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Assessing Year-Round Capacity of Single-Species and Mixed Hedges to Provide Rainfall Attenuation—Case Study of Containerised Model Hedges

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Abstract

Single-species hedges can help mitigate a range of urban and climate change-related issues, such as slowing stormwater flow and reducing rainfall runoff, particularly during the growing season. There is, however, little information on the service delivery of *mixed hedges* and their comparison to single-species, *year-round*, as well as on the practicality of functional rather than ornamental plant mixing. Here, we report on an initial case study to address this. Chosen hedge taxa (*Crataegus monogyna*, *Elaeagnus* × *submacrophylla* 'Gilt Edge', *Ligustrum ovalifolium*, *Thuja plicata* 'Atrovirens') represented a range of plant characteristics. These were trialled outdoors in Reading (SE England, UK) as treatment groupings of either single-species or mixed-species ('evergreen' and 'broadleaf' mix), along with a bare soil control, in 110 L troughs. We applied 5 min simulated rainfall onto each treatment twice in every meteorological season and assessed canopy throughfall. We also monitored substrate moisture content change as a proxy for evapotranspiration and substrate storage capacity of subsequent rainfall. During summer, the deciduous taxa and mixed hedges had the highest evapotranspiration rates, suggesting their potential to influence soil water storage, but in our experimental setup, that did not translate into significant differences in substrate moisture between treatments. During autumn and winter, the single-species *Thuja* treatment had the highest rainfall interception rate, followed by both mixed species treatments. In winter, canopy and leaf characteristics rather than physiological activity correlated with increased rainfall attenuation. However, by the end of the experiment (spring 2023), *Crataegus*, *Thuja* and both mixed hedge treatments had significantly lower throughfall (higher interception) compared to bare soil. We are continuing to test these treatments in a longer-term field experiment. Management of mixed-species hedges for rainfall attenuation is practically achievable, despite some differences in individual species' growth rates and plant habits.

Keywords: canopy retention; *Crataegus*; *Elaeagnus*; hawthorn; *Ligustrum*; *Thuja*; soil moisture

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1. Introduction

Over the last two decades, environmental problems within cities have received much attention. The urban heat island effect, increased risk of flooding, and decline in biodiversity are all linked to increases in the proportion of built-up and non-vegetated areas relative to green spaces (e.g., [1]).

Implementation of various forms of green infrastructure (cultivated plants and landscapes) is a well-evidenced positive approach to minimise or eliminate some of those problems through the provision of ecosystem services (ESs). Trees and provision of air cooling [2], green roofs or perennial planting and rainfall attenuation [3,4], green facades and biodiversity [5] are just some of the many plant forms and urban environmental issues whose interconnections have been explored. With ground space at a premium for development in the urban context and the ongoing 'battle' for space and funding between grey and green infrastructure, simple and (cost) effective green interventions stand the greatest chance of implementation. This is where hedges, as linear, space-saving, relatively low-maintenance and inexpensive living interventions, have the potential to come into their own.

In the UK context, urban hedges (within or as perimeters in domestic gardens, and public green spaces—parks, playgrounds, roads) are already a significant and common feature [6,7]. More than 85% of UK households have their own private garden [8], and more than 40% of those contain hedges [9]. Hedges' capacity to play a practical role (replacing outdoor walls between property boundaries, fences and other human-made urban surfaces of division), coupled with their ability to provide a range of ecosystem services, makes them a uniquely useful urban greening tool.

Hedges and the multiple ESs they provide have been studied in various contexts. An extensive body of literature deals with their role as barriers to particulate air pollution (e.g., [10,11]). Their support for biodiversity has also received attention [12,13]. Furthermore, there is some evidence for their role in noise attenuation (although that research points to a greater role of soils underneath, with plants themselves being secondary) [14]. Previous research by our group investigated the role of hedge traits in rainfall attenuation and runoff reduction [15]. This is coupled with good evidence that hedges reduce rainfall runoff and soil erosion in rural and agricultural contexts (e.g., [16,17]).

The role of hedges in rainfall retention and water flow regulation has been investigated at various scales, from catchment (particularly in an agricultural context (e.g., [18,19]) to single-tree or even leaf-level droplet retention [20,21]. Two broad themes exist in this type of literature. One investigates rainfall interception and evapotranspiration, the slowing down of flows and hedges/trees' capacity to perform this service and reduce runoff (more applicable to wet/temperate contexts) (e.g., [15,22]). The other, in arid/semi-arid contexts, focuses on the capacity of species to act as conduits via stemflow, capturing and channelling rainfall into the ground, enabling recharging of dry soils [23,24].

Different plant species will, of course, have different capacities for rainfall attenuation. Research on trees revealed significant species differences in rainfall interception [21,23]. Xiao and McPherson [21] studied 20 urban tree species and assessed both with and without-leaf scenarios (for the deciduous species). Rainfall interception varied three-fold among tree species, with conifers such as *Picea pungens* (Colorado spruce) having the highest interception rates due to their leaf and stem morphologies and higher surface roughness [21]. Factors such as leaf hydrophobicity, branch and leaf angles, petiole strength, specific leaf area (SLA) and bark texture all influence the quantity of rainwater retained or released through the canopy and plant stems [23,24].

While research to date clearly highlights the potential of single-species hedges ('monocultures') to be a positive environmental force (e.g., [6,7]), there is very little information on the service delivery of *mixed hedges* and their comparison to hedge 'monocultures' across all seasons. There are a host of ecological reasons why mixes, in addition to monocultures, should be considered. The structural diversity, alongside the habitat connectivity, that mixed hedges provide has been shown to play a positive role in biodiversity-linked ecosystem services in agricultural settings [25].

In the context of mitigating rainfall and runoff, examples from other functional plant groups and forms of green infrastructure also show that vegetation mixes with high species diversity (and correspondingly high structural and functional diversity) reduce hydraulic resistance and soil erosion [26]. For example, combinations of species with high branch density and those with rhizomes and/or high leaf area deliver a greater extent and a number of benefits related to slowing water flows and reducing soil erosion in agricultural fields, compared to individual constituent species alone [26]. In trees, higher species diversity has been shown to improve cooling potential in warmer months [27]. This is partly attributed to more effective utilisation of the entire above-ground canopy area (multi-layered canopy effect). This could also be the case for mixed-species hedges, particularly combinations that maximise colonisation/utilisation of the entire above-ground hedge space.

Irrespective of the species composition within a hedge, reduced rainfall runoff due to hedges' presence occurs via two primary mechanisms: (1) rainfall interception/retention in the canopy and (2) water retention and use within the soil where a hedge is grown. Canopy rainfall retention is the proportion of rainfall intercepted and temporarily stored within a plant's canopy, i.e., water held on leaves, branches and bark [28]. Water intercepted by the canopy either evaporates or, once canopy storage capacity is saturated, more gradually reaches the ground below. Temporary rainwater storage in the canopy contributes to mitigating soil erosion and surface runoff, as the canopy reduces rainfall intensity and droplet speed and size before they reach the ground [29,30]. Plant evapotranspiration (ET) (primarily water loss through plant leaf stomata/transpiration) creates soil water deficit and increases the soil's capacity to store subsequent rainfall. There is also an indirect impact of hedges on soil properties (e.g., via production of leaf litter; [31]). Furthermore, soils under hedges tend to have a larger proportion of smaller soil pores (improved water retention) and better structure, with increased soil organic matter and larger soil aggregates increasing soil porosity and improving infiltration rates compared to grassland soils [22].

Within this project, we included some genera (*Crataegus*, *Thuja*) whose capacity for intercepting rainfall and reducing runoff has previously been quantified [15] and also included new evergreen and semi-evergreen representatives (*Elaeagnus* and *Ligustrum*). We know from past research [15] that broadleaved deciduous species (such as *Crataegus*) outperform evergreen species in the period when they are most physiologically active (and have the largest leaf area (LA) and leaf area index (LAI)). This is in part due to deciduous broadleaved species being physiologically more active and having higher ET rates than evergreen and coniferous species (e.g., [32]). Deciduous shrubs are, however, not in leaf for a significant part of the year (and thus with no/minimal ET), hence the idea to practically pair them with evergreen species to extend the 'service provision' of a hedge into a period of leaf fall. This is coupled with the acknowledgement that mixed hedges' performance, relying on ET, will likely be lower in the summer (due to species mixing) but enhanced in winter. Under a climate change scenario of milder, wetter autumns and winters [33], understanding how we can increase rainfall attenuation in the period of leaf fall, while maintaining the diversity benefits of mixed plantings in summer, is important.

Due to growing evidence of the benefits of plant mixes (and resultant diversity) for the delivery of ecosystem services, and the relative paucity of year-round measurements, we compared single-species and mixed-species hedge treatments for rainfall attenuation and runoff reduction. In this one-year case study, using container-grown mini-model hedges, we tested the practicality of mixing species based on certain functional and structural (canopy) traits. We explored the extent to which autumn and winter outdoor experiments were meaningful and could address (1) how hedge canopies retain rainfall, and (2) how substrate moisture content under/around hedges varies, depending on species composition

and season. Findings are intended to be a starting point for future, longer-term in situ assessments of ground-grown mature hedges.

2. Materials and Methods

Experiments were conducted between March 2022 and April 2023 at the outdoor experimental grounds of the School of Agriculture, Policy and Development, University of Reading, UK (51.437069, −0.942115). The site is nestled between the University buildings on the main campus and experiences temperate climatic conditions, with four meteorological seasons. Average daily min/max temperatures (obtained from the nearby University Meteorological Observatory) for the four seasons are 14/6 °C (spring), 22/12 °C (summer), 15/8 °C (autumn) and 8/2 °C (winter) [34].

2.1. Plant Species and Planting Arrangements

Four plant taxa (purchased from Paramount Plants and Gardens, London, UK) were chosen for the experiments, representing a range of plant characteristics (Table 1). They were planted in groups of three to create either a 'monoculture' or 'mixed-hedge' combination [evergreen: 1 × *Ligustrum*, 1 × *Elaeagnus*, 1 × *Thuja*; or broadleaved: 1 × *Ligustrum*, 1 × *Elaeagnus*, 1 × *Crataegus*].

Table 1. Information on plant species and treatments.

Plant Taxon	Age at Planting (Years)	Arrived as	Description	Used Within Treatment Number
Elaeagnus × *submacrophylla* 'Gilt Edge' (Oleaster 'Gilt Edge')	3–4	10 L pots	Evergreen broadleaved shrub, physiologically active [35]	Monoculture (1) Evergreen mix (5) Broadleaved mix (6)
Crataegus monogyna (Common hawthorn)	2	Bare-rooted	Deciduous broadleaved, native to the UK, widely used hedging plant, physiologically active [15]	Monoculture (2) Broadleaved mix (6)
Thuja plicata 'Atrovirens' (Western red cedar 'Atrovirens')	4	Rootballed	Evergreen coniferous, large canopy with scaley leaves known to retain rainfall within it, but less physiologically active than broadleaved evergreen taxa sampled [15]	Monoculture (3) Evergreen mix (5)
Ligustrum ovalifolium (Garden privet)	3–4	10 L pots	Semi-evergreen broadleaved species, high level of physiological activity when in leaf [36]	Monoculture (4) Evergreen mix (5) Broadleaved mix (6)

The idea behind creating these particular mixes was to explore the impact of combining taxa with varying, but potentially complementary, functional and structural characteristics (ET rate/water use, deciduous/evergreen canopy) on the ability of hedges to reduce runoff.

Plants were planted into 110 L troughs [1 m (L) × 0.4 m (w) × 0.45 m (d)] with Sylvamix growing substrate (6:2:2 sylvafibre:growbark pine:coir *v*/*v*; Melcourt, Tetbury, UK) with a slow-release fertiliser feed (6-8 months, Osmocote, Scotts, Marysville, OH, USA) (see Figure 1A). Each monoculture or mixed hedge had three replicate troughs. We also included a control treatment: troughs with bare substrate only, at the same volume as in the plant treatments.



(**A**). Potting up the plants, February 2022



(**B**). Experimental site setup, March 2022



(**C**). Rainfall applicator and a tripod stand



(**D**). Experimental site, December 2022

Figure 1. Visuals of the potting-up process (**A**), the experimental site where troughs with hedges were placed (**B**,**D**) and the rainfall simulator used in the experiments (**C**).

Before planting in early February 2022, 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. The mesh was then covered with 10 L of horticultural gravel (size 10 mm), followed by 80 L of substrate.

Plants were maintained outdoors and watered as required. We allowed a period for hedge establishment and acclimation to the site (February–July 2022), during which only a small number of preliminary measurements were made, with the aim of developing research methods/protocols.

At the beginning of the experiment, troughs with hedge plants and bare soil were put into fixed positions in a field plot (Figure 1B). Each trough was placed onto a plastic tray [1.1 m (L) × 0.45 m (w) × 0.05 m (d)], and both were then elevated onto a 10 cm pedestal at a 4° angle, constructed from bricks. This was done with the intention of making it comparable to our previous work on monoculture hedges [15]. The 21 experimental troughs were arranged in three parallel rows of five plants and one row of six; the exact arrangement of troughs on the plot is shown in Figure S1 (Supplementary Materials).

2.2. Application of Simulated Rainfall

Simulated rainfall was applied to each treatment, using the setup described in detail in [15] Blanusa and Hadley (2019), two times in every season: summer (August) 2022, autumn (October/November) 2022, winter (December/February) 2022/23, and spring (April/May) in 2023 (Table 2).

Table 2. Timings of key measurements analysed in this paper.

Measurement	Timing of Measurements	Notes
Simulated rainfall/attenuation by canopies	Summer: 8 and 30 August 2022 Autumn: 25 October, 12 November 2022 Winter: 6 and 10 February 2022 Spring: 24 April, 18 May 2023	Measurements were made on days with lowest forecasted wind speed in the season
Substrate moisture content	Summer: start 7 June and 12 July 2022 Autumn: start 4 November 2022 Winter: start 29 November and 5 December 2022 Spring: May 2023	Weeks with high likelihood of a rain-free forecast were chosen for measurements
Leaf stomatal conductance to water vapour	Summer: 11 July 2022 Autumn: 10 October 2022 Winter: 1 February 2023 Spring: 4 April 2023	Days with little/no cloud cover were chosen, to characterise plants' maximal capacity to transpire
Plant height/width	Summer: August 2022 Autumn November 2022 Spring: May 2023	-
Leaf area	Summer: August 2022 Autumn: November 2022 Spring: May 2023	Estimate based on branch number and length and leaf area of a subsample of branches

Briefly, this rainfall application system, produced 'in-house' by an irrigation specialist at RHS Garden Wisley, consisted of a Lechler 460 608 nozzle attached to a 2 m length of hosing connected to a flow control, which consisted of 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 main water supply [15]. The nozzle, hosing and simulator were fastened to an adjustable photography tripod stand, which was raised to 2.3 m high (*Elaeagnus*, *Crataegus* and Bare soil) or 2.6 m (*Thuja*, *Ligustrum*, broadleaf and evergreen mix) so that the distance from the rain nozzle to the top of the canopy (i.e., the length travelled by the raindrop from the applicator to the canopy) remained the same throughout all replications (Figure 1C). Attached to the main body of the stand was the measuring cylinder (at the approximate height of the top of the hedge, around 1.5 m). Its purpose was to check for the uniformity of simulated rainfall applications between runs in each experiment. Our system was set up to apply 15 mm of rain h^{-1} (15 L m^{-2} h^{-1}).

Preliminary tests carried out over several days in March 2022, in the glasshouse and at the field site, focused on assessing the duration of application required to enable us to determine the delay of runoff by holding rainfall within the canopies. Our setup, in still weather (windspeed up to 5 m s^{-1}), enabled us to apply statistically similar rainfall volumes onto each replicate of each treatment over 5 min application periods. This duration was chosen, after testing a range of other durations, as the point at which even our largest plants (e.g., *Thuja*) began to 'leak' rainfall into the collecting vessels below the canopies (reaching maximum capacity to retain rainfall within the canopy). Much of the focus of

this case study was on the details of the canopies' retention of rainfall; these were more pronounced during shorter rainfall events, which then influenced our duration choice.

2.3. Measurements

Experiments focused on measuring two main parameters (on one or two occasions in each of the four seasons, Table 2).

1. Ability/capacity of hedges to retain rainfall within plant canopies.

This was assessed by measuring the volume of water collected in containers on the substrate surface; the containers fully covered the surface of the substrate underneath the canopy (Figure 2). Simulated rainfall was applied for 5 min in the conditions described above. We then recorded the volume of rainfall ('throughfall') collected in the containers at the end of the 5 min period (to assess retention/attenuation of rainfall by the canopies), as well as 5 min after the rainfall stopped ('drained' rainfall, to assess the leakage of rainfall from the canopies).



Figure 2. Position of containers collecting runoff from canopies during and after 5 min simulated rainfall application.

2. Soil/substrate moisture (linked to the ability of hedges to remove water from the soil and thus increase the soil's water-holding capacity for subsequent rainfall).

This was tested by measuring substrate moisture content (SMC) over 5 rain-free days, starting from fully saturated soil and monitoring SMC decline at 24 h intervals. On Day 1, containers were hose-watered to full container water-holding capacity and allowed to rest for 1 h before the first measurement. SMC was measured using a 'WET' sensor (0–0.8 $\pm$ 0.04 m^3 m^{-3} range) connected to an HH2 Moisture Meter (Delta-T Devices Ltd., Cambridge, UK) in six locations per container, 5 cm away from each plant's main stem, on opposite stem sides.

Additionally, we measured several 'explanatory' parameters, including each plant's height/width, leaf area, and leaf stomatal conductance to water vapour, once in each season.

The height and width of each plant within a trough (across the trough) were measured in all the single-species treatments, and the average for the trough was calculated (for single species and mixes) 3 times in the experiment (summer, autumn and spring measurements; Table 2). Over the course of the experiment, the plants were not pruned, apart from small branch sections taken (see below) for estimation of canopy leaf areas.

The process adopted to estimate the leaf areas for each species, and each trough as a whole, was to count branch numbers and measure lengths on six randomly chosen plants per species. This enabled us to calculate the total average length of branches for each individual species. In addition, we destructively sampled 6 branch sections (ranging from 45 to 93 cm) from each plant species and determined the leaf area for each of those branch section lengths using a WinDIAS leaf area meter (Delta-T Devices, Cambridge, UK). Knowing the total branch length per plant enabled us to estimate leaf area for the individual plants for each species (Table 3). Measurements were done for three out of the four seasons, as we assumed little/no leaf area increase in the winter months. The leaf area index (LAI) was calculated by dividing the total estimated leaf area of the species by its rectangular ground projection (obtained from the measurements of hedge width/depth).

Table 3. Average total leaf area per trough for all plant treatments within the experiments, along with the calculated leaf area index (LAI) at three measurement points (summer/August, autumn/November 2022, and spring/May 2023).

Plant Species/Mix	Summer 2022		Autumn 2022		Spring 2023	
	Leaf Area (m^2)	LAI	Leaf Area (m^2)	LAI	Leaf Area (m^2)	LAI
Elaeagnus	2.1	2.9	4.6	3	7.4	3.5
Crataegus	0.9	0.6	0	0	4.2	1.9
Thuja	1.7	1.8	3.1	2.7	5.8	3.3
Ligustrum	2.1	1.3	5.4	2.7	7.2	2.6
Evergreen mix	2.0	1.3	4.4	2.8	6.8	3.1
Broadleaf mix	1.7	1.6	3.3	1.9	6.3	2.7

Leaf stomatal conductance to water vapour (g_s) was measured (using an AP4 porometer, Delta-T Devices Ltd., Cambridge, UK) once in each experimental season, on a sunny, still day, when the plants were well-watered (i.e., substrate moisture content > 0.30 m^3 m^{-3}), to assess the maximal capacity of plants for transpiration. All treatments were measured on the same day in a random order: on two young but fully expanded leaves per plant and on two plants per species in each of the three monoculture troughs per species (12 replicates per species).

In addition, we collected information on the maximum and minimum air temperatures and relative humidity, as well as the wind speed, from the University of Reading meteorological station, located 600 m from the experimental plots.

2.4. Statistical Analyses

A total of 21 troughs were monitored over a total of 8 separate weeks, two in each of the four temperate seasons, resulting in up to 126 longitudinal records per measured parameter.

Three different Linear Mixed Models (LLMs) were fitted to the collected data to assess species and seasonal differences in 1. 'throughfall', 2. 'drainage' and 3. substrate moisture change. We used so-called 'marginal LLMs': this type of model accounts for random differences (e.g., between individual troughs or weeks in the same season) before estimating the differences between fixed effects (i.e., hedge species). This gave us a clearer picture of the data and enabled us to investigate differences between hedge species for the parameters in question. The clustering effect 'trough_id' was included to account for the non-independent repeated measurements of each trough. The fitting method was REML (Restricted Maximum Likelihood), a common approach for obtaining an accurate estimate

of variance components in mixed models. A Kenward–Roger approximation was used to test the hypotheses, providing a more accurate estimation of the degrees of freedom. A detailed description of such models is found in [37].

To enable a comparison of all plant treatments within a season to the bare soil treatment, as a control, we applied Dunnett multiplicity adjustment [38]. To compare just plant species within a season, as well as each species over the four seasons, a Tukey multiplicity adjustment was applied [38]. Residual plots were inspected for each of the models to ensure the suitability of the statistical design. The modelled estimates represent the underlying patterns in the observed data after accounting for random variation, covariates, and the structure of the experiment. In Section 3, we include the raw data along with the estimated data to make the link between the two as clear as possible.

Specifically, to assess differences between species, seasons and their interaction, the model structure for both 'throughfall' and 'drainage' included season, week, species, and 'season by species' as fixed effects and 'trough_id' as a clustering effect. We analysed the canopy 'throughfall' in absolute terms and also relative to the leaf area of each trough.

To assess how different plant species and mixtures influence substrate moisture over time, we analysed changes in substrate moisture between Day 0, when troughs were watered to container capacity, and Day 3 (72 h later), during which no additional watering occurred. This approach also allowed us to evaluate the potential of each planting mix to create a greater capacity within the soil for future rainfall storage. To assess differences between species, seasons, and their interaction on substrate moisture, the model structure included air temperature and relative humidity as continuous covariates (using the average values for the 72 h period between Days 1 and 3) and 'season', 'species' and 'season by species' as fixed effects and 'trough_id' as a clustering effect. The effect of week nested within season was not added to this model as its effect was absorbed by weekly changes of both air temperature and relative humidity.

Leaf stomatal conductance was analysed using one-way Analysis of Variance (ANOVA) to compare differences between species within each season.

3. Results

3.1. Capacity of Hedge Canopies to Retain Rainfall

3.1.1. What Is a Canopy Throughfall During a 5 min Rainfall Event?

Within this paper, we assume that the better 'service' of a hedge for the purpose of flood mitigation potential is linked to less throughfall—expressed as both unadjusted and adjusted leaf area values (Figure 3A,B). The outputs of our mixed model highlight significant differences in throughfall between seasons (F pr = 0.0003), weeks within the same season (F pr = 0.0004) and between species (F pr < 0.0001). Additionally, a significant interaction was found between season and species (F pr = 0.0003).

Outputs from the model fitted to our collected data show that in the summer 2022 measurement period, *Elaeagnus* (p = 0.0115) and *Thuja* (p = 0.0005) had less throughfall than bare soil, but the remaining plant treatments, including mixes, did not differ from bare soil. In autumn and winter, there were no differences between plant treatments and bare soil in the volume of water collected as throughfall. In spring 2023, *Crataegus* (p = 0.0085), *Thuja* (p = 0.0010), and both hedge mixes (evergreen p = 0.0504; broadleaf p = 0.0076) all had lower throughfall than bare soil, with *Elaeagnus* and *Ligustrum* not being different (Figure 3A).

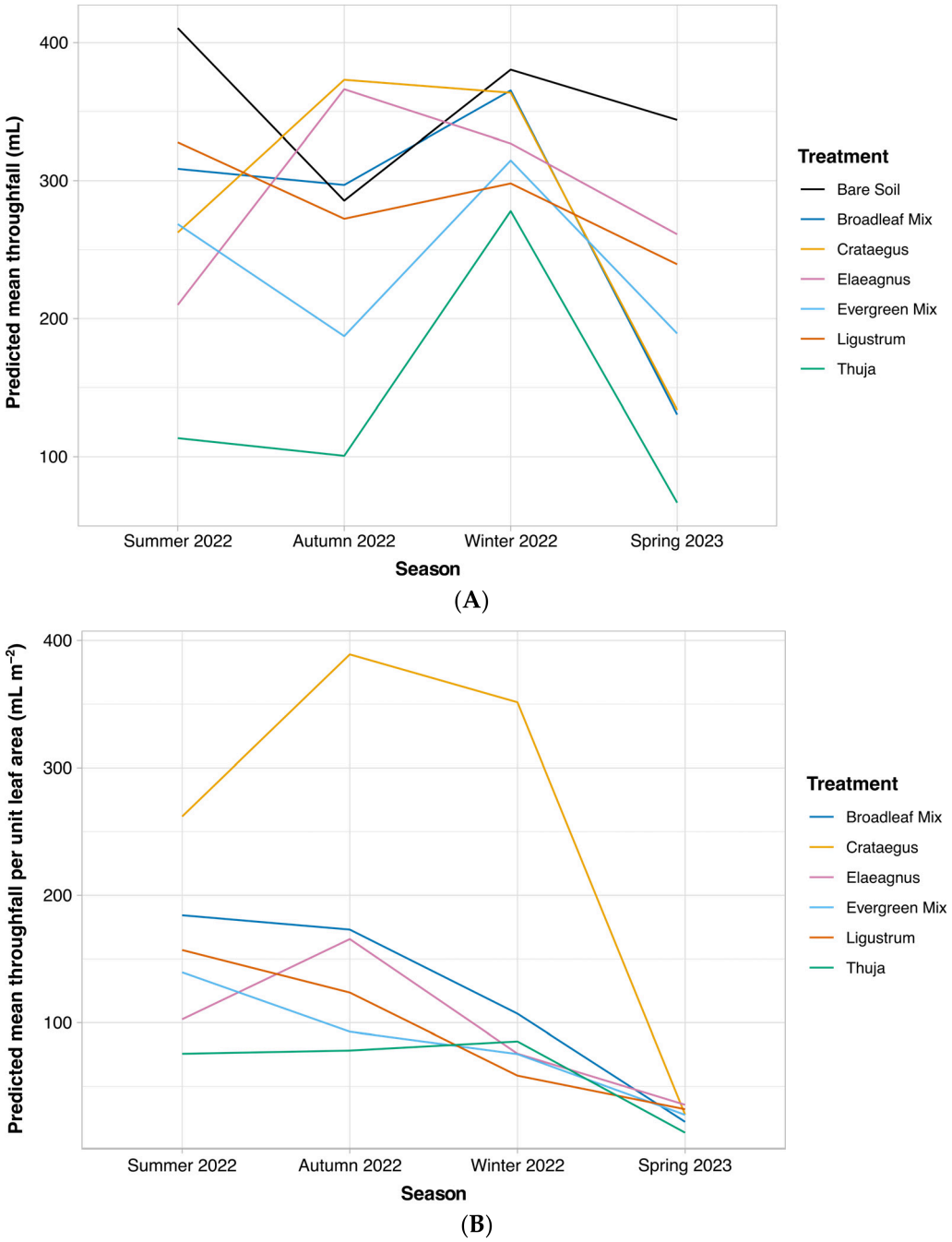


Figure 3. Predicted mean volumes of rainfall collected under the canopies ((**A**) absolute values; (**B**) values relative to leaf area of hedges) after 5 min simulated rainfall application, over 4 seasons.

In terms of species comparisons, *Thuja* had the lowest predicted throughfall at the end of the 5 min rainfall event in most seasons compared to the other treatments, even when accounting for leaf area (Figure 3B). In the initial summer measurements, *Elaeagnus* had the second-lowest predicted throughfall, but in subsequent measurement points, this was not maintained. *Crataegus* struggled with establishment (and thus had low leaf area in summer and autumn 2022 and, as a deciduous species, no leaves in winter; Table 3). Consequently, it had high throughfall values until spring 2023, when its throughfall became the second lowest (Figure 3A,B for predicted; Figure 4 for raw data). In spring 2023, the broadleaf mix also had low throughfall values, similar to those of *Crataegus*. The evergreen mix had the lowest throughfall of all treatments, apart from *Thuja*, in winter 2022 (Figure 3A,B for predicted; Figure 4 for raw data).

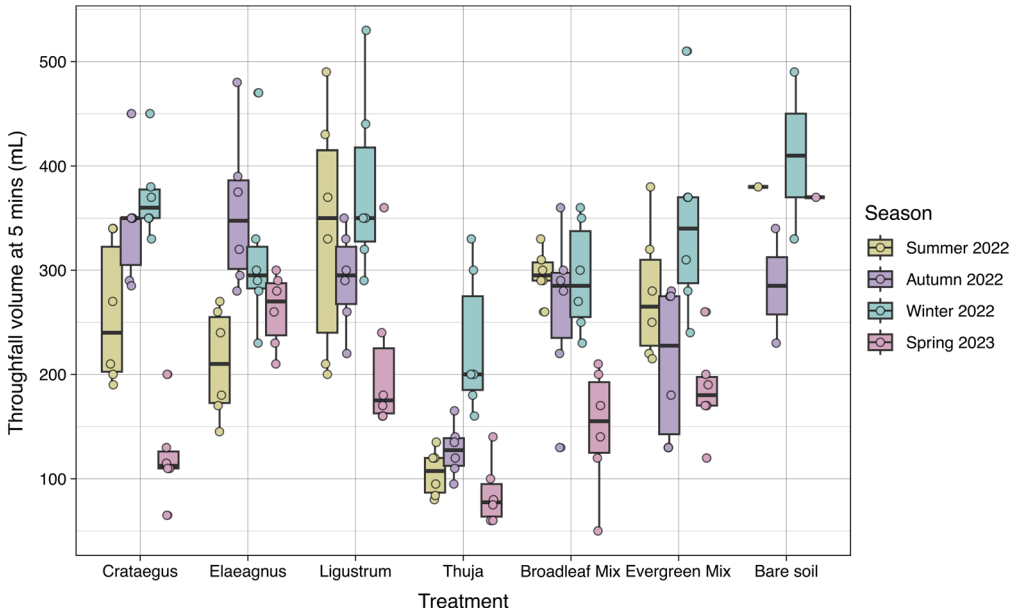


Figure 4. Boxplot of all raw data for throughfall volume at the end of a 5 min simulated rainfall event per treatment, used to fit the mixed model.

3.1.2. What Drains off the Canopy Within 5 min of Rainfall Stopping?

Thuja and the evergreen mix (containing *Thuja*, *Ligustrum*, and *Elaeagnus*) had higher predicted rates of drainage from the canopy in winter, compared to the other seasons. All other species and the broadleaved mix had similar rates of drainage post-rainfall in different seasons. In most seasons (summer and autumn 2022, and spring 2023), there were no significant differences between the species in the drained volume after the rainfall stopped. Using an evergreen mix as a benchmark/control, in winter 2022, *Thuja* had significantly more predicted drainage than the evergreen mix, and all other species were similar but with significantly less drainage than evergreen. All raw data used to fit the mixed model are shown in Figure 5.

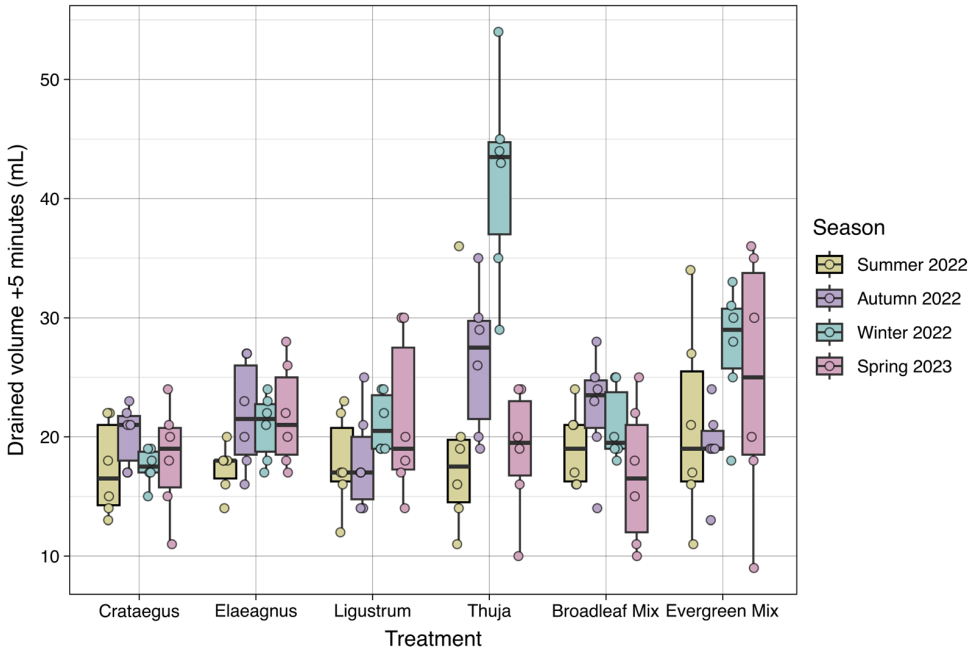


Figure 5. Boxplot of all raw data for drained volume 5 min after rainfall stopped, per treatment, used to fit the mixed model.

3.2. Decrease in Substrate Moisture over Time in Different Plant Mixes

The data presented here show the predicted *difference* in SMC after 72 h of starting the measurements for six plant treatments and bare soil (Figure 6). Our assumption was that the better 'service' of a hedge for flood mitigation potential is linked to greater SMC decline (so higher values on the y-axis).

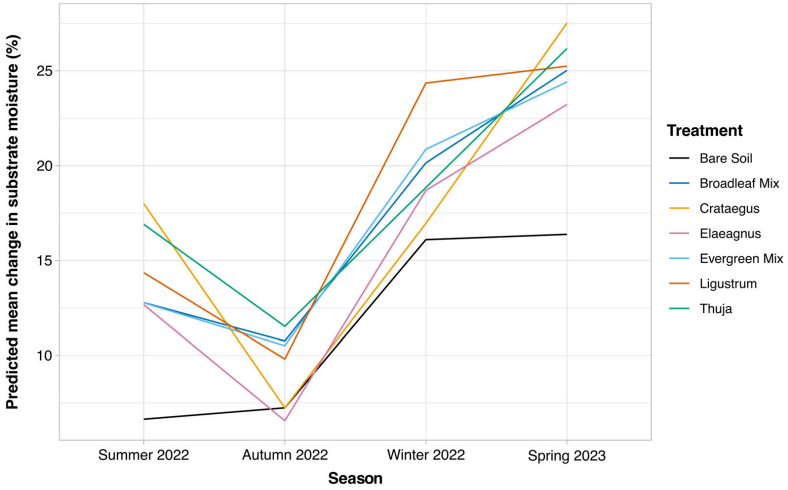


Figure 6. Predicted mean difference in substrate moisture content over a period of 72 h.

In spring and summer, all plant treatments were significantly different from bare soil and had a greater predicted decrease in substrate moisture. In autumn, this was true only for *Thuja* ($p = 0.0164$ in comparison to bare soil), and in winter, for *Ligustrum* ($p = 0.004$) (Figure 6).

Despite the high level of variation in SMC (Figure 7), predicted differences between plant treatments themselves were small for the most part (Figure 6). In summer, for example, *Crataegus* and *Thuja* reduced substrate moisture the most (e.g., *Crataegus* more than *Elaeagnus*, $p = 0.0054$, as well as better than the mixes, $p = 0.007$; *Thuja* more than *Elaeagnus*, $p = 0.05$). In autumn, *Thuja* showed some advantage (e.g., decreasing SMC more than *Elaeagnus*, $p = 0.012$); in winter, the impact of *Ligustrum* on reducing SMC approached significance in comparison to that of *Elaeagnus* ($p = 0.07$) and *Thuja* (0.09). In spring and summer, 'monocultures' (e.g., *Elaeagnus*, or *Thuja*) decreased SMC more than the mixes they were part of (Figure 6).

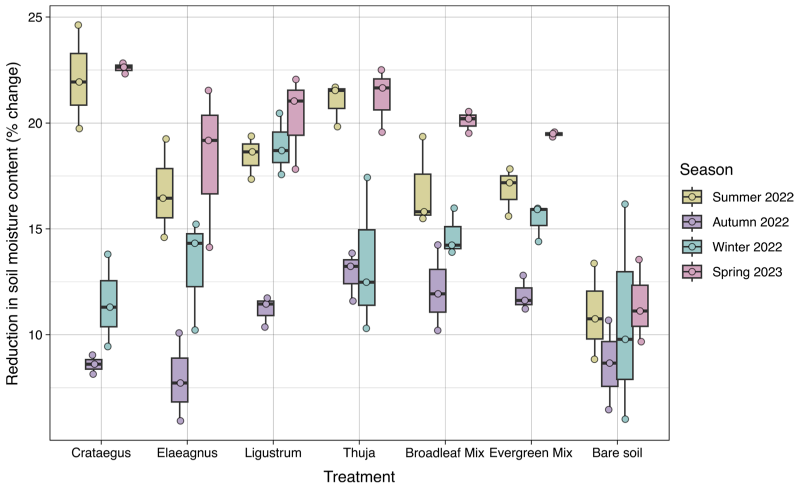


Figure 7. Boxplot of all raw data for substrate moisture content change over 72 h (% change), per treatment, used to fit the mixed model.

3.3. Leaf Stomatal Conductance to Water Vapour (g_s)

In summer 2022, we measured the highest stomatal conductance in *Elaeagnus*, followed by *Crataegus* (both over 150 mmol m^{-2} s^{-1}), with these two species also having the highest g_s in autumn measurements (both over 350 mmol m^{-2} s^{-1}). During the winter measurement point, as expected, g_s was significantly lower than in the other seasons, but *Elaeagnus* and *Thuja* had the highest g_s (83 and 49 mmol m^{-2} s^{-1} on average, respectively; statistically non-significant). In spring 2023, measurements of g_s were very low, all below 60 mmol m^{-2} s^{-1}; we believe that at this point, the plants were becoming pot-bound (i.e., roots fully filling the trough and beginning to circle round it), which would have impacted g_s.

4. Discussion

We approached this project as an initial case study in which we used container-grown model hedges to explore the practicality of mixing plant species based on certain functional and canopy traits and carried out year-round outdoor experiments. Our idea of mixing was distinct from the concept of mixed hedges in a horticultural sense [39,40]; it did not prioritise plant origin (native vs. non-native) or centre solely on identical management requirements (although those were considered). Within it, we focused on determining the ability of model hedges to attenuate rainfall via canopy capture and to decrease soil water saturation through evapotranspiration (ET). The hedge species chosen for the experiment represented a range of plant characteristics—evergreen and deciduous, scale-leaved and broad-leaved, with higher and lower ET rates, as monocultures and as mixed hedges.

4.1. Is Functional Species Mixing for Hedges Practical?

Elaeagnus and *Ligustrum* formed the basis of all model mixed hedges, with the 'broadleaf' mix including *Crataegus* and 'evergreen' including *Thuja*. Plants grew rapidly over the four seasons of the experiments, with *Elaeagnus* and *Ligustrum* more than doubling their leaf area between the summer and autumn measurement points, and *Thuja* achieving just under a 2-fold increase (Table 3). On-site observations also showed that *Elaeagnus* grew sideways more than upright compared to the other species in the study. When mixed with a more upright taxon like *Thuja* 'Atrovirens', it creates a hedge with uneven height, which will require an adjustment by pruning in the initial years of establishment. Our more recent observations of the same species mixes planted in the field suggest that after two field growing seasons, with two light prunes (mid-spring and mid-autumn) per calendar year, we were able to achieve a uniform height and conventional hedge look.

4.2. What Additional Insights Have We Gained from Year-Round Experimentation?

Our past work investigated the ability of single-species model hedges during summer months to provide rainfall attenuation and runoff reduction, when their capacity is likely at its peak [15]. Very few studies have assessed the provision of ESs year-round. A study of mixed rural hedgerows (composed of two deciduous species: *Crataegus monogyna* and *Acer campestre*) in SE England [16] provided significant insight into stomatal conductance, sap fluxes and resultant substrate water content changes over approximately 6 months while these species were in leaf. It suggested that while their impact on substrate moisture decline is greatest during the summer months, it extends all the way to mid-autumn [16]. Our work encompassed evergreen and semi-evergreen species (*Elaeagnus*, *Thuja* and *Ligustrum*) and included winter measurements (December and February). The winter growth rates and physiological activity (as judged by g_s measurements) of the semi-evergreen/evergreen plants in our experiment (all of which retained leaves at our experimental site) were significantly lower compared to the spring–autumn period, but were detectable nonetheless.

Mild microclimatic conditions at our site, which is relatively shielded and surrounded by built structures, may have contributed to the continued (albeit low) level of physiological activity. We suggest that the outcomes and meaningfulness of winter physiological measurements will, to an extent, depend on site and prevailing weather conditions, as well as the questions being studied. A study on *Thuja* and *Chamaecyparis* in a range of winter scenarios highlighted a significant drop in photosynthetic activity due to low temperatures alone, along with photoinhibition in sunny winter conditions, which is exacerbated at low temperatures [41]. However, measurements of rainfall interception relying on structural plant characteristics (structure of branches) in winter months on deciduous trees showed a considerable contribution even on leafless branches [42].

4.3. Rainfall Capture by Canopies

In the context of our experiment, we were interested in determining the extent to which hedge canopies can attenuate rainfall and reduce the volume of water reaching the ground and how species and mixes perform year-round. Our plants were still rapidly establishing over the course of this year-long case study, so the findings are preliminary only. The more established our model hedges became (i.e., by spring 2023), the more pronounced the effects, with *Crataegus*, *Thuja* and both mixes showing increasingly significant interception rates relative to bare soil. Interception rates in our 5 min event were highest in *Thuja*, after normalising for leaf area, suggesting that other canopy and leaf properties (i.e., scale-like leaves and rough bark) contribute towards water retention. In *Elaeagnus* and *Ligustrum,* despite greater leaf areas than *Thuja*, throughfall rates were slightly higher than (or at least not significantly different to) bare soil. This was unexpected, because throughfall would be expected to be maximised (interception zero) on bare soil. However, this is attributed to variability in water volumes applied by the rainfall simulator, the likelihood of splash out from unimpeded raindrops on the bare soil treatment (high energy, no attenuation by canopy), canopy architecture effects, and the uninhibited movement of rainwater sliding off less wettable leaves. *Crataegus* had low throughfall once it was established in our final set of measurements (spring 2023). Leaf inclination and petiole angles impact the number of droplets that can be stored within canopies, and species differences have been reported (e.g., [43]). The seemingly more wettable leaf surface of *Crataegus* compared to *Elaeagnus* and *Ligustrum* may have contributed to its better performance once it became more established (personal observation). Work by Li et al. [44] highlighted the contribution of a very wide range of leaf and branch traits to rainfall retention within canopies, including: leaf area, leaf biomass, leaf morphology and branch/canopy density, branch count, branch length, and woody surface area (branch/stem).

Our working hypothesis was that the contribution of mixes to rainfall retention will come predominantly in the form of reduced rainfall throughfall by year-round leaf biomass and that this will be most pronounced in winter. The evergreen mix was the second-best for reducing winter throughfall (after *Thuja* alone), likely due to the presence of one species (*Thuja*) in a three-plant mix, which individually performed well. The mixes consistently performed as averages of constituent species. In our experiment, there were no differences between the two mixes in different seasons. This is likely in part because our data was obtained from young, still establishing plants; only in the final experimental season (spring 2023, about a year after planting) did we begin to see more significant differences between species and mixes. This, however, may also be linked to droplet retention on the *Crataegus* 'network' of bare branches, covered in rough bark [44]. We are continuing our assessments with maturing hedges: we transplanted the containerised model hedges into the ground at the end of this case study and are providing ongoing management in line with practical horticultural standards.

While not measured in our case study, additional unintended consequences of combining plant species could come from changes in leaf litter properties underneath the planting, in monocultures compared to mixes. Litter composition (which influences its water repellence), along with litter density and water storage capacity (both negatively correlated with individual leaf area) [31], would likely vary in mixes compared to individual species. This would necessitate further nuance in planting selection.

Our measurements in this case study related to a short 5 min rainfall event, where *Thuja* and a hedging mix containing it showed initial ability to slow the flow (although in winter, some heightened 'drainage' into the soil after the rainfall stopped was also observed). Our previous work with longer (20 min) rainfall application onto individual species (including *Thuja* and *Crataegus*) with more established/older plants showed the greatest rates of throughfall for *Thuja* [15]. This was apparently due to the canopy architecture of the *Thuja* plants—more effectively capturing and funnelling the rainfall down into the containers, leading to them receiving higher volumes relative to bare soil. We suggested that this could be advantageous on lighter, sandy soils [15].

4.4. Decrease in Substrate Moisture over Time in Different Plant Mixes

In the experiments, we used a reduction in substrate moisture in the topsoil layer over a 72 h period as an indicator of the soil's capacity to store any subsequent rainfall and reduce runoff. In spring and summer, all plant treatments (single-species and mixes) were significantly different from bare and had a greater decrease in substrate moisture. Summer experiments confirmed our earlier findings [15] (Blanusa and Hadley, 2019) that *Crataegus* and *Thuja* reduced substrate moisture the most during this season, with *Thuja* also continuing to show some advantage in autumn. In our experimental setup, species differences were, however, small even in warmer seasons (e.g., summer) when the plants were more physiologically active. In winter, within our setup, the mixes of plant species, or the evergreen single species, did not provide an advantage in terms of SMC reduction. Changes in plants' canopy sizes over time (increases due to annual growth, decreases due to pruning and hedge management) will, among other factors, influence hedges' capacity to remove water from the soil [45].

Additionally, soils, as a significant contributor to rainfall attenuation ([15] and references therein), differ in the extent to which hedges influence their structure [22]. Overall, hedges tend to affect soil pore size positively, as well as increase soil organic matter and water-holding capacity via litter and turnover of fungal hyphae [46]. We have now set up a longer-term field experiment to investigate substrate moisture changes at a range of depths.

4.5. Mixed Hedges and Services Beyond Rainfall Mitigation

Our case study showed the practical potential to mix hedge taxa based on their structure and function and the capacity to deliver ecosystem services, using rainfall attenuation as an example. There is, however, a range of other benefits that could potentially be provided by combining species based on their structural and functional traits. For example, inclusion of marcescent species (i.e., leaves withering but remaining attached to the stem, e.g., those within genus *Fagus*) may act as a deterrent to winter browsing herbivores and minimise nutrient leaching due to the extended period of leaf drop [47]. Furthermore, in rural hedgerows, the structural diversity of hedges was found to be positively correlated with animal species diversity [25]. Similarly, Gosling et al. [48] found that more diverse hedgerows were able to support a greater diversity of invertebrates in both urban and rural settings.

Mixing may also be helpful in the context of hedges' continued function, growth and survival in potential scenarios of temporary water scarcity and drought. Research on

trees highlights the capacity of certain species to shift water uptake to deeper soil layers compared to others [49]. The presence of species with different strategies within hedging mixes could offer this advantage.

4.6. Experimental Context and Lessons Learned

To rapidly start the experimental work, as per the requirement of the project funder, the use of containers to grow model hedges (composed of three plants per container) enabled us to quickly establish mini-model hedges. We strived and took care to obtain plants of similar age/height at the start of the experiment, but *Crataegus* was only available as bare-rooted and consequently required the best part of the 2022 growing season to establish. As a result, the measurements in this period underestimated *Crataegus'* capacity to perform the measured services compared to more established plants of the other species. *Ligustrum*, on the other hand, was obtained containerised with an already highly developed root system, so it experienced more than a doubling of its leaf area between summer and autumn measurements. Our measurements of leaf stomatal conductance (g_s) in summer suggest that it may have shown signs of being 'container-bound' and thus, its ET would have been lower than if the plants were field-grown.

For the purposes of this project, we applied only one intensity and duration of rainfall to gain a broad initial insight into species/mix differences. However, we are mindful that intensity change and durations will result in different storage volumes and storage potentials within the canopy [44] and will also impact the retention and loss ('splash') from throughfall monitoring containers.

It is a challenge to experiment outdoors in an island country due to the influence of multiple and fast-moving weather fronts and the rarity of still-weather days. We therefore needed to be reactive and pick and move our measurement dates at short notice to accrue information on plants' responses in certain sets of weather conditions, which we thought important to characterise. However, the work within this initial study is, however, informing our follow-up multi-year field experiment, where we created wind shields and soil covers to work around weather limitations and to minimise responses related to root restriction.

5. Conclusions

In this case study experiment with containerised model hedges, we found evidence to support the hypothesis that plant mixes (containing evergreen and deciduous plants) confer some benefit, in terms of providing canopy *structure* for water retention. This could have a positive impact on slowing the rainfall in autumn and winter months. However, autumn and winter *functional activity* (substrate moisture decrease, an indicator of plant water use) was low, so the main benefit of individual species and mixes in those periods of the year came from the structural rather than the functional side. We are using these findings as a starting point for continued, longer-term field observations of these mixes, to ascertain the capacity of 'mixed' *versus* 'monoculture' hedges to deliver multiple environmental benefits.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/environments13050252/s1, Figure S1: Layout of treatments on the experimental plot.

Author Contributions: Conceptualisation and funding acquisition: T.B.; methodology: T.B. and J.H.; formal analysis: T.B. and J.H.; investigation: T.B. and J.H.; writing—original draft preparation, T.B.; writing—review and editing, J.H., E.K.L., J.B., and M.B.G. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

ESs—ecosystem services; ET—evapotranspiration; g_s—leaf stomatal conductance to water vapour; LA—leaf area; LAI—leaf area index; SMC—substrate moisture content.

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