high and 1 m across; this was then secured to a pre-existing metal frame in both glasshouse and field set-up, which run above all containers or troughs in the experiment.

The height of the nozzle was 0.7-0.9 m above the top of the experimental containers/troughs, depending on the height of the canopy in different species; this is in line with the heights of other rainfall simulators cited in the literature, typically for used in soil erosion and runoff studies, which vary between 0.7 and 3 m above the ground (e.g. Humphry et al. 2002; Fister et al. 2012). To further characterise the simulated rainfall, average raindrop size was measured using the flour pellet method described by Clarke and Walsh (2007). The diameters of all raindrops in three representative 4 x 4 cm areas were then measured using Image J software (National Institutes of Health, USA). Raindrop sizes ranged from 0.21 to 2.76 mm with the majority of droplets (70%) smaller than 1 mm diameter, similar to the simulated raindrops produced in other studies (e.g. Iserloh et al. 2012; Fister et al. 2012).

Experiments with individual hedge plants

Experiments were carried out in the period May-June 2016 in the ventilated glasshouses at the University of Reading (UK), where temperatures were maintained in the range 23-25 ^{o}C during daytime and 17-18 ^{o}C at night-time, with ambient light levels Four-year-old plants of seven hedge species, grown individually in 10 l containers, with John Innes no 3 compost (7:3:2 sterilised loam:peat:coarse sand v/v, Westland, Dungannon, UK), were used. Species included five evergreen: *Photinia* x *fraseri (cv* 'Red Robin'), *Thuja plicata (cv.* ‘Atrovirens’), *Taxus baccata, Ligustrum ovalifolium (cvs. ‘*Aureum*’ and ‘Argenteum’)* and *Cotoneaster franchetii,* as well as two deciduous species: *Crataegus monogyna* and *Fagus sylvatica.* Six replicates of each species were used, along with three containers with just bare substrate.

Two types of experiments were carried out. One was measuring contribution of canopy to runoff reduction (so carried out on plants immediately after the substrate was saturated to full container capacity (> 0.40 m^3 m^{-3})). The other was measuring the importance of substrate moisture content and different ET rates to runoff reduction, by rainfall applications 3 days post saturation, with no additional watering in the 3 day period.

At the start of the experiment all containers were watered to full container capacity. Rainfall was applied either for 20 minutes (when measuring canopy interception, in containers where substrate was fully water-saturated) or 40 minutes (when containers were not watered for 3 consecutive days). Before simulated rainfall application, plant containers were placed within another ‘collection’ container which closely fitted but was 10 cm deeper, so that only the runoff from the substrate can be collected. To determine the runoff from each of the plant containers, water volume collected within the ‘collection’ container was measured after plants were left to drain for 1 h after the ‘rainfall’ stopped. For all rainfall applications, the rainfall simulator was fixed in a same position on a pre-existing metal frame within the glasshouse compartment. Position of the containers underneath the rainfall simulator was established by prior tests with 54 empty buckets (Kemp 2018, Kemp et al 2018) to determine the uniformity of rainfall application and volume of applied rainfall. The positions underneath the rainfall simulator nozzle which provided an average volume of 28 ± 0.9 mm h^{-1} were chosen. Additionally, we determined the volumes of water captured in containers of various diameters (d = 28 cm, 41 cm and 69 cm, all circular, plus a 100 x 100 cm tray). The mean volumes of rainfall (from 2 tests) captured after a 40 m simulated rainfall event in these trays were 820 ml, 1100 ml, 3145 and 8500 ml (on order of progressing size) That enabled us to calculate volumes of water received by canopies of various diameters and with different horizontal canopy projections. Once the experiment started, simulated rainfall for all replicate plants within one species would have been applied during the same day, by testing three and then two individual containers in the pre-determined fixed positions below the nozzle. As we had 7 species/cultivars to test in each experimental run, two days were required to test all species/plants. In testing the canopy retention, substrate was fully saturated just before the start of the experiment on each occasion, so the timing of rainfall application would have made no difference to the outcome. I If testing the contribution of ET, the fact that experimentation was carried out over two days was mitigated by adding the water lost in the first 24 h cycle (as determined by weighing the plants) to the containers which would have been measured on the later day, so that altogether all plants experienced 72 h of ET loss at the moment of testing.

Before the start of the experiment, canopy width was determined by taking two perpendicular measurements. This was so that we can calculate plants' horizontal canopy projection which is capturing, and funnelling, rainfall and thus estimate the volumes of water which each canopy received. Wider canopies are exposed to - and have a potential to 'catch' - more water, so they could produce more runoff. We therefore expressed our runoff data as a % of runoff water relative to the volume of rainfall received, in addition to absolute values of runoff volume. Additionally, plant height was measured, so that the canopy volume could be calculated from height and width measurements.

Measured parameters relating to canopy's capacity to capture rainfall included the weight of the containers with plants before and after rainfall application; this enabled us to quantify the weight of rainfall retained on the canopy in the situation when soil was fully saturated, as all the weight increase would be a result of what is held in the canopy (Eq 1).

$Cs = Wr – Ws$ (Eq 1)

where: Cs - canopy rainfall storage capacity, Wr - weight of a plant and saturated container at the end of rainfall application, Ws - weight of a plant and saturated container just before rainfall application.

We also measured the substrate moisture content (SMC) using a SM300 sensor connected to a HH2 Moisture Meter (Delta-T Devices Ltd., Cambridge, UK) in two locations per container.

All species were then left for 72 h without watering and all containers were weighed daily using a precision balance (CBK 32, Adam Equipment, Milton Keynes, Buckinghamshire, UK), to estimate daily evapo-transpiration (ET) by plants and bare substrate. Substrate moisture content (SMC) was also recorded daily. After this 72 h period without watering, plants were subjected to second simulated rainfall and the volume of rainfall runoff was recorded. In doing that, we investigated the impact of plant ET and different rates of substrate drying in different species, on the volume of rainfall runoff. Both canopy sequestration and ET contribution experiments were repeated twice over a two week period with different species tested in random order on the two occasions to minimise the impact of slight possible environmental differences in the glasshouse compartment on different days. Runoff data from both repeats matched closely, so only the data from the second repeat are shown in this paper.

Leaf stomatal conductance to water vapour was measured (using AP4 porometer, Delta-T Devices Ltd., Cambridge, UK) twice during the experiment: at the start of the experiment when plants were well-watered (i.e. substrate moisture content > 0.30 m^3 m^{-3} and also at the end of the experiment when the substrate was allowed to dry (< 0.20 m^3 m^{-3}). All treatments were measured on the same day in random order; three young fully expanded leaves per plant on five plants per species were used.

Additionally, at the end of the experiment, leaf area was measured destructively on three plants per species (apart from *Fagus* and *Crataegus* which were not measured) using a WinDIAS leaf area meter (Delta-T Devices, Cambridge, UK).

Experiments with model hedges in troughs

Experiments were carried out in the period May-June 2017 on the outdoor field plots within the glasshouse complex at the University of Reading (UK). Five year old plants of *Crataegus monogyna* (common name: hawthorn), *Cotoneaster franchetii* and *Thuja plicata* (common name: yew) were transplanted from 10 L into 110 L troughs (1 m (l) x 0.4 m (w) x 0.45 m (d)) with Sylvamix substrate (6:2:2 sylvafibre: growbark pine: coir v/v; Melcourt, Tetbury, UK) with a slow-release fertiliser feed (Osmocote, Scotts, Marysville, OH, USA) in March 2017. There were three plants per container and three containers per species, along with three containers with just bare substrate (‘control’).

Before transplanting, each container was lined with a double layer of fine horticultural mesh (Veggiemesh Insect Netting, 1.35 mm mesh size) to aid retention of small substrate particles and prevent blockage of drainage holes. Mesh was then covered with 10 L of horticultural gravel (size 10 mm), followed with 80 L of substrate.

Plants were maintained outdoors and watered as required. Two weeks before the start of rainfall experiments, plants were cut into a hedge shape; *Thuja* and *Crataegus* were 1.1 m wide and *Cotoneaster* 1.2 m. Height and depth dimensions for each species are shown in Table 1. Height and depth measurements were made on three sections per trough, for each of the troughs at the start of the experiment. Indicative leaf area for each species was determined destructively at the end of the experiment by cutting out two 15 cm x 15 cm x 15 cm sections in each replicate of the model hedges and measuring with leaf area meter (Delta-T Devices, Cambridge, Cambridgeshire, UK).

[Insert Table 1]

At the beginning of the experiment, troughs with hedge plants and bare soil were put into fixed positions in a field plot. The twelve experimental troughs were arranged in two parallel rows of six; arrangement of troughs within a row was random. Each trough was placed onto a plastic tray (1.1 m (l) x 0.45 m (w) x 0.05 m (d)) and both were then elevated onto a pedestal at 4^{o} angle, constructed from bricks and wood planks; this enabled the water to drain freely through the holes drilled on one end of the tray. During the experiment, to collect the rainfall runoff, plastic containers were fitted under the tray holes. Experimental setup is shown in Figure 1.

[Insert Figure 1]

The time taken for runoff to be generated from trays with bare substrate was pre-tested with the chosen rainfall simulator settings, and found to vary between 5 and 15 minutes, depending on initial substrate moisture content. As the plants would be increasing rainfall retention, to ensure that measurable runoff was always generated from all planted treatments and all substrate moisture conditions, it was therefore decided to simulate rainfall for 20 minutes (for troughs saturated to full water-holding capacity, where the role of canopy retention in runoff reduction was measured) or 60 minutes (for troughs after 3 days without irrigation, where the role of ET in runoff reduction was measured) for each container/trough (Table 2).

To set up the rainfall applicator, on the ground, at the back of the trough, a fixed position for the timber support and rainfall applicator was marked at the same distance from each trough, so all rainfall applications were administered from the same location for each trough.

Since rainfall could only be applied to one trough at a time, this meant that only 8 troughs could be tested in a working day (when the 60 min application time and subsequent draining times were factored in). Each experimental run was therefore conducted over two consecutive days, testing two replicates from each treatment on day 1 and one replicate on day 2. Experimental runs were carried on relatively still days, with wind speed < 5 m s^{-1}.

Two types of experiments were carried out (Table 2). One was measuring contribution of canopy (so carried out on hedges where the substrate is saturated to full container capacity (> 40 m^3 m^{-3})). The other was measuring the importance of substrate moisture content and different ET rates for runoff reduction, by rainfall applications after 3 days post-saturation. Due to the treatments' different ET rates, this would have led to different starting SMCs for this experiment. Details of measurements are shown in Table 2.

[Insert Table 2]

At the start of the first experiment all containers were watered to full capacity.

Experiments were repeated three times in a four week period and all data was analysed together as described in the Statistics section.

Before the start of the rainfall runoff experiments, a baseline measurement of leaf stomatal conductance to water vapour and net CO_2 assimilation of each plant treatment was made to establish plants' ET capacity, when substrate moisture content is at the field capacity. Three young fully expanded leaves per plant, on every plant, in two troughs per species (i.e. 9 measurements per trough, 18 per species) were measured using LCpro infra-red gas analyser (ADC Bioscientific, Hoddesdon, UK).

Before each simulated rainfall run, substrate moisture content in each through was measured using a SM300 sensor connected to a HH2 Moisture Meter (Delta-T Devices Ltd., Cambridge, UK) in four locations per trough.

Statistical analysis

For experiments with individual containers, an analysis of variance (ANOVA) was performed using GENSTAT (18th Edition, VSN International, Hemel Hempstead, Hertfordshire, UK). There, we compared means for each measured parameter (runoff volumes, canopy retention, leaf stomatal conductance, water loss by plants etc.) between different species. Variance levels were checked for homogeneity and values were presented as means with associated least significant differences, which were used to assess variations at a 5% significance level. Additionally, linear regression analysis was performed to establish a relationship between parameters such as ET and g_s, and runoff volumes.

For the experiments with hedges in troughs, to analyse runoff volumes from three consecutive sets of experiments, a repeated measurements analysis was employed. Linear mixed models were used to model the relationship of responses with the explanatory factors and covariates. The response ‘runoff volume’ was modelled on a logarithmic scale, hence its effect measures are expressed in Results tables as ratios of predicted means. ‘Species’ and ‘minutes after rainfall application ceased’ were fitted as fixed effects; ‘date’ and ‘trough’ were fitted as random effects to make results from this experiment more generalizable to users. To account for the correlated measurements taken on the same trough over time, an unstructured marginal covariance structure was used for the term ‘minutes after rainfall application ceased’. All overall F-test were adjusted using a Kenward-Roger method in PROC MIXED of SAS version 9.4. Finally, post-modelling pairwise comparisons between species were adjusted for multiplicity using a Holm method. For the analysis of substrate moisture content within troughs, net leaf CO_2 assimilation and leaf stomatal conductance on individual dates, a one-way ANOVA was performed as described for individual containers.

Results

Experiments with individual hedge plants

In our experiment, *Photinia* ‘Red Robin’ had the largest canopy leaf area (1.64 m^2), with all other species being statistically similar and averaging around 0.65 m^2 (data not shown). The branch orientation and crown horizontal canopy ground projection differed between the species, with *Cotoneaster* and *Photinia* having largest and *Thuja* having lowest canopy ground projection (Table 3). Canopy volume was greatest for *Cotoneaster* and *Photinia* and lowest for *Thuja* (Table 3). Plant heights however, were mostly similar between species (averaging 113 cm) with just *Photinia* being significantly taller, at 143 cm (data not shown).

Canopy retention of the rainfall was greatest in the two *Ligustrum* cultivars (averaging close to 400 ml per plant), and lowest in *Thuja* (below 250 ml per plant), with other species being similar at around 310 ml per plant (Table 3). Linear regression analysis revealed no statistically significant relationship between canopy volume and canopy retention ($p = 0.19$).

[Insert Table 3]

Leaf stomatal conductance (measured when plants were well watered, on Day 1 of the experiment) was highest in *Cotoneaster* and *Crataegus* (around 200 μmol m^{-1} s^{-1}) and lowest in *Thuja* and *Taxus* (below 100 μmol m^{-1} s^{-1}) (Table 3). *Cotoneaster*, *Crataegus* and *Photinia* lost most water per plant (over 2000 ml in a in 72 h period) with *Thuja* losing least of all plant treatments (<1500 ml). All plant treatments lost significantly more water than just bare soil (just over 600 ml in a 3-day period) (Table 3).

Substrate moisture content after 3 days with no irrigation was lowest in *Cotoneaster* (0.20 m^3 m^{-3}) and highest in bare substrate (0.45 m^3 m^{-3}); all other plant treatments had SMC between 0.28 and 0.30 m^3 m^{-3} (data not shown). Canopies of different species have different spreads, and thus different ground projections (Table 3). Water volumes received by different canopies are thus also different (Table 4).

[Insert Table 4]

Runoff from the containers, where rainfall was applied after 3 days with no watering, was negligible from *Crataegus* both in absolute terms (Table 4), and when expressed relative to the volume of water received (Figure 2). *Cotoneaster* too had lower volume of runoff (when rained on after 3 days with no watering) compared to all other species (apart from *Crataegus,* relatively expressed) (Figure 2). In absolute terms, but also in relation to the volume of rainfall received, *Thuja* had the highest runoff off all the plant species, although it was still lower than for the bare substrate (Table 4, Figure 2).

[Insert Figure 2]

Linear regression analysis revealed no statistically significant relationship between ET or g_s, and runoff volumes (data not shown). There was a statistically significant ($p = 0.05$) positive linear relationship between SMC and runoff volume (when expressed as a % volume received) ($R^2 = 0.14$).

Experiments with model hedges in troughs

Substrate moisture content was similar for all the treatments at the start of the experiment, then lower in all plant treatments after 3 and 5 days of drying compared bare soil (Table 5). Additionally, net CO_2 assimilation and leaf stomatal conductance were statistically significantly higher, when measured on Day 1 of the experiment in well-watered *Cotoneaster* than in *Crataegus* and *Thuja* (Table 5).

[Insert Table 5]

When substrate was fully saturated (i.e. only the canopy provided the barrier to rainfall), runoff was recorded first from a bare substrate treatment, then *Thuja* followed by *Cotoneaster* and *Crataegus* (Table 6A); statistical analysis showed significant treatment differences (P = 0.032, data not shown). *Cotoneaster* and *Crataegus* delayed runoff longer than bare substrate (Holm p-values 0.055 and 0.051, respectively). Statistical analysis showed no significant influence of either canopy volume or canopy density on the delay of runoff (p = 0.3669 and 0.6167, respectively) (data not shown).

In terms of volumes of runoff after the rain stopped falling on previously saturated substrate there were significant treatment differences. The volume of runoff generated at the end of rainfall was greatest in bare soil and *Thuja*, least in *Cotoneaster* and *Crataegus* (Table 6B). *Cotoneaster* and *Crataegus* produced statistically significantly less runoff than bare soil (e.g. at the end of the rainfall: Holm p-values 0.010 and 0.013 respectively).

[Insert Table 6]

After three days with no irrigation, substrate moisture content was on average 0.27, 0.18, 0.17 and 0.18 m^3 m^{-3} for bare soil, *Thuja*, *Crataegus* and *Cotoneaster* respectively (Table 5). Statistically, at that time point all plant species had similar substrate moisture, and all statistically lower than bare soil (Table 5).

When rainfall was applied to treatments after 3 days of no irrigation there were significant treatment differences in terms of the extent of runoff delay. There was a significant species effect (p = 0.0110) in the delay of runoff, with both *Cotoneaster* and *Crataegus* delaying runoff more than bare substrate and *Thuja* (Table 7A). In terms of volumes of runoff there were again significant species differences (p = 0.0258). Particularly, after 60 min draining there was significantly less runoff from *Crataegus* and *Cotoneaster* compared to bare substrate (p = 0.0083) (Table 7).

[Insert Table 7]

Statistical analysis showed the significant influence of substrate moisture content on both delay of runoff and the volumes of runoff (p = 0.0397 and 0.0551, respectively), but there was no impact of leaf stomatal conductance (p = 0.5414 and 0.4470, respectively).

Discussion

Loss of vegetation in urban areas, and in domestic gardens (in the UK) in particular can be linked to higher incidences of localised flooding in urban areas (Perry and Nawaz 2008; Warhurst et al. 2014). In a context of most domestic households in the UK having their own domestic garden (Cameron et al., 2012), urban hedges as a ubiquitous garden feature could be seen as a frontline protection for households from localised flooding. This is due to the delay of rainfall runoff when rainfall is captured on the canopies (i.e. canopy interception) and absorbed into the soil. With front gardens and associated hedges increasingly being lost to paving, making sure that the hedges we do plant and retain are providing maximal rainfall attenuation is important. We argue that through careful choice of hedge species, rainfall mitigation by urban hedges can be maximised.

Previous research found that depending on the intensity of the rainfall, canopy capture (e.g. in juniper trees) can represent 20-60% of bulk precipitation, with more canopy capture in less intense events (Carlyle-Moses, 2004, Owens et al., 2006). Additionally, in a young sitka spruce plantation, canopies captured 30% of rainfall annually (Ford and Deans 2018). Rainfall captured and temporarily retained in the canopy is especially important in a scenario of rainfall events happening in close sequence, when there is insufficient time for ET (particularly plants' transpirational component which removes water from the soil) to make a significant contribution to runoff reduction. Characteristics such as area covered by vegetation, branch angle, the uniformity in crown height, nature of the bark, leaf shape and inclination, and leaf area index will all influence rainfall interception by the canopies (Crockford and Richardson 2000). Branch diameter was also found to be positively correlated with canopy rainfall retention in several forest coniferous species (Liu 1998). Additionally, factors such as intensity of rainfall and other meteorological conditions (temperature, humidity, wind speed etc.) will have a role (Crockford and Richardson 2000, Toba and Ohta, 2005). While the conclusions about the contribution of various factors to rainfall capture and runoff reduction are generated largely from the forest and individual trees literature, they none the less present a starting point in interpreting a role that different hedges' forms and function might have in these processes. Due to the smaller area they cover, impact of hedges, of course will be more localised e.g. affecting an individual garden rather than a street-level catchment.

In our experiment, although species with greater leaf area (e.g. *Ligustrum*) generally retained more rainfall in the canopy, this was not always the case (e.g. *Photinia*). In our experiment just one rainfall intensity was tested; a response of different canopy structures to a change on rainfall intensity might vary (Carlyle-Moses and Gash, 2011). Based on our measurements, canopy leaf area, or even canopy volume, were clearly not the only explanatory variables of canopy retention, with species having similar leaf areas but different canopy retentions (e.g. *Ligustrum* vs *Taxus* or *Thuja*). While we could not numerically capture all the possible parameters potentially influencing canopy retention, the presence of clear species differences and anecdotal observations within our experiment would suggest that factors such as dense or more horizontal branch architecture, concave leaf shape and presence of structures like leaf hairs played a role in improving rainfall canopy capture.

While acknowledging the importance of canopy structural characteristics in rainfall retention, our primary interest was in establishing the contribution of plant functional characteristics such as ET and leaf stomatal conductance to runoff reduction. This was because of their impact on soil/substrate content which had been shown, in a green roof context at least, as an important predictor of rainfall runoff reduction (Kemp et al., 2018; Stovin et al. 2012; Poë et al. 2015).

Larger canopies receive more water into the canopy and filter it towards the ground (Ford and Deans, 1978). In our experiment, *Cotoneaster* covered the largest area over the ground, hence was exposed to most rainfall, yet had one of the lowest runoff rates. *Thuja,* conversely, has the smallest ground projection, but together with *Photinia* has highest runoff values amongst the studied species. Our observations in the outdoor experiment suggest that it was the branch architecture of *Thuja* (where branches are generally at 30-45^{o} away from the trunk) which encouraged more water to be funnelled towards the trunk and ultimately soil (causing more runoff), compared with species where branches and leaves are positioned closer to a 90°. This however could be seen as a positive on more free-draining soils (as it would channel more rainfall towards the ground). Conversely, *Cotoneaster* and *Crataegus* would offer best protection in soils which are less free-draining.

In both sets of experiments antecedent substrate moisture content was positively correlated with volumes of runoff. Our earlier preliminary experiment with the same species showed that *Cotoneaster* and *Crataegus* lost most water per m^2 of leaf area in any 24 h period (Blanusa et al. 2017) and they were the ones which then produced lowest runoff rates in subsequent experiments. In our experiment with hedges in troughs outdoors, runoff was lower in all plant treatments compared to bare substrate. This would thus suggest that lowering SMC and higher ET had some advantage in the first 2-3 days after the rainfall in an outdoor summertime scenario.

Individually, other functional parameters such as leaf stomatal conductance and ET were not statistically significantly linked to a delay or reduction of runoff. It is therefore likely that while low antecedent substrate moisture plays an important in delaying and reducing the runoff in hedge species, an additional complex combination of variables such as canopy shape and leaf properties (e.g. leaf hydrophobicity, Holder 2013) as well as root density and structure also play part.

Conclusions

Urban hedges are an important green infrastructure component in urban areas and particularly in people’s domestic (front) gardens in the UK where they are a popular and, arguably, widely spread feature. They have a capacity to delay and reduce rainfall runoff and thus offer protection from localised flooding, within an urban environment where loss of vegetated surfaces has been lined with increased incidents of flooding. Our experiments showed a significant impact of species choice on a hedge's capacity to retain water on the canopy, as well as to delay and reduce runoff. Of the studied species, *Ligustrum* and *Cotoneaster* retained largest rainfall volumes within their canopies. While we could not numerically capture all the possible parameters potentially influencing canopy retention, the presence of clear species differences and observations within our experiment suggest that factors such as dense or more horizontal branch architecture, concave leaf shape and presence of structures like leaf hairs played a role in improving rainfall canopy capture.

Hedge species such as *Cotoneaste*r and *Cataegus*, delayed the start of runoff (by as much to 10-15 minutes compared to bare substrate) as well reduced the volume of rainfall runoff. For example, <5% of the applied rainfall had runoff with *Cotoneaste*r and *Crataegus,* compared with >40% in bare substrate. Substrate moisture content at the time of rainfall (which is linked to plants' ET rate) seems to be the key explanatory variable.

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List of Table captions

Table 1. Mean hedge height and depth (in cm), as well as a mean indicative leaf area (in cm^2) collected from a 15 cm x 15 cm x 15 cm a section within hedge canopy. Data are mean of two (leaf area) or three (height and depth) sections of hedge on each trough with associated least significant difference (LSD) between means ($P < 0.05$). Different letters next to the means in a column denote statistically significant difference between those means.

Table 2. Details of experimental conditions and measurements made in the outdoor experiment with model hedges in troughs.

Table 3. Average canopy volume, rainfall canopy retention, leaf stomatal conductance and ET, with the associated least significant differences between the means. Different letters next to the means in a column denote statistically significant difference between those means ($P = 0.05$). Degrees of freedom (d.f.) are also shown.

Table 4. Mean rainfall volume received within a 40 minute event and volume of runoff. Least significant difference (LSD) and degrees of freedom (d.f.) are also shown. Different letters next to the means in a column denote statistically significant difference between those means ($P = 0.05$).

Table 5. Mean substrate moisture content on days 1, 3, and 5 of the first experimental round (22-25 May 2017) along with net CO_2 assimilation and stomatal conductance values on day 1 when all plants were well watered. Least significant difference (LSD) and degrees of freedom (d.f.) are also shown. Different letters next to the means in a column denote statistically significant difference between those means ($P = 0.05$); NS = non-significant.

Table 6. Predicted mean time to runoff (A) and runoff volumes (B) when rainfall was applied for 20 min onto troughs where substrate was fully saturated. Data are predicted means of three repeated experiments for all treatments and three troughs per treatment. Discussion of statistical significance in the body of the text is based on Holm p-values.

Table 7. Mean time to runoff (A) and runoff volumes (B) when rainfall was applied for 60 min onto troughs where substrate was not watered for 3 days. Data are predicted means of three repeated experiments for all treatments and three troughs per treatment. Discussion of statistical significance in the body of the text is based on Holm p-values.

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Figure 1. Setup for the outdoor experiment with model hedges in troughs.

Figure 2. Percent runoff in relation to the rainfall volume received per canopy, after a 40 min simulated rainfall event with the intensity of 28 mm. Rainfall was applied 72 h after the plants were watered. Values are means of six replicates per plant species and three replicates for bare soil. Error bar represents least significant difference between the means (LSD, P = 0.05).

Table 1. Mean hedge height and depth (in cm), as well as a mean indicative leaf area (in cm^2) collected from a 15 cm x 15 cm x 15 cm a section within hedge canopy. Data are mean of two (leaf area) or three (height and depth) sections of hedge on each trough with associated least significant difference (LSD) between means ($P < 0.05$). Different letters next to the means in a column denote statistically significant difference between those means.

Species	Height (cm)	Depth (cm)	Leaf area (cm^2) within a 15 x 15 x 15 cm section of the canopy
Cotoneaster	73.3 a	120.4 a	801
Crataegus	51.8 b	114.0 a	1165
Thuja	151.1 c	61.2 b	1282
LSD	6.77 ***	15.65 ***	496.8 (ns)

Table 2. Details of experimental conditions and measurements made in the outdoor experiment with model hedges in troughs.

Type of experiment	Watering and substrate moisture	Rainfall duration	Observations and measurements made				
			Time to runoff (min)	Volume of runoff at the end of the rainfall (ml)	Volume of runoff 20 min after rainfall end (ml)	Volume of runoff 60 min after rainfall end (ml)	Volume of runoff after 3 h (ml) = 'total'
Canopy interception	Watered to full container capacity before experiment start	20 min	X	X	X	X	X
Canopy and substrate interception	Not watered for 72 h prior to the start of experiment	60 min	X	X	X	X	X

Table 3. Average canopy volume, rainfall canopy retention, leaf stomatal conductance and ET, with the associated least significant differences between the means. Different letters next to the means in a column denote statistically significant difference between those means (P = 0.05). Degrees of freedom (d.f.) are also shown.

Treatment	Canopy volume (m^3)	Canopy retention (ml)	Canopy ground projection (m^2)	Leaf stomatal conductance (μmol m^{-1} s^{-1})	ET per plant in a 72 h period (ml)
Soil	-	-		-	627 e
Thuja	0.352 c	245 d	0.30 e	90.8 de	1465 d
Taxus	0.393 bc	280 cd	0.35 de	67.2 e	1917 bc
Crataegus	0.390 bc	287 bcd	0.37 de	198.7 a	2237 abc
Fagus	0.474 bc	295 bcd	0.42 cd	125.8 c	1842 cd
Ligustrum 'Argenteum'	0.505 bc	400 a	0.46 cd	160.8 b	1993 bc
Ligustrum 'Aureum'	0.557 b	373 ab	0.47 bc	110.9 cd	2339 ab
Photinia 'Red Robin'	0.805 a	324 abcd	0.56 b	59.6 e	2485 a
Cotoneaster	0.753 a	354 abc	0.64 a	211.9 a	2639 a
LSD (d.f.)	0.1763 (47)	92.1 (47)	0.118 (47)	35.76 (119)	439.6 (50)

Table 4. Mean rainfall volume received within a 40 minute event and volume of runoff. Least significant difference (LSD) and degrees of freedom (d.f.) are also shown. Different letters next to the means in a column denote statistically significant difference between those means (P = 0.05).

Treatment	Water volume received (ml) in a 40 min rainfall event	Total runoff volume (ml) after a 40 min rainfall event
Soil	820 a	396 bc
Thuja	3320 b	556 c
Taxus	3890 bc	218 ab
Crataegus	4030 bcd	15 a
Fagus	4660 bcd	187 ab
Ligustrum 'Argenteum'	5100 cd	446 c
Ligustrum 'Aureum'	5170 cd	476 c
Photinia 'Red Robin'	6160 de	638 c
Cotoneaster	7020 e	121 ab
LSD (d.f.)	1296 (39)	376.6 (39)

Table 5. Mean substrate moisture content on days 1, 3, and 5 of the first experimental round (22-25 May 2017) along with net CO_2 assimilation and stomatal conductance values on day 1 when all plants were well watered. Least significant difference (LSD) and degrees of freedom (d.f.) are also shown. Different letters next to the means in a column denote statistically significant difference between those means (P = 0.05); NS = non-significant.

Treatment	Substrate moisture content (m^3 m^{-3})			Net CO_2 assimilation (μmol $m^{-2}s^{-1}$)	Leaf stomatal conductance (mmol $m^{-2}s^{-1}$)
	Day 1	Day 3	Day 5	Day 1	Day 1
Bare substrate	0.32	0.27 a	0.23 a	-	-
Cotoneaster	0.26	0.18 b	0.05 b	9.2 a	170.1 a
Crataegus	0.31	0.17 b	0.06 b	6.8 b	103.0 b
Thuja	0.25	0.18 b	0.08 b	5.6 b	94.6 b
LSD (d.f.)	0.068 (47) NS	0.029 (47)	0.019 (47)	1.39 (53)	27.19 (53)

Table 6. Predicted mean time to runoff (A) and runoff volumes (B) when rainfall was applied for 20 min onto troughs where substrate was fully saturated. Data are predicted means of three repeated experiments for all treatments and three troughs per treatment. Discussion of statistical significance in the body of the text is based on Holm p-values.

A

Treatment	Predicted mean time to runoff (min)	95% CI: lower bound	95% CI: upper bound
Bare substrate	4.4	-1.4	10.3
Cotoneaster	19.5	14.4	24.6
Crataegus	21.0	15.9	26.1
Thuja	13.2	8.1	18.2

B

Treatment	Runoff volume at the end of 20 min rainfall (ml)	Runoff volume after 20 min draining (ml)	Runoff volume after 60 min draining (ml)
Bare substrate	256	715	597
Cotoneaster	89	200	97
Crataegus	103	315	118
Thuja	703	779	141

Table 7. Mean time to runoff (A) and runoff volumes (B) when rainfall was applied for 60 min onto troughs where substrate was not watered for 3 days. Data are predicted means of three repeated experiments for all treatments and three troughs per treatment. Discussion of statistical significance in the body of the text is based on Holm p-values.

A

Treatment	Predicted mean time to runoff (min)	95% CI: lower bound	95% CI: upper bound
Bare substrate	17.8	6.9	28.8
Cotoneaster	31.0	22.9	39.2
Crataegus	38.7	29.4	47.9
Thuja	21.3	12.2	30.5

B

Treatment	Runoff volume at the end of 60 min rainfall (ml)	Runoff volume after 20 min draining (ml)	Runoff volume after 60 min draining (ml)
Bare substrate	1086	1738	1445
Cotoneaster	1545	471	154
Crataegus	739	255	82
Thuja	2932	943	268

Figure 1. Setup for the outdoor experiment with model hedges in troughs.

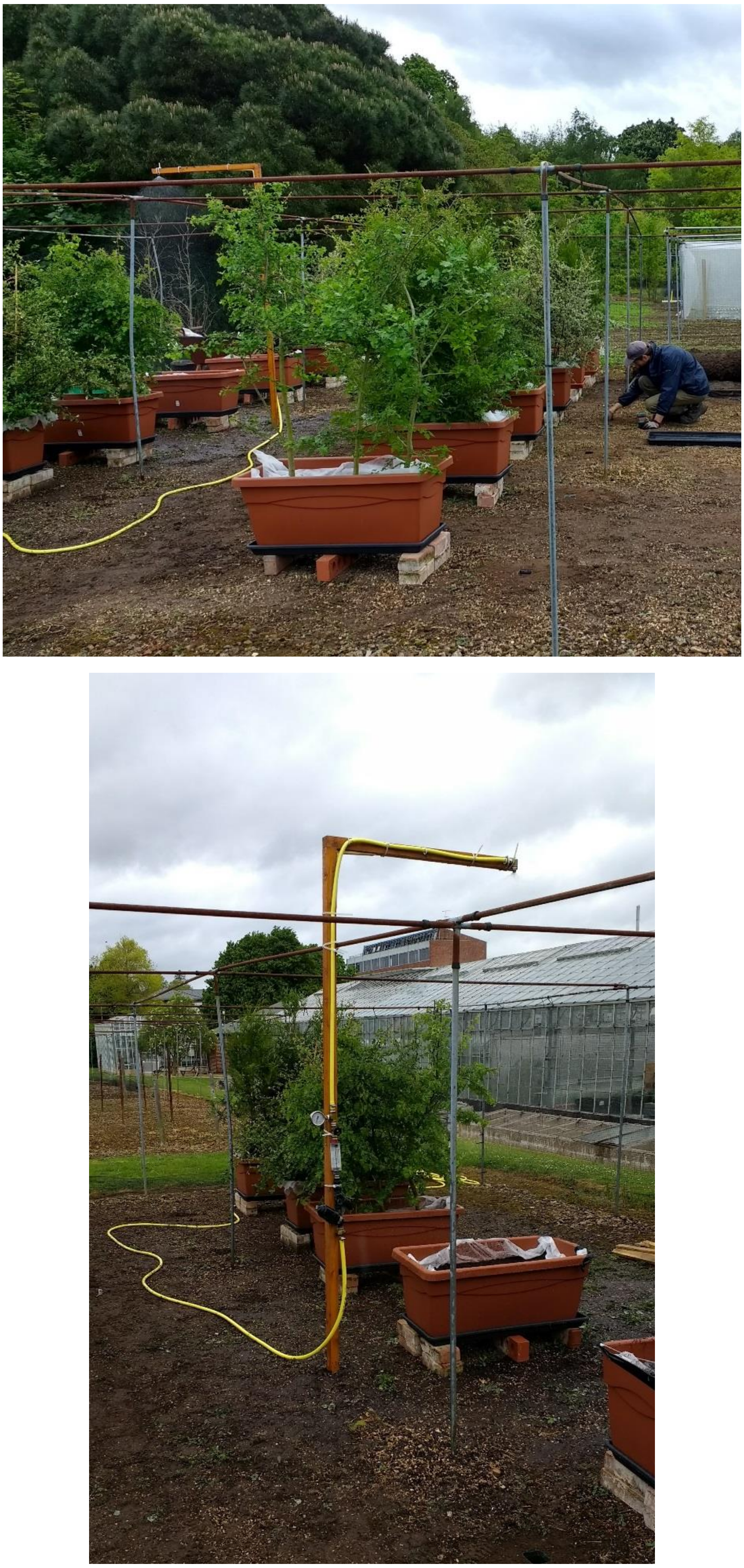

Figure 2. Percent runoff in relation to the rainfall volume received per canopy, after a 40 min simulated rainfall event with the intensity of 28 mm. Rainfall was applied 72 h after the plants were watered. Values are means of six replicates per plant species and three replicates for bare soil. Error bar represents least significant difference between the means (LSD, P = 0.05).