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

2   T. Blanusa[1, 2, *], J. Hadley[2]

4   [1] Science Department, Royal Horticultural Society, Garden Wisley, Woking GU23

5   6QB, Woking, UK

6   [2] School of Agriculture, Policy and Development, University of Reading, RG6 6AS,

7   UK

8   * Corresponding author: tijanablanusa@rhs.org.uk

10   Abstract

11

12   Soil sealing and a decrease in vegetation cover in urban areas increase the

13   likelihood and frequency of localised flooding. Populating the remaining green areas

14   with vegetation, which can efficiently capture excess rainfall, is therefore important.

15   We argue that urban hedges can be a useful tool in mitigating rainfall, so the

16   understanding of optimal plant choice, and underlying traits which enable most rain

17   attenuation, is needed.

18   We tested the hypothesis that higher plant evapo-transpiration rates and larger

19   canopy size can be linked with reduced rainfall runoff in urban hedge species. We

20   first characterised seven hedge species grown in individual containers. These were

21   both deciduous and evergreen species, with a range of inherent canopy sizes and

22   water requirements. We assessed their plant water use, leaf stomatal conductance,

23   canopy rainfall retention, and runoff delay and reduction capacity. The species

24   showing highest and lowest potential for runoff reduction were then investigated for

25   their outdoor performance, when planted in a hedge-like form. Our findings suggest

26   that – after three days between rainfall events - species such as *Cotoneaste*r and

27   *Crataegus* with larger and wide canopies, and with high evapo-transpiration / water

28   use rates, delayed the start of runoff (by as much to 10-15 minutes compared to bare

29   substrate) as well reduced the volume of rainfall runoff. For example, <5% of the

30   applied rainfall had runoff with *Cotoneaste*r and *Crataegus,* compared with >40% in

31   bare substrate. Substrate moisture content at the time of rainfall (which is linked to

32   plants' ET rate) was the key explanatory variable.

33

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

35

Introduction

36

37 Rapid urbanisation and an increase in sealed surfaces due to paving over (Smith

38 2010; Verbeeck et al. 2011) can be linked to higher incidences of localised flooding

39 in urban areas (Perry and Nawaz 2008; Warhurst et al. 2014). However,

40 appropriately chosen and well managed vegetation in different forms of green

41 infrastructure (GI) can play a role in reducing flood risks. This includes domestic

42 gardens (Cameron et al. 2012; Kelly 2016; Warhurst et al. 2014), street trees (Xiao

43 and McPherson 2002), vegetation strips such as grass verges (Charlesworth 2010),

44 as well as urban hedgerows and garden hedges (O'Sullivan et al. 2017). All these

45 green areas help rainfall management chiefly through maintaining soil, as the main

46 natural water store in urban areas (Pit et al. 1999). Presence of vegetation also

47 increases the soil's ability to receive subsequent rainfall through increasing soil's

48 water-storage capacity by water loss via evapo-transpiration (Stovin et al. 2012).

49 Additionally, plant roots can improve soil structure and increase porosity, increasing

50 drainage and soil's water-holding capacity (Bartens et al. 2008; Mueller and

51 Thompson 2009). There is also an element of rainfall interception and retention in

52 the canopy, thus delaying runoff (Crockford and Richardson 2000).

53 In the UK, domestic gardens in urban areas take up a significant proportion of urban

54 footprint (15-25%, Cameron et al. 2012; Gaston et al. 2005). Garden hedges are a

55 ubiquitous feature of UK front gardens and can thus provide a number of frontline

56 services including rainwater capture and localised flood protection. A recent survey

57 by the Royal Horticultural Society (RHS) suggested that the vegetated area of front

58 gardens across the UK has decreased by as much as 15% in the period 2005-2015.

59 Additionally, one in four UK front gardens are paved-over and nearly one in three

60 front gardens have no plants (Anon 2016). We argue therefore, that maintaining

61 unsealed surfaces in domestic gardens, including features such as garden hedges,

62 can reduce the flooding risks for domestic households and streets/neighbourhoods.

63 The question, however, is to what extent can we maximise canopy capture and

64 runoff reduction by careful plant species choice, with traits to maximise this service?

65 Previous work in our group (Blanusa et al. 2015; Blanusa et al. 2013; Cameron and

66 Blanuša 2016; Vaz Monteiro et al. 2017; Kemp et al. 2017) provides evidence for the

67 notion that differences in plant structure and the rate/mode of physiological function

68 lead to differences in the provision of various ecosystem services by urban

69 vegetation. E.g. plants with larger leaf areas, lighter leaf colour and greater rates of

70 evapo-transpiration (ET) provide greater extent of building and ambient cooling by

71 green roofs, by reducing soil heat flux and increasing latent heat fluxes (Vaz

72 Monteiro et al. 2017). Larger leaf areas and greater ET rates of vegetation on green

73 roofs have also been linked to reduced rainfall runoff rates (Kemp 2018).

74 Recent work on urban hedgerows (O'Sullivan et al. 2017) suggested that species

75 with high water use are more efficient at reducing flooding risks. Ranking of species

76 in that study is based on Roloff et al. (2009) work on drought tolerant trees (i.e.

77 O'Sullivan et al. (2017) assume that less drought tolerant species have higher water

78 use and thus offer greater flood protection). While this is a logical principle, no

79 practical testing of hedge species had been carried out to explore this in practice. In

80 the urban setting, other green infrastructure installations such as rain gardens or

81 bioswales, and green roofs have been extensively studied for their capacity to

82 reduce rainfall runoff (Berretta et al. 2014; Cameron and Hitchmough 2016;

83 Scharenbroch et al. 2016), but the role of hedgerows in rainfall mitigation has been

84 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

110   canopy water storage, but more strongly for broadleaved than for needle-leaved

111   species (Keim et al. 2006).

112   The aim of our study was therefore to test a range of urban hedge species (both

113   deciduous and evergreen) differing in inherent vigour and canopy sizes, and with

114   varying water use requirements and evapo-transpiration rates. We hypothesised that

115   species exhibiting higher evapo-transpiration rates, which lead to a reduction in soil

116   moisture content, can be linked with reduced rainfall runoff. We also hypothesized

117   that species with larger canopy would exhibit greater runoff reduction. Our approach

118   was two-pronged. We first characterised individual plant specimens of the selected

119   species: their plant water use, leaf stomatal conductance, canopy rainfall retention,

120   and runoff delay and reduction capacity. We have then selected the species showing

121   highest and lowest runoff reduction and investigated their outdoor performance,

122   when planted in a hedge-like form. Our findings suggest that the species with high

123   water use rates, which reduced substrate moisture more before the rainfall was

124   applied, better delayed the start of runoff as well reduced the volume of runoff.

125

126   **Materials and methods**

127   <u>Rainfall application setup</u>

128   To simulate natural rainfall in a controlled and repeatable manner, a sprinkler system

129   based on the design described by Iserloh et al. (2012), produced 'in house' by an

130   irrigation specialist at RHS Garden, Wisley, was used. The system consisted of a

131   Lechler 460 608 nozzle attached to a 2 m length of hosing (Tricoflex, Hozelock Ltd.,

132   Birmingham, UK) to a flow control, which was a series of pressure gauges and filters

133   that ensured that the water flow and the characteristics of the droplets produced

134   were constant. The system was connected to the mains water supply by hosepipe,

135   and rainfall could be turned on and off directly on the simulator (Figure 1). The

136   optimum flow pressure to achieve consistent rainfall in terms of droplet size and

137   distribution was found to be 0.15 bars (15 kPa), and so this pressure setting was

138   used for all rainfall simulations. The nozzle, hosing and simulator were fastened to

139   an L-shaped timber support structure 2.4 m high and 1 m across; this was then

140   secured to a pre-existing metal frame in both glasshouse and field set-up, which run

141   above all containers or troughs in the experiment.

142   The height of the nozzle was 0.7-0.9 m above the top of the experimental

143   containers/troughs, depending on the height of the canopy in different species; this is

144   in line with the heights of other rainfall simulators cited in the literature, typically for

145   used in soil erosion and runoff studies, which vary between 0.7 and 3 m above the

146   ground (e.g. Humphry et al. 2002; Fister et al. 2012). To further characterise the

147   simulated rainfall, average raindrop size was measured using the flour pellet method

148   described by Clarke and Walsh (2007). The diameters of all raindrops in three

149   representative 4 x 4 cm areas were then measured using Image J software (National

150   Institutes of Health, USA). Raindrop sizes ranged from 0.21 to 2.76 mm with the

151   majority of droplets (70%) smaller than 1 mm diameter, similar to the simulated

152   raindrops produced in other studies (e.g. Iserloh et al. 2012; Fister et al. 2012).

153   <u>Experiments with individual hedge plants</u>

154   Experiments were carried out in the period May-June 2016 in the ventilated

155   glasshouses at the University of Reading (UK), where temperatures were maintained

156   in the range 23-25 °C during daytime and 17-18 °C at night-time, with ambient light

157   levels Four-year-old plants of seven hedge species, grown individually in 10 l

158   containers, with John Innes no 3 compost (7:3:2 sterilised loam:peat:coarse sand

159   v/v, Westland, Dungannon, UK), were used. Species included five evergreen:

160   *Photinia* x *fraseri (cv* 'Red Robin'), *Thuja plicata (cv.* 'Atrovirens'), *Taxus baccata,*

161   *Ligustrum ovalifolium (cvs.* 'Aureum' *and* 'Argenteum') and *Cotoneaster franchetii,* as

162   well as two deciduous species: *Crataegus monogyna* and *Fagus sylvatica.* Six

163   replicates of each species were used, along with three containers with just bare

164   substrate.

165   Two types of experiments were carried out. One was measuring contribution of

166   canopy to runoff reduction (so carried out on plants immediately after the substrate

167   was saturated to full container capacity (> 0.40 m^3 m^{-3})). The other was measuring

168   the importance of substrate moisture content and different ET rates to runoff

169   reduction, by rainfall applications 3 days post saturation, with no additional watering

170   in the 3 day period.

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

172   Rainfall was applied either for 20 minutes (when measuring canopy interception, in

173   containers where substrate was fully water-saturated) or 40 minutes (when

174   containers were not watered for 3 consecutive days). Before simulated rainfall

175   application, plant containers were placed within another 'collection' container which

176   closely fitted but was 10 cm deeper, so that only the runoff from the substrate can be

177   collected. To determine the runoff from each of the plant containers, water volume

178   collected within the 'collection' container was measured after plants were left to drain

179   for 1 h after the 'rainfall' stopped. For all rainfall applications, the rainfall simulator

180   was fixed in a same position on a pre-existing metal frame within the glasshouse

181   compartment. Position of the containers underneath the rainfall simulator was

182   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

208   therefore expressed our runoff data as a % of runoff water relative to the volume of

209   rainfall received, in addition to absolute values of runoff volume. Additionally, plant

210   height was measured, so that the canopy volume could be calculated from height

211   and width measurements.

212   Measured parameters relating to canopy's capacity to capture rainfall included the

213   weight of the containers with plants before and after rainfall application; this enabled

214   us to quantify the weight of rainfall retained on the canopy in the situation when soil

215   was fully saturated, as all the weight increase would be a result of what is held in the

216   canopy (Eq 1).

217    $Cs = Wr - Ws$ (Eq 1)

218   where: Cs - canopy rainfall storage capacity, Wr - weight of a plant and saturated

219   container at the end of rainfall application, Ws - weight of a plant and saturated

220   container just before rainfall application.

221   We also measured the substrate moisture content (SMC) using a SM300 sensor

222   connected to a HH2 Moisture Meter (Delta-T Devices Ltd., Cambridge, UK) in two

223   locations per container.

224   All species were then left for 72 h without watering and all containers were weighed

225   daily using a precision balance (CBK 32, Adam Equipment, Milton Keynes,

226   Buckinghamshire, UK), to estimate daily evapo-transpiration (ET) by plants and bare

227   substrate. Substrate moisture content (SMC) was also recorded daily. After this 72 h

228   period without watering, plants were subjected to second simulated rainfall and the

229   volume of rainfall runoff was recorded. In doing that, we investigated the impact of

230   plant ET and different rates of substrate drying in different species, on the volume of

231   rainfall runoff. Both canopy sequestration and ET contribution experiments were

232   repeated twice over a two week period with different species tested in random order

233   on the two occasions to minimise the impact of slight possible environmental

234   differences in the glasshouse compartment on different days. Runoff data from both

235   repeats matched closely, so only the data from the second repeat are shown in this

236   paper.

237   Leaf stomatal conductance to water vapour was measured (using AP4 porometer,

238   Delta-T Devices Ltd., Cambridge, UK) twice during the experiment: at the start of the

239   experiment when plants were well-watered (i.e. substrate moisture content > 0.30 m^3

240   m^{-3} and also at the end of the experiment when the substrate was allowed to dry ($<$

241   0.20 m^3 m^{-3}). All treatments were measured on the same day in random order; three

242   young fully expanded leaves per plant on five plants per species were used.

243   Additionally, at the end of the experiment, leaf area was measured destructively on

244   three plants per species (apart from *Fagus* and *Crataegus* which were not

245   measured) using a WinDIAS leaf area meter (Delta-T Devices, Cambridge, UK).

246   <u>Experiments with model hedges in troughs</u>

247   Experiments were carried out in the period May-June 2017 on the outdoor field plots

248   within the glasshouse complex at the University of Reading (UK). Five year old

249   plants of *Crataegus monogyna* (common name: hawthorn), *Cotoneaster franchetii*

250   and *Thuja plicata* (common name: yew) were transplanted from 10 L into 110 L

251   troughs (1 m (l) x 0.4 m (w) x 0.45 m (d)) with Sylvamix substrate (6:2:2 sylvafibre:

252   growbark pine: coir v/v; Melcourt, Tetbury, UK) with a slow-release fertiliser feed

253   (Osmocote, Scotts, Marysville, OH, USA) in March 2017. There were three plants

254   per container and three containers per species, along with three containers with just

255   bare substrate ('control').

256 Before transplanting, each container was lined with a double layer of fine horticultural

257 mesh (Veggiemesh Insect Netting, 1.35 mm mesh size) to aid retention of small

258 substrate particles and prevent blockage of drainage holes. Mesh was then covered

259 with 10 L of horticultural gravel (size 10 mm), followed with 80 L of substrate.

260 Plants were maintained outdoors and watered as required. Two weeks before the

261 start of rainfall experiments, plants were cut into a hedge shape; *Thuja* and

262 *Crataegus* were 1.1 m wide and *Cotoneaster* 1.2 m. Height and depth dimensions for

263 each species are shown in Table 1. Height and depth measurements were made on

264 three sections per trough, for each of the troughs at the start of the experiment.

265 Indicative leaf area for each species was determined destructively at the end of the

266 experiment by cutting out two 15 cm x 15 cm x 15 cm sections in each replicate of

267 the model hedges and measuring with leaf area meter (Delta-T Devices, Cambridge,

268 Cambridgeshire, UK).

269 [Insert Table 1]

270 At the beginning of the experiment, troughs with hedge plants and bare soil were put

271 into fixed positions in a field plot. The twelve experimental troughs were arranged in

272 two parallel rows of six; arrangement of troughs within a row was random. Each

273 trough was placed onto a plastic tray (1.1 m (l) x 0.45 m (w) x 0.05 m (d)) and both

274 were then elevated onto a pedestal at 4° angle, constructed from bricks and wood

275 planks; this enabled the water to drain freely through the holes drilled on one end of

276 the tray. During the experiment, to collect the rainfall runoff, plastic containers were

277 fitted under the tray holes. Experimental setup is shown in Figure 1.

278 [Insert Figure 1]

13

279   The time taken for runoff to be generated from trays with bare substrate was pre-

280   tested with the chosen rainfall simulator settings, and found to vary between 5 and

281   15 minutes, depending on initial substrate moisture content. As the plants would be

282   increasing rainfall retention, to ensure that measurable runoff was always generated

283   from all planted treatments and all substrate moisture conditions, it was therefore

284   decided to simulate rainfall for 20 minutes (for troughs saturated to full water-holding

285   capacity, where the role of canopy retention in runoff reduction was measured) or 60

286   minutes (for troughs after 3 days without irrigation, where the role of ET in runoff

287   reduction was measured) for each container/trough (Table 2).

288   To set up the rainfall applicator, on the ground, at the back of the trough, a fixed

289   position for the timber support and rainfall applicator was marked at the same

290   distance from each trough, so all rainfall applications were administered from the

291   same location for each trough.

292   Since rainfall could only be applied to one trough at a time, this meant that only 8

293   troughs could be tested in a working day (when the 60 min application time and

294   subsequent draining times were factored in). Each experimental run was therefore

295   conducted over two consecutive days, testing two replicates from each treatment on

296   day 1 and one replicate on day 2. Experimental runs were carried on relatively still

297   days, with wind speed < 5 m s^{-1}.

298   Two types of experiments were carried out (Table 2). One was measuring

299   contribution of canopy (so carried out on hedges where the substrate is saturated to

300   full container capacity (> 40 m^3 m^{-3})). The other was measuring the importance of

301   substrate moisture content and different ET rates for runoff reduction, by rainfall

302   applications after 3 days post-saturation. Due to the treatments' different ET rates,

14

303 this would have led to different starting SMCs for this experiment. Details of

304 measurements are shown in Table 2.

305 <mark>[Insert Table 2]</mark>

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

307 Experiments were repeated three times in a four week period and all data was

308 analysed together as described in the Statistics section.

309 Before the start of the rainfall runoff experiments, a baseline measurement of leaf

310 stomatal conductance to water vapour and net CO_2 assimilation of each plant

311 treatment was made to establish plants' ET capacity, when substrate moisture

312 content is at the field capacity. Three young fully expanded leaves per plant, on

313 every plant, in two troughs per species (i.e. 9 measurements per trough, 18 per

314 species) were measured using LCpro infra-red gas analyser (ADC Bioscientific,

315 Hoddesdon, UK).

316 Before each simulated rainfall run, substrate moisture content in each through was

317 measured using a SM300 sensor connected to a HH2 Moisture Meter (Delta-T

318 Devices Ltd., Cambridge, UK) in four locations per trough.

319 Statistical analysis

320 For experiments with individual containers, an analysis of variance (ANOVA) was

321 performed using GENSTAT (18th Edition, VSN International, Hemel Hempstead,

322 Hertfordshire, UK). There, we compared means for each measured parameter

323 (runoff volumes, canopy retention, leaf stomatal conductance, water loss by plants

324 etc.) between different species. Variance levels were checked for homogeneity and

325 values were presented as means with associated least significant differences, which

326 were used to assess variations at a 5% significance level. Additionally, linear

327 regression analysis was performed to establish a relationship between parameters

328 such as ET and g_s, and runoff volumes.

329 For the experiments with hedges in troughs, to analyse runoff volumes from three

330 consecutive sets of experiments, a repeated measurements analysis was employed.

331 Linear mixed models were used to model the relationship of responses with the

332 explanatory factors and covariates. The response 'runoff volume' was modelled on a

333 logarithmic scale, hence its effect measures are expressed in Results tables as

334 ratios of predicted means. 'Species' and 'minutes after rainfall application ceased'

335 were fitted as fixed effects; 'date' and 'trough' were fitted as random effects to make

336 results from this experiment more generalizable to users. To account for the

337 correlated measurements taken on the same trough over time, an unstructured

338 marginal covariance structure was used for the term 'minutes after rainfall application

339 ceased'. All overall F-test were adjusted using a Kenward-Roger method in PROC

340 MIXED of SAS version 9.4. Finally, post-modelling pairwise comparisons between

341 species were adjusted for multiplicity using a Holm method. For the analysis of

342 substrate moisture content within troughs, net leaf CO_2 assimilation and leaf

343 stomatal conductance on individual dates, a one-way ANOVA was performed as

344 described for individual containers.

345

346 **Results**

347 Experiments with individual hedge plants

348 In our experiment, *Photinia* 'Red Robin' had the largest canopy leaf area (1.64 m^2),

349 with all other species being statistically similar and averaging around 0.65 m^2 (data

350 not shown). The branch orientation and crown horizontal canopy ground projection

351 differed between the species, with *Cotoneaster* and *Photinia* having largest and

352 *Thuja* having lowest canopy ground projection (Table 3). Canopy volume was

353 greatest for *Cotoneaster* and *Photinia* and lowest for *Thuja* (Table 3). Plant heights

354 however, were mostly similar between species (averaging 113 cm) with just *Photinia*

355 being significantly taller, at 143 cm (data not shown).

356 Canopy retention of the rainfall was greatest in the two *Ligustrum* cultivars

357 (averaging close to 400 ml per plant), and lowest in *Thuja* (below 250 ml per plant),

358 with other species being similar at around 310 ml per plant (Table 3). Linear

359 regression analysis revealed no statistically significant relationship between canopy

360 volume and canopy retention (p = 0.19).

361 [Insert Table 3]

362 Leaf stomatal conductance (measured when plants were well watered, on Day 1 of

363 the experiment) was highest in *Cotoneaster* and *Crataegus* (around 200 μmol m^{-1} s^{-1}

364) and lowest in *Thuja* and *Taxus* (below 100 μmol m^{-1} s^{-1}) (Table 3). *Cotoneaster*,

365 *Crataegus* and *Photinia* lost most water per plant (over 2000 ml in a in 72 h period)

366 with *Thuja* losing least of all plant treatments (<1500 ml). All plant treatments lost

367 significantly more water than just bare soil (just over 600 ml in a 3-day period) (Table

368 3).

369 Substrate moisture content after 3 days with no irrigation was lowest in *Cotoneaster*

370 (0.20 m^3 m^{-3}) and highest in bare substrate (0.45 m^3 m^{-3}); all other plant treatments

371 had SMC between 0.28 and 0.30 m^3 m^{-3} (data not shown). Canopies of different

372 species have different spreads, and thus different ground projections (Table 3).

373 Water volumes received by different canopies are thus also different (Table 4).

374 <mark>[Insert Table 4]</mark>

375 Runoff from the containers, where rainfall was applied after 3 days with no watering,

376 was negligible from *Crataegus* both in absolute terms (Table 4), and when

377 expressed relative to the volume of water received (Figure 2). *Cotoneaster* too had

378 lower volume of runoff (when rained on after 3 days with no watering) compared to

379 all other species (apart from *Crataegus,* relatively expressed) (Figure 2). In absolute

380 terms, but also in relation to the volume of rainfall received, *Thuja* had the highest

381 runoff off all the plant species, although it was still lower than for the bare substrate

382 (Table 4, Figure 2).

383 <mark>[Insert Figure 2]</mark>

384 Linear regression analysis revealed no statistically significant relationship between

385 ET or g_s, and runoff volumes (data not shown). There was a statistically significant (p

386 = 0.05) positive linear relationship between SMC and runoff volume (when

387 expressed as a % volume received) (R^2= 0.14).

388

<u>Experiments with model hedges in troughs</u>

390 Substrate moisture content was similar for all the treatments at the start of the

391 experiment, then lower in all plant treatments after 3 and 5 days of drying compared

392 bare soil (Table 5). Additionally, net CO_2 assimilation and leaf stomatal conductance

393 were statistically significantly higher, when measured on Day 1 of the experiment in

394 well-watered *Cotoneaster* than in *Crataegus* and *Thuja* (Table 5).

395 [Insert Table 5]

396 When substrate was fully saturated (i.e. only the canopy provided the barrier to

397 rainfall), runoff was recorded first from a bare substrate treatment, then *Thuja*

398 followed by *Cotoneaster* and *Crataegus* (Table 6A); statistical analysis showed

399 significant treatment differences (P = 0.032, data not shown). *Cotoneaster* and

400 *Crataegus* delayed runoff longer than bare substrate (Holm p-values 0.055 and

401 0.051, respectively). Statistical analysis showed no significant influence of either

402 canopy volume or canopy density on the delay of runoff (p = 0.3669 and 0.6167,

403 respectively) (data not shown).

404 In terms of volumes of runoff after the rain stopped falling on previously saturated

405 substrate there were significant treatment differences. The volume of runoff

406 generated at the end of rainfall was greatest in bare soil and *Thuja*, least in

407 *Cotoneaster* and *Crataegus* (Table 6B). *Cotoneaster* and *Crataegus* produced

408 statistically significantly less runoff than bare soil (e.g. at the end of the rainfall: Holm

409 p-values 0.010 and 0.013 respectively).

410 [Insert Table 6]

411 After three days with no irrigation, substrate moisture content was on average 0.27,

412 0.18, 0.17 and 0.18 m^3 m^{-3} for bare soil, *Thuja*, *Crataegus* and *Cotoneaster*

413   respectively (Table 5). Statistically, at that time point all plant species had similar

414   substrate moisture, and all statistically lower than bare soil (Table 5).

415   When rainfall was applied to treatments after 3 days of no irrigation there were

416   significant treatment differences in terms of the extent of runoff delay. There was a

417   significant species effect (p = 0.0110) in the delay of runoff, with both *Cotoneaster*

418   and *Crataegus* delaying runoff more than bare substrate and *Thuja* (Table 7A). In

419   terms of volumes of runoff there were again significant species differences (p =

420   0.0258). Particularly, after 60 min draining there was significantly less runoff from

421   *Crataegus* and *Cotoneaster* compared to bare substrate (p = 0.0083) (Table 7).

422   [Insert Table 7]

423   Statistical analysis showed the significant influence of substrate moisture content on

424   both delay of runoff and the volumes of runoff (p = 0.0397 and 0.0551, respectively),

425   but there was no impact of leaf stomatal conductance (p = 0.5414 and 0.4470,

426   respectively).

427

428   **Discussion**

429   Loss of vegetation in urban areas, and in domestic gardens (in the UK) in particular

430   can be linked to higher incidences of localised flooding in urban areas (Perry and

431   Nawaz 2008; Warhurst et al. 2014). In a context of most domestic households in the

432   UK having their own domestic garden (Cameron et al., 2012), urban hedges as a

433   ubiquitous garden feature could be seen as a frontline protection for households

434   from localised flooding. This is due to the delay of rainfall runoff when rainfall is

435   captured on the canopies (i.e. canopy interception) and absorbed into the soil. With

436   front gardens and associated hedges increasingly being lost to paving, making sure

437   that the hedges we do plant and retain are providing maximal rainfall attenuation is

438   important. We argue that through careful choice of hedge species, rainfall mitigation

439   by urban hedges can be maximised.

440   Previous research found that depending on the intensity of the rainfall, canopy

441   capture (e.g. in juniper trees) can represent 20-60% of bulk precipitation, with more

442   canopy capture in less intense events (Carlyle-Moses, 2004, Owens et al., 2006).

443   Additionally, in a young sitka spruce plantation, canopies captured 30% of rainfall

444   annually (Ford and Deans 2018). Rainfall captured and temporarily retained in the

445   canopy is especially important in a scenario of rainfall events happening in close

446   sequence, when there is insufficient time for ET (particularly plants' transpirational

447   component which removes water from the soil) to make a significant contribution to

448   runoff reduction. Characteristics such as area covered by vegetation, branch angle,

449   the uniformity in crown height, nature of the bark, leaf shape and inclination, and leaf

450   area index will all influence rainfall interception by the canopies (Crockford and

451   Richardson 2000). Branch diameter was also found to be positively correlated with

452   canopy rainfall retention in several forest coniferous species (Liu 1998). Additionally,

453   factors such as intensity of rainfall and other meteorological conditions (temperature,

454   humidity, wind speed etc.) will have a role (Crockford and Richardson 2000, Toba

455   and Ohta, 2005). While the conclusions about the contribution of various factors to

456   rainfall capture and runoff reduction are generated largely from the forest and

457   individual trees literature, they none the less present a starting point in interpreting a

458   role that different hedges' forms and function might have in these processes. Due to

459   the smaller area they cover, impact of hedges, of course will be more localised e.g.

460   affecting an individual garden rather than a street-level catchment.

461 In our experiment, although species with greater leaf area (e.g. *Ligustrum*) generally

462 retained more rainfall in the canopy, this was not always the case (e.g. *Photinia*). In

463 our experiment just one rainfall intensity was tested; a response of different canopy

464 structures to a change on rainfall intensity might vary (Carlyle-Moses and Gash,

465 2011). Based on our measurements, canopy leaf area, or even canopy volume, were

466 clearly not the only explanatory variables of canopy retention, with species having

467 similar leaf areas but different canopy retentions (e.g. *Ligustrum* vs *Taxus* or *Thuja*).

468 While we could not numerically capture all the possible parameters potentially

469 influencing canopy retention, the presence of clear species differences and

470 anecdotal observations within our experiment would suggest that factors such as

471 dense or more horizontal branch architecture, concave leaf shape and presence of

472 structures like leaf hairs played a role in improving rainfall canopy capture.

473 While acknowledging the importance of canopy structural characteristics in rainfall

474 retention, our primary interest was in establishing the contribution of plant functional

475 characteristics such as ET and leaf stomatal conductance to runoff reduction. This

476 was because of their impact on soil/substrate content which had been shown, in a

477 green roof context at least, as an important predictor of rainfall runoff reduction

478 (Kemp et al., 2018; Stovin et al. 2012; Poë et al. 2015).

479 Larger canopies receive more water into the canopy and filter it towards the ground

480 (Ford and Deans, 1978). In our experiment, *Cotoneaster* covered the largest area

481 over the ground, hence was exposed to most rainfall, yet had one of the lowest

482 runoff rates. *Thuja,* conversely, has the smallest ground projection, but together with

483 *Photinia* has highest runoff values amongst the studied species. Our observations in

484 the outdoor experiment suggest that it was the branch architecture of *Thuja* (where

485 branches are generally at 30-45º away from the trunk) which encouraged more water

486 to be funnelled towards the trunk and ultimately soil (causing more runoff), compared

487 with species where branches and leaves are positioned closer to a 90°. This

488 however could be seen as a positive on more free-draining soils (as it would channel

489 more rainfall towards the ground). Conversely, *Cotoneaster* and *Crataegus* would

490 offer best protection in soils which are less free-draining.

491 In both sets of experiments antecedent substrate moisture content was positively

492 correlated with volumes of runoff. Our earlier preliminary experiment with the same

493 species showed that *Cotoneaster* and *Crataegus* lost most water per m^2 of leaf area

494 in any 24 h period (Blanusa et al. 2017) and they were the ones which then

495 produced lowest runoff rates in subsequent experiments. In our experiment with

496 hedges in troughs outdoors, runoff was lower in all plant treatments compared to

497 bare substrate. This would thus suggest that lowering SMC and higher ET had some

498 advantage in the first 2-3 days after the rainfall in an outdoor summertime scenario.

499 Individually, other functional parameters such as leaf stomatal conductance and ET

500 were not statistically significantly linked to a delay or reduction of runoff. It is

501 therefore likely that while low antecedent substrate moisture plays an important in

502 delaying and reducing the runoff in hedge species, an additional complex

503 combination of variables such as canopy shape and leaf properties (e.g. leaf

504 hydrophobicity, Holder 2013) as well as root density and structure also play part.

505 **Conclusions**

506 Urban hedges are an important green infrastructure component in urban areas and

507 particularly in people's domestic (front) gardens in the UK where they are a popular

508 and, arguably, widely spread feature. They have a capacity to delay and reduce

509 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 *Cotoneaster* 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 *Cotoneaster*

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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656

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.

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

692

693 Table 7. Mean time to runoff (A) and runoff volumes (B) when rainfall was applied for
694 60 min onto troughs where substrate was not watered for 3 days. Data are predicted
695 means of three repeated experiments for all treatments and three troughs per
696 treatment. Discussion of statistical significance in the body of the text is based on
697 Holm p-values.

698

699

711   Table 1. Mean hedge height and depth (in cm), as well as a mean indicative leaf

712   area (in cm^2) collected from a 15 cm x 15 cm x 15 cm a section within hedge canopy.

713   Data are mean of two (leaf area) or three (height and depth) sections of hedge on

714   each trough with associated least significant difference (LSD) between means (P <

715   0.05). Different letters next to the means in a column denote statistically significant

716   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)

717

718

719   Table 2. Details of experimental conditions and measurements made in the outdoor

720   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

721

722

723 Table 3. Average canopy volume, rainfall canopy retention, leaf stomatal

724 conductance and ET, with the associated least significant differences between the

725 means. Different letters next to the means in a column denote statistically significant

726 difference between those means (P = 0.05). Degrees of freedom (d.f.) are also

727 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)

728

729

730   Table 4. Mean rainfall volume received within a 40 minute event and volume of

731   runoff. Least significant difference (LSD) and degrees of freedom (d.f.) are also

732   shown. Different letters next to the means in a column denote statistically significant

733   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)

734

735

736 Table 5. Mean substrate moisture content on days 1, 3, and 5 of the first

737 experimental round (22-25 May 2017) along with net CO_2 assimilation and stomatal

738 conductance values on day 1 when all plants were well watered. Least significant

739 difference (LSD) and degrees of freedom (d.f.) are also shown. Different letters next

740 to the means in a column denote statistically significant difference between those

741 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)

742

743 Table 6. Predicted mean time to runoff (A) and runoff volumes (B) when rainfall was

744 applied for 20 min onto troughs where substrate was fully saturated. Data are

745 predicted means of three repeated experiments for all treatments and three troughs

746 per treatment. Discussion of statistical significance in the body of the text is based on

747 Holm p-values.

748 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

749

750 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

751

752 Table 7. Mean time to runoff (A) and runoff volumes (B) when rainfall was applied for

753 60 min onto troughs where substrate was not watered for 3 days. Data are predicted

754 means of three repeated experiments for all treatments and three troughs per

755 treatment. Discussion of statistical significance in the body of the text is based on

756 Holm p-values.

757 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

758

759 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

760

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

762

763

764 Figure 2. Percent runoff in relation to the rainfall volume received per canopy, after a
765 40 min simulated rainfall event with the intensity of 28 mm. Rainfall was applied 72 h
766 after the plants were watered. Values are means of six replicates per plant species
767 and three replicates for bare soil. Error bar represents least significant difference
768 between the means (LSD, P = 0.05).

769