Rainwater retention and evapotranspiration as affected by groundcover plants: The influence of leaf morphology

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This thesis is dedicated to my beloved parents;
my father Ismail Jamaluddin, and my late mother Noraini Abu Bakar.

DECLARATION

I declare that no portion of the work contained in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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ABSTRACT

Green infrastructure (GI) as an adaptation strategy to mitigate the effects of climate change has been widely advocated due to their wide range of benefits (ecosystem services). Determining the importance of GI to help alleviate stormwater runoff is made more urgent, when the unpredictability of rainfall, caused by climate change is combined with rapid urbanisation and city densification. In urban areas, increasing volumes, intensities and frequencies of rainfall are exacerbated by soil sealing via hard impervious surfaces, thereby further increasing risks of urban flooding. The potential of trees to capture rainfall, slow down runoff, retain and release moisture has been documented. However, the value of groundcover urban plants with regards to these hydrological activities is less well researched. This research aimed to understand the relationship between plant leaf morphology and hydrological performance, namely rainwater interception, retention (and detention) and the redistribution of moisture via evapotranspiration (ET). The research focuses on groundcover vegetation (ornamental herbaceous plants and sub-shrubs), as these are more commonly used in GI approaches, and can be widely implemented in urban areas.

A small range of genotypes with contrasting leaf traits was chosen to determine their ability to retain water on their leaves, and to observe their ability to dry out their growing media, yet survive during dry periods. A series of experiments was conducted to assess the hydrologic responses of the plants under various scenarios (e.g. ET under natural vs. semi-controlled conditions, water interception and retention under natural vs. artificial rainfall, and large vs. small canopy size). Leaf morphology was found to significantly affect retention and moisture loss rates by the different plant species. The data suggests that plants with narrow leaves retain a proportionally greater depth of rainwater than plants possessing broad leaves or many small leaves. This may be attributed to plants with narrow leaves having various leaf angles and orientation, as well as high number of leaves, thus forming a denser canopy cover. Similarly, ET rates were also highest with narrow-leaved plants, though broad-leaved species were also observed to have high ET rates under certain situations. The data is discussed within the context of utilizing small-scale GI to influence urban stormwater flows.

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GLOSSARY OF TERMS

Detention	: Moisture that is temporarily retained on leaf or stem surfaces before eventually falling onto the ground (usually due to saturated plant surface / moisture storage, or being moved by other droplets).
Evaporation	: The process of liquid turning into vapour; either from leaf surfaces or surface of the soil (mm).
Evapotranspiration (ET)	: The combined process of transpiration (water use) by plants and evaporation from leaf and / or soil surfaces (mm).
Hydrological performance	: The ability for plants to capture, retain and evapotranspire moisture most effectively.
Interception	: The process of raindrops that falls and hits a plant canopy (including leaves, branches and stems). The water can then either be 'retained' or 'detained' on the plant surfaces / within the plant canopy.
Leaf Area Index (LAI)	: Total leaf area per unit of ground surface area (m^2).
Moisture storage	: Moisture held on leaf surfaces, within leaf tissues or within soil pores.
Retention	: Moisture that is retained or held within the canopy; either on the surfaces of leaves or stem until it is evaporated back to the atmosphere, or a small portion can be absorbed into plant leaf cells (mm).
Stormwater runoff	: Rainwater that is not captured by vegetation, or captured, but goes through the plant and reaches the ground, which then flows over impermeable surfaces.
Sustainable drainage systems (SuDS):	: Water management practices designed to maximize the opportunities and benefits of managing rainwater using natural elements (i.e. vegetation and soil).
Total leaf area	: The sum of individual leaf areas (adaxial, i.e. top side only) (m^2).
Transpiration	: The process of water movement through the plant from the roots up the stem and evaporation through leaf stomata.
Efficient in Water Use (EWU)	: Plant's ability to effectively control their stomata under stressed environment to maintain healthy condition.

CHAPTER 1

INTRODUCTION, AIMS, OBJECTIVES AND LITERATURE REVIEW

1.1 Introduction

Unpredictability of weather conditions affecting different regions has caused severe flooding events. This is intensified especially in densely urbanised areas, where pervious surfaces (i.e. soils) are lacking; thereby increasing the velocity and volume of stormwater runoff. The need for a 'greener' and more sustainable solution is in demand now more than ever, hence application of green infrastructures to mitigate stormwater runoff, widely referred to as sustainable drainage systems (SuDS), to help manage runoff effects via functions of natural elements, such as vegetation and soils.

The functions of vegetation to capture, retain and subsequently evaportranspire moisture has been widely studied for around three decades. However, research has been more focused on larger plants and wider-scale vegetation (e.g. forests). Even in the few studies of interception and retention by shrubs or low-growing vegetation, these tended to focus more on arid shrub species, which may be irrelevant as urban planting design, or green roof plants that were focused more on *Sedum*, grass and forbs. Therefore, there are still gaps in the literature regarding the influence of smaller scale urban planting in affecting rainfall interception, retention and evapotranspiration (ET). Interest in smaller scale plantings such as shrubs species, herbaceous and groundcover plants has been less, as they are perceived to be less significant and important in terms of rainfall retention and ET due to smaller surface areas. It is not highlighted in many studies that these smaller scale plantings have a wider variety of leaf characteristics and canopy architecture than trees / forests, which therefore can be advantageous in influencing the hydrological performances with regards to water retention and ET.

Comparisons between broad-leaved and needle-leaved trees have been widely researched, mostly in the context of forests. While a number of studies concluded that interception is more effective by needle-leaved trees compared to broad-leaved, ET by these tree types still has conflicting reviews. However, the available knowledge on large-scale vegetation can be used as reference for this research. With the lack of research on the hydrological performance by low-growing groundcover plants, especially with regards to how different leaf morphology affects retention and ET performance, the opportunities to observe these differences can be explored and further investigated. Moreover, the extent of water capture, retention and ET rates that is the focus of this research can provide new insights on the roles that groundcover vegetation, such as shrubs and herbaceous plants can play in the context of implementing SuDS designs to influence urban stormwater flows.

1.2 Overall aim, hypotheses and objectives of research

The primary aim of this research is to determine the hydrological performance of selected groundcover landscape plants, and to identify the effectiveness of different plants with contrasting leaf traits to capture and retain rainwater, and re-distribute it back to the atmosphere. Factors influencing plant performance such as microclimate, rainfall depth, moisture content and drying cycles as well as plant leaf area are taken into consideration.

The main hypotheses of this research are; i) groundcover plants are capable of helping to reduce impact of stormwater runoff; and ii) plant morphological features have a significant influence on the hydrological processes in which the plants intercept, retain and release moisture. The main objective of this research is to investigate the importance of plant species choices in determining water capture and release characteristics within small-scale urban green infrastructure and SuDS systems.

1.3 Thesis structure and chapter overviews

This thesis comprises six chapters. Chapter 1 contains the introduction of the research and justification for the need of the research, followed by the overall aims, hypotheses and objectives, as well as a review of relevant literature. Impacts of stormwater runoff and flooding are outlined for an urban context. The roles of urban green infrastructure and sustainable drainage systems (SuDS) to help mitigate future flood threats are discussed. This includes a critique of how plants interact with too much and too little water, and how this might influence plant choice for effective urban plantings.

Chapter 2 outlines the materials and general methodologies used in the research to address the primary objectives of the study. This research employs experimental approaches to quantify water use (capture and dissipation) by a limited range of 'model' species. The experiments are categorised into four experimental designs (one small-scale preliminary experiment and three main experiments) to investigate hydrological processes under different environments, and these are described in the subsequent three chapters.

Chapter 3 presents the first experiments that were undertaken to determine interception and retention performance by different plant canopy covers. This involves comparisons in an extensive indoor test to identify moisture storage capacity of individual plants with different leaf traits, followed by similar comparisons but in an outdoor natural environment.

Chapter 4 explores how plant canopies of different species affect rainfall interception, retention as well as moisture loss (ET) from the plant. These were derived from recordings of daily mass of six model species that vary in canopy characteristics, which were exposed to natural climatic conditions. Plants' biological changes over time were also observed and evaluated to identify signs of stress.

The final experimental chapter, Chapter 5 investigates daily ET rates across six plant species and the factors that influence these when held in a semi-controlled laboratory environment. This was done by observing weight loss continuously over a 12-day monitoring period.

Finally, Chapter 6 combines the findings of the experimental chapters to provide a more holistic understanding of how such landscape plants may influence the hydrology of small-scale urban landscapes, and compares these findings with the wider literature. Conclusions and recommendations for landscape practice are included, as are the limitations and implications of the research findings.

1.4 Literature review and background

One of the emerging challenges for urban landscapes is dealing with climate change, and the impact of related weather events that have a strong influence on the urban hydrological cycle. The impacts of climate change are becoming more tangible and demonstrable (Lowe *et al.*, 2018). In the context of urban drainage systems, the increasing severity of extreme weather conditions associated with rainfall (especially the increased frequency, intensity and duration of rainfall) challenges the conventional approach in managing urban hydrological flows. This presents a number of threats including urban flooding, which is predicted to become more frequent and severe in the future (Environment Agency, 2018; Zscheischler *et al.*, 2018). The impact of climate change is especially crucial in urban areas where natural land uses have been altered and replaced with hard impermeable surfaces (Zabret and Šraj, 2015). Even in the UK, in 2014, 83% of the population resided in urban areas (UK Department for Environment, Food and Rural Affair, 2019), and this increases demands for urbanisation (i.e. building densification and increase in impermeable surfaces). The expansion of grey infrastructures such as roadways, pavements and building rooftops that replace permeable soils greatly intensify urban surface runoff by changing the catchment’s response to rainfall, thereby reducing the opportunity for groundwater recharge (Musa *et al.*, 2011). Reduced opportunity for rainwater to infiltrate into the soil causes accelerated and increased volume and rates of surface water flows / runoff (Véliz-Chávez *et al.*, 2014). Urbanisation and the modifications to the landscape typology result in a significant imbalance of spatial and temporal distribution of the hydrological cycle, thereby reducing the ability of drainage systems to mitigate excess water and increase the risks of urban flash flood occurrences (Tkachenko *et al.*, 2016) (Figure 1.1).

1.5 Impacts of urban flooding

Climate change prediction projects that urban flooding will be more frequent as rainfall becomes more unpredictable (Tkachenko *et al.*, 2016; Zscheischler *et al.*, 2018). According to the National Climate Change Projection (UKCP18), in the UK, rainfall is predicted to increase significantly in winter and decrease significantly in summer, however, rainfall occurrence in summer will be more intense, though this depends on regions and emissions (Lowe *et al.*, 2018). In Asia, monsoon rainfall accounts for up to 80% of annual rainfall where flooding occurrences are regular hazards (Mirza, 2011). With increased volume, frequency and intensity of rainfall resulting in higher runoff volume in urban areas, flooding is considered one of the biggest challenges faced by many cities today. The impact of urban flooding affects millions of lives as well as the built environment and infrastructures (Mirza, 2011; Zscheischler *et al.*, 2018), and is severely impacting different areas of social, community, environment and the economy of a locale, and is not one to be taken lightly. Tkachenko *et al*. (2016) mentioned that flooding occurrences are inconsistent and subject to change as effects of climate change are unpredictable.

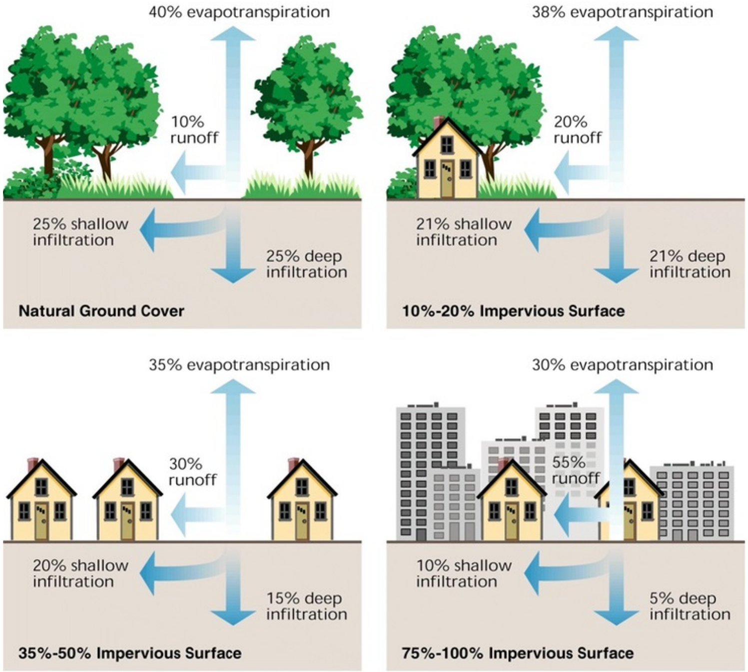


Figure 1. 1: Impact of increased impervious surfaces due to urbanization enhances surface runoff, as more water is unable to be intercepted by vegetation and infiltrate into pervious soil surfaces (Image source: In Stream Corridor Restoration: Principles, Processes, and Practices, Federal Interagency Stream Restoration Working Group (FISRWG), 1998).

The incapability of drainage systems to cope with the excess runoff causes problems such as rising vulnerability of housing risks as settlements are still being developed on flood prone areas (urban areas) (Tkachenko *et al*., 2016). Flooding events also result in physical and psychological illnesses due to the trauma that ensues (Gill *et al.*, 2007). There are also direct effects with increases in traffic interruption, property damage and economic losses due to maintenance and repairs that need to be done that are the result of damages caused by the flood (Gill *et al*., 2007; Qin *et al*., 2013).

In addition, flooding events increase health and life risks due to pollution and waterborne diseases (Okaka and Odhiambo, 2018).

The impacts of flooding also greatly affect the environment, affecting vegetation production, growth and survivability (Blom and Voesenek, 1996). The ability of plants to survive under these extreme conditions varies with plant species. Some terrestrial plants can tolerate excessive water and can adapt to prolonged wet environments, while others cannot due to deficit of oxygen, sunlight and carbon dioxide, therefore hindering photosynthesis and growth, in which plants will become stressed and die (Voesenek and Bailey-Serres, 2013). These differences in adaptability strategies are due to the heterogeneity of plants' functions, based on their physiological and morphological traits, which is one of the main focuses of this research.

1.6 Green infrastructure

Green infrastructure (GI) is a sustainable approach with multi-functional benefits, aiming to reverse the impact of climate severity and counter a number of urban environmental issues (Figure 1.2) by mimicking natural processes such as infiltration by soil and evaporation / transpiration by vegetation (Rouse *et al*., 2013; Hansen and Pauleit, 2014; Sussams *et al*., 2015; Xiao and McPherson, 2016). One of the known benefits of GI is to manage the quantity of surface (also known as stormwater) runoff, by reducing the volume and velocity of water runoff on impervious surfaces. Stormwater runoff has traditionally been managed using conventional engineering solutions, which use piped drainage to collect and convey stormwater to treatment facilities (Berland *et al.*, 2017). However, with the increased awareness of environmental sustainability, this grey infrastructure has been augmented (and in some cases replaced) by the application of GI, that constitutes a 'more sustainable' stormwater runoff management approach compared to the conventional 'grey infrastructure' with its dependence on pipes and sewers (Stovin *et al*., 2012).

Interest in GI has risen in the past three decades. In 1994, the Florida Greenway Commission described GI as a new way of conserving the built environment and believed its approach of integrating natural systems should be of the same level of importance as the conventional grey infrastructure in managing and conserving the built environment (Rouse *et al*., 2013). The perceived broad range and multi-functional capabilities and benefits of GI are becoming widely understood and have created greater awareness especially to those involved in the environmental industry. In today's built environment, the roles of landscape practitioners / landscape architects are not only to design green space and provide aesthetic resource to a place, but also to protect and manage the natural environment, and improve the quality of life for people and other living things (Rouse *et al.*, 2013).

Figure 1. 2: Benefits of green infrastructures associated with the environment, social and economic aspects (Forest Research, 2010; US EPA, 2018).

1.7 Sustainable drainage systems (SuDS)

Sustainable drainage systems (SuDS) are a part of the GI strategy to sustainably manage stormwater runoff (see Figure 1.3), especially in urban areas where runoff is mostly managed by conventional pipe drainage (Stovin *et al.*, 2012). SuDS design addresses four requirements; i) to control the quantity of runoff; ii) to manage the quality of runoff; iii) to create amenity spaces for people; and iv) to increase biodiversity (Woods-Ballard *et al.*, 2015). Some examples of SuDS include green roofs, rain gardens, pervious pavements, swales, and in some cases just planting trees, because trees help to capture and release rainwater back into the atmosphere

(Woods-Ballard *et al.*, 2015). The effectiveness of SuDS in reducing urban runoff and risks of urban flooding are dependent on various factors. This mainly includes rainfall characteristics, SuDS design (e.g. size and storage capacities, designs, structures and properties), vegetation types and also local infiltration rates (Chapman and Horner, 2010; Qin *et al.*, 2013). However, assessments of the potential of GI as a stormwater management strategy, or SuDS, have been largely focused on infiltration based solutions such as green roofs, rain gardens, bioswales and permeable pavements (Berland *et al.*, 2017). For example, studies on the effectiveness of runoff reduction by green roofs, compared to the conventional 'grey' roof found that green roofs are capable of eliminating between 50 to 70% of annual runoffs (Dietz, 2007; Stovin *et al.*, 2012), and they can also delay and prolong the runoff from roofs by reducing its peak rate by 30 to 78% (Alfredo *et al.*, 2010, cited in Stovin *et al.*, 2015). Permeable pavement was also found to reduce runoff from the impermeable surfaces of a car park by more than 70% (Abbott and Comino-Mateos, 2003). Moreover, although Armson *et al.*, (2013) suggested that the presence of vegetation (i.e. grass and a tree) effectively reduced a large amount of surface runoff (60% for the tree and up to 99% for grass) compared to surface with no plants (asphalt), the reduction by the tree was not solely due to canopy interception, but also in conjunction with infiltration through the soil system. However, according to Kemp *et al.*, (2019) soils or substrates of these types of infrastructures usually have a finite storage capacity, in which it can retain a maximum amount of water during a rainfall event - any more water added will become runoff (Sims *et al.*, 2016).

The roles of vegetation as part of SuDS to solely and significantly reduce the impact of stormwater runoff have not been widely emphasized. Kemp *et al.* (2019) noted that in circumstances where rainfall occurrences are very close together and there is not enough time for soil moisture storage capacity to recharge via drainage, evaporation and evapotranspiration (ET), canopy interception may be the sole retention mechanism. This is because vegetation can help retain and detain rainwater in its canopy (hence slowing the process of water reaching the ground), therefore, functional canopy characteristics are important to help manage and reduce stormwater runoff more effectively.

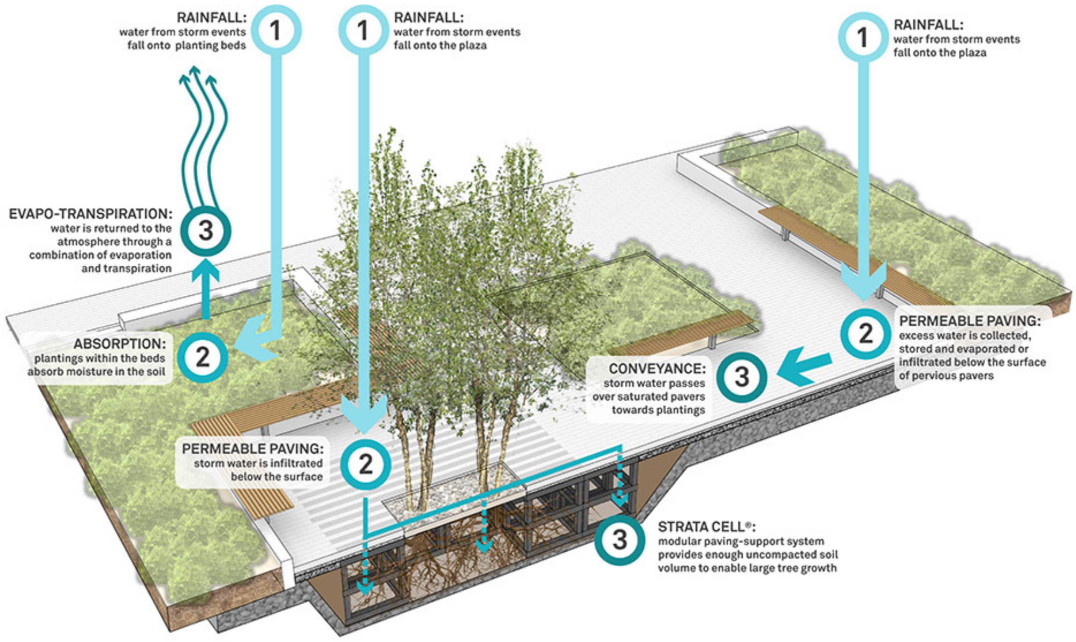


Figure 1. 3: An example of SuDS design that consists of different elements that help reduce stormwater runoff (Image source: Ulam, 2014).

1.8 Importance of vegetation in stormwater management

Vegetation is widely considered an essential element in urban areas. Vegetation plays a vital role in helping to infiltrate, redistribute, store and manage runoff flows (Berland *et al.*, 2017), however, its effectiveness in practice depends on various factors. Vegetation can help reduce runoff rates and volume by rainfall capture (interception), retention, detention and evapotranspiration (ET) from the urban hydrologic cycle, by providing relatively dense vegetation in a small footprint with extensive canopies and subsurface root systems that can capture and 'pump' water back to the atmosphere (Berland *et al.*, 2017). Vegetation can control stormwater at the source of formation, i.e. before the water reaches the ground and runs along pavements and streets (Xiao and McPherson, 2016). In general, vegetation captures rainwater in their canopies and retains a portion of this water while the rest falls onto the ground. The amount of rainwater captured in the plant's canopy is however, dependent upon the vegetation type and varies according to plant characteristics and retaining capacity (Nagase and Dunnett, 2012; Cameron and Blanuša, 2016; Holder and Gibbes, 2017).

The importance of urban vegetation in mitigating surface runoff has been widely studied. Different plant types respond differently, whether physically, physiologically or ecologically to precipitation (Wang *et al.*, 2015a; Klamerus-iwan and Błon, 2018). Leaf types (size, form and texture), canopy architecture, branch textures and root density all influence moisture retention, storage and subsequent ET from the plant into the atmosphere. It is generally understood that interception of rainfall and ET is influenced by the degree of vegetative cover (i.e. leaf area index). Hence, previous studies have highlighted that interception by trees is greater than that of groundcover or low-growing plants (Clark, 1940), therefore previous studies have mainly focused on the effectiveness of vegetation in a community or large scale planting (i.e. forests). However, it is also critical to note the importance of smaller scale plantings, which have not been widely documented. These include the roles of individual plant species or groundcover plants such as shrubs (herbaceous and ornamentals), crops and grasses.

1.8.1 Roles of groundcover vegetation / small-scale green infrastructure

As the hydrological performances of large-scale vegetation such as forests, urban trees, agricultural crops and grassland are better understood, there is still a lack of research on the roles of smaller plants (i.e. herbaceous and shrub vegetation) (Sikorska *et al.*, 2017). Groundcover plants generally refer to low-growing vegetation cover, that helps to inhibit weed germination, while providing ornamental quality to the landscape. While interception by larger-scale vegetation such as forests and even individual trees is perceived to be significantly greater than that of smaller plants, the lack of interest is attributed to the fact that smaller plants are perceived to intercept and store less moisture, due to their overall lower surface areas exposed to rainfall (Clark, 1940; Tromble, 1983). Similarly, evapotranspiration (ET) is also understood to be higher by forests compared to smaller vegetation (e.g. grass), due to the capacity of forests to intercept higher amounts of rainfall (Tobón Marin *et al.*, 2000).

However, this assumes that at the landscape scale, such plants would work at an individual level, whereas in reality, their functions would often be in a group or community. Thus, it is arguable that small-scale plants are of no less value in helping to alleviate urban drainage problems, as these smaller plants may be used more commonly in SuDS approaches, especially in the limited or confined spaces available within highly densified urban areas, e.g. city centres (Woods-Ballard *et al.*, 2015). The wide range of genotypes that constitute 'smaller plants' means that shrubs and other groundcover ornamentals can be specifically selected due to their abilities to intercept and store runoff. In addition, smaller plantings can be designed in a more flexible manner, fitting into areas of restricted space, or used to ‘soften’ areas of pavement or other hard standings. They can be a component or link into other green infrastructure interventions (Woods-Ballard *et al.*, 2015) such as rain gardens, green roofs, stormwater planters or stormwater curbs (Figure 1.4). A number of these small-scale typologies can be specifically designed to capture and reduce stormwater runoff on impervious surfaces in urban areas. These systems are likely to use small-scale plantings because they are more flexible in location and range of designs, thus can be modified to fit most urban physical settings compared to trees (Yuan, 2016; Fairbrass *et al.*, 2018).

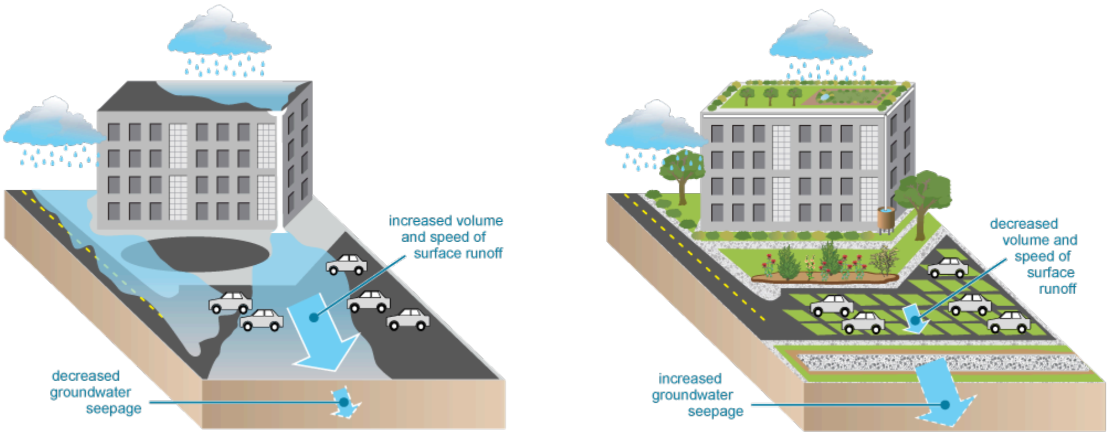


Figure 1. 4: Green infrastructures that can be implemented in various forms and scales helps control surface runoff by decreasing its volume and runoff velocity from its source (rainfall) (Image source: Georgetown Climate Centre, n.d.).

1.9 Hydrological processes within vegetation

In general, the relationships between rainfall and plants are correlated significantly with the plant’s physiological, ecological and hydrological factors (Tobon Marin *et al.*, 2000; Iida *et al.*, 2005). During a rainfall event, raindrops that fall onto a plant are either intercepted by the canopy, or splash off the foliage and branches and run off onto the ground. Water that does not reach the soil surface may either be held on the surface of leaves and branches and eventually evaporate into the atmosphere, or can be absorbed across the leaf cuticle to the internal organs of the plant (as leaf water uptake, although this tends to be minimal) (Liang *et al.*, 2009). Water that is absorbed into the leaf cells or enters plants through their roots is also subsequently lost through the transpiration stream, as plants open their stomata to allow photosynthesis to take place (Liang *et al.*, 2009). Water that reaches the soil may run off across the ground surface, or infiltrate through fissures and pores and disperse through the soil (Herwitz, 1987). The surplus of the infiltrated water will percolate through the root zone and continue towards the water table until it reaches bedrock and replenishes ground water aquifers (Freeze and Cherry, 1979). Water that is held on the surface or within the soil can be lost back to the atmosphere through evaporation.

1.10 Canopy interception

Rainfall that falls onto a plant is partitioned into three processes; canopy interception, stemflow and throughfall (canopy dripping) (Rutter *et al.*, 1975; Iida *et al.*, 2005; Guevara-Escobar *et al.*, 2007; Xiao and McPherson, 2011) (Figure 1.5). In general, canopy interception refers to a fraction of precipitation that hits the plant surface, and interception loss is the fraction that is retained within the vegetation and does not reach the soil surface. Rainfall interception by plant canopy is considered one of the most important hydrologic processes. This is because it controls rainwater from its source (rainfall), and it affects the rate, depth and spatial distribution of water that is made available for other processes such as transpiration by the plant, evaporation from plant and soil surfaces, or even both (ET) (Gómez *et al.*, 2001). Canopy interception also accounts for the largest portion of rainfall partitioning amongst stemflow and throughfall (Guevara-Escobar *et al.*, 2007). According to Carlyle-Moses and Gash (2011), canopy interception, or interception losses (retention) can account for up to 50% of gross annual precipitation, and are determined by various hydrological and ecological factors. Interception is strongly driven by three main categorical variables; rainfall magnitudes and patterns, vegetation types and characteristics and also meteorological factors (Li *et al.*, 2016).

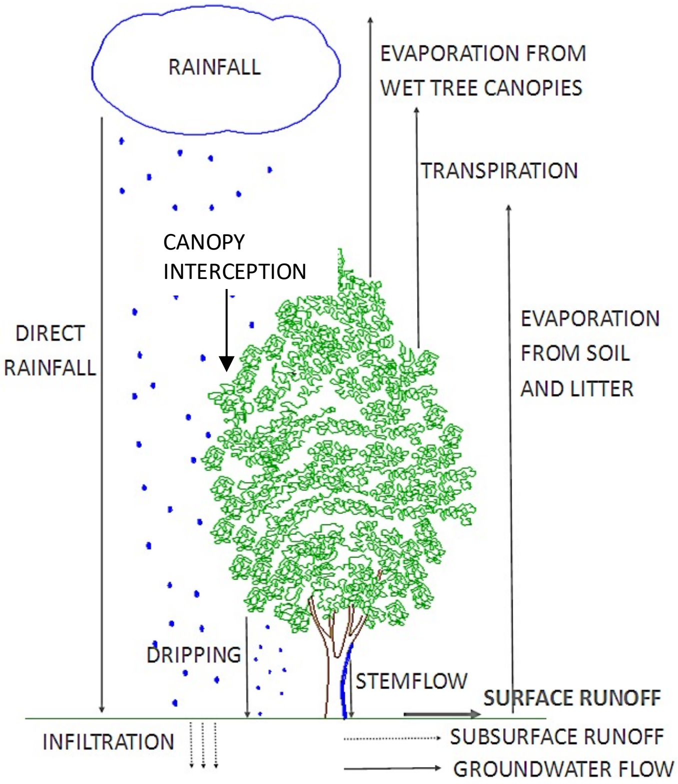


Figure 1. 5: Rainfall partitioning by a tree (Image source: Zabret and Šraj (2015)).

As mentioned above, interception studies on smaller plants are less documented compared to larger scale vegetation such as trees and forests. However, one of the few studies available on interception by shrubs or smaller vegetation indicated that shrubs species (*Diospyrus texana*, *Acacia farnesiana* and *Prosopis laevigata*) can intercept and retain between 21.7 to 62.1% of gross rainfall, in a semi-arid environment (Návar and Bryan, 1990). Similar findings by Domingo *et al.* (1998) found interception to be between 21% (*Retama sphaerocarpa*) and 40% (*Anthyllis cytisoides*) of gross rainfall. Zhang *et al.* (2009) also found interception losses by *Artemisia ordosica Krasch*. to be 15%, and by *Caragana korshinskii Kom* to be 27% of gross rainfall. The variation in these retention percentages might have been due to different experimental approaches, climatic and site conditions, geographical factors, different rainfall characteristics and more importantly the variation in plant species that were investigated.

Some morphology studies looked at water retention capabilities of smaller plants in the context of green roofs; mainly extensive green roofs. A recent study by Kemp *et al*. (2019) observed the relationship between canopy properties (e.g. density, small leaf size, hairiness) and retention capacity, and found that broad-leaved species *Stachys byzantine* and *Salvia officinalis* could retain 72.9% and 63.6% of the applied simulated rainfall (9.3 mm) respectively. Nagase and Dunnett (2012) found grass species (e.g. *Anthoxanthum odoratum*) to have higher retention capabilities, followed by forbs (non-grass herbaceous flowering plants) and *Sedum*. Similar findings were found by Lundholm *et al.* (2010), where grass species had higher moisture retention, followed by forbs and succulents. MacIvor and Lundholm (2011) found monoculture graminoids can retain up to 75% of simulated rainfall (10 mm) and outperformed other plants such as tall, creeping forbs and creeping shrubs. Fern was found to retain the highest amount of water in a tropical climate, followed by herbs, *Sedum* and grass (Krishnan and Ahmad, 2014) in a green roof context. A study by Yuan *et al.* (2017) looked at retention by rain gardens and found forb perennials and mown grasses to retain between 14.6 mm and 16.8 mm (66 – 76%); other rain garden studies were more focused on infiltration performance for stormwater control.

Most of the studies on rainfall interception by smaller vegetation are focused around semi-arid landscape and green roof plants. Arid plants have different ecological and physiological functions to those of urban plants, in that semi-arid species may have higher interception and retention capabilities as well as better water use compared to urban vegetation (Su *et al.*, 2016). In terms of studies on green roof plants, due to the limitations of extensive green roof to cater for load weight, most of these studies only looked at retention by grass, graminoids, forbs, and *Sedum*; less focus is given on different shrubs and sub-shrub species, which is the structural focus of this study as they could be implemented in wider range of urban planting designs and SuDS. Thus, there is still a paucity of information in the available literature on the roles of different leaf morphology and characteristics, and how these may influence the hydrological performance under different environmental and moisture conditions. Hence, the opportunity to explore interception and retention, as well as ET performances by groundcover urban vegetation for the application of SuDS in an urban context, is relevant.

1.10.1 Rainfall characteristics and raindrop size

Rainfall characteristics (e.g. intensity, frequency and duration), raindrop characteristics (e.g. size, volume and angle) and also spatial distribution of rainfall play an important role in affecting rainfall redistribution and partitioning onto plants (Hall and Calder, 1993; Li *et al.*, 2016). As a raindrop falls onto a vegetated area, the first surface that it will encounter is the crown or canopy of the plant. Upon reaching the surface of a leaf, the behaviour of the raindrop may vary depending on its size, terminal velocity and how it interacts with the leaf characteristics (i.e. leaf angle and orientation, texture, pliability and size) (Herwitz, 1987).

Hall and Calder (1993) implied that rainfall interception by the canopy depends on the volume of the initial raindrop and the number of secondary droplets formed after these rebounds, or splash off the leaf surface. The secondary droplets usually tend to be smaller than the initial droplet and will often land on the lower layer of leaves. A number of authors indicated that canopy interception increases as raindrop size and rainfall intensity decrease (Calder *et al.*, 1996; Calder, 1999; Wang *et al.*, 2007). This re-enforces earlier studies by Clark (1940), who suggested that canopy interception can approach 90% for light rainfall (lower intensity and depth), but is nearer an average of 25% for heavy rainfall events. These findings were supported by a number of other studies that found interception losses were most effective when rainfalls were of lower intensity (Navar *et al.*, 1999; Gómez *et al.*, 2001; Holman-dodds *et al.*, 2003; Carlyle-Moses, 2004; Owens *et al.*, 2006; Hood *et al.*, 2007; Xiao and McPherson, 2011; 2016), with different findings between shorter duration but more frequent events or longer duration.

A study by Gómez *et al.* (2001) reported that interception by olive trees were as high as 85% for light rainfall events (lower depth of rain) and decreased exponentially as rainfall depth increased. Owens *et al.* (2006) found interception under low intensity rainfall to be more than 60% of rainfall, compared to the 20% under higher intensity rainfall. He attributed this to the understanding thay smaller rainfall events typically do not produce stemflow, therefore most of the intercepted water remains in the canopy until it is lost via ET. However, while much literature found interception losses to be higher with smaller ‘sized’ (and intensity) rainfall, the effects of rainfall intensities on canopy interception may still have conflicting findings. Aston (1979) and Keim *et al.*, (2006) found that interception and plant storage capacity increased with increased rainfall intensity, and noted that storage capacity is filled faster during high instensity rainfall than low intensity rainfall.

Nonetheless, the interaction between interceptions with regards to rainfall intensities is not the main focus of this research. The point is made that GI / SuDS typology may interact with different rainfall characteristics, and that optimum design and plant choice may vary depending on the type of rainfall encountered.

1.10.2 Antecedent conditions

Canopy interception and retention is influenced by the capacity of the plant canopy to retain rainwater, which is indirectly a function of ET. Antecedent conditions of both climate (dry or wet antecedent days) and moisture conditions (in which both of these are interrelated) influence interception and retention by the plant and soil. Sims *et al.* (2016) indicated that the antecedent moisture conditions at the beginning of rainfall govern retention capacity, as this is when high storage capacity is obtained. Xiao *et al.* (2000) also reported that retention is higher during the beginning stages of rainfall, and decreases during the later stage as plant's moisture storage capacity becomes saturated. However, this also depends on the duration of antecedent dry days. The antecedent dry weather period greatly controls the amount of moisture that is evapotranspired, therefore restoring the moisture storage capacity within the plant and the soil system (Voyde *et al.*, 2010b; Stovin *et al.*, 2015). Therefore, the longer the antecedent dry days (as more ET takes place), the greater the retention opportunities; such was observed by Yuan *et al.* (2017).

1.10.3 Vegetation type and plant characteristics

Plant type and particularly its eco-physiology (how it performs, evolves and adapts to its natural environment) and eco-hydrology are keys to determining efficient water capture and water use (EWU). Plants tend to 'adapt' or make physiological adjustments based on their nature of origin (Körner, 2016; Su *et al.*, 2016). For example, plants in deserts and arid zones may be dependent on very infrequent rainfall or need to harvest moisture from maritime fog (moisture derived from the ocean and blown inland, and being 'harvested' by the plant as dew, adhering to fine hairs on the plant) (Katata *et al.*, 2010; Aparecido *et al.*, 2017). Alpine plants that typically grow in rocky, elevated regions or around mountains, may have needle-leaved conifers that are not only frequently exposed to colder (boreal) climate with high winds and snow or frost, but also with typically high light levels (Körner and Diemer, 1987). These types of plants usually encounter extreme climatic situations; therefore, are more easily adapted to high amount of moisture while some can also survive in drought. In contrast, in tropical regions, where the climate is humid with high summer rainfall, broad-leaved trees are more adapted to well-moistured conditions (in the soil and in the atmosphere due to high humidity). These types of plants can withstand warm temperature of the tropics; due to high rainfall regimes in such regions, they can also adapt well to having frequent wet leaves (Aparecido *et al.*, 2017). Therefore, in terms of leaf morphology and based on their eco-hydrology, it is hypothesized that needle-leaved species are able to withstand more extreme water conditions such as water-logging or drought stress compared to broad-leaved species, while broad-leaved species may be able to evapotranspire more efficiently, given ample moisture supplies. This is because broad-leaved species are accustomed to higher temperature, therefore tending to 'pump' out its moisture (via ET) more effectively.

A number of researchers have reviewed and suggested that factors such as leaf type (size, shape, texture, orientation and surface area value), leaf and branch pliability, stem and branch inclination, as well as the overall vegetation structure and plant growth development, all affect the influence of water movement within / across a plant (Herwitz, 1987; Watanabe and Mizutani, 1996; Domingo *et al.*, 1998). The roles of leaf morphology, especially the contrasting traits of broad-leaved trees and coniferous (needle-leaved) trees on rainfall interception have gained interest in previous research. However, as previously mentioned, more attention was given to larger scale planting, namely forests.

It was generally found that trees with needle-like leaves (i.e. conifers) are more effective at rainfall interception than trees with broad leaves (Clark, 1940; Xiao *et al.*, 2000; Wang *et al.*, 2007; Carlyle-Moses and Gash, 2011; Li *et al.*, 2016). Calder (1999) associated this with the predominant climatic conditions both types were found in. Higher interception losses by conifers are due to the typical small raindrop size and low rainfall intensities experienced in temperate regions, compared to smaller interception by broad-leaves, which are associated with higher intensity rainfall and larger sized droplets of sub-tropical regions (Calder, 1999; Wang *et al.*, 2007). However, the complexity in leaf morphology and physiology are also contributing factors in this finding. For example, Carlyle-Moses and Gash (2011) found interception by coniferous forest to be between 18 and 45% of total precipitation compared to 18 to 29% of broad-leaved deciduous forest, though these numbers depend on the stand characteristics. These differences are attributed to conifers having larger leaf surface area, tighter crown shape and more overlapping leaves, therefore greater storage capacities than broadleaf trees (Xiao *et al.*, 2000; Li *et al.*, 2016). Needle-leaved species also tend to have greater variety of leaf angles and more overlapping branches and foliage, resulting in denser crowns, thereby increasing the storage capacities and chances of higher water interception; whereas most broad-leaved species have smoother leaf surfaces and more open canopies with lower leaf densities, and tend to shed raindrops immediately (Clark, 1940; Li *et al.*, 2016).

1.10.4 Water storage capacity in leaves

A small amount of water that is absorbed into the pores in the epidermis of the leaf is held temporarily within the intercellular spaces of the leaf (Figure 1.6), which act as moisture storage areas in plant leaves (Liang *et al.*, 2009). The water is either stored in the spaces between cells and / or also absorbed into cells (leaf vacuole). The moisture storage capacity of the plant will eventually be saturated, after which no more water can then be taken in (Liang *et al.*, 2009). On the other hand, water can also be retained (or detained) on the external leaf surface that can be lost through drainage (water droplets drip off the canopy and leaf tips) or evaporation from the leaf surface. Some studies found that between 10 and 70% of the intercepted water can be lost through drainage after the cessation of rainfall, due to the saturation of moisture storage in the leaves and crown (Rutter *et al.*, 1971; Pitman, 1989; Li *et al.*, 2016). The duration for plants to reach their maximum storage capacity was found to be influenced by rainfall (e.g. intensity and duration) and plant characteristics (e.g. leaf area index, leaf wettability, leaf morphology) (Herwitz, 1987; Gómez *et al.*, 2001; Kume *et al.*, 2008; Li *et al.*, 2016; Xiao and McPherson, 2016; Klamerus-iwan and Błon, 2018). Li *et al.* (2016) found interception was more than 50% in the first minute of rainfall. This was mainly due to the relatively dry crown (i.e. larger storage capacity), and after 10 minutes of rain, interception significantly decreased to less than 9% as the leaves become saturated (Li *et al.*, 2016).

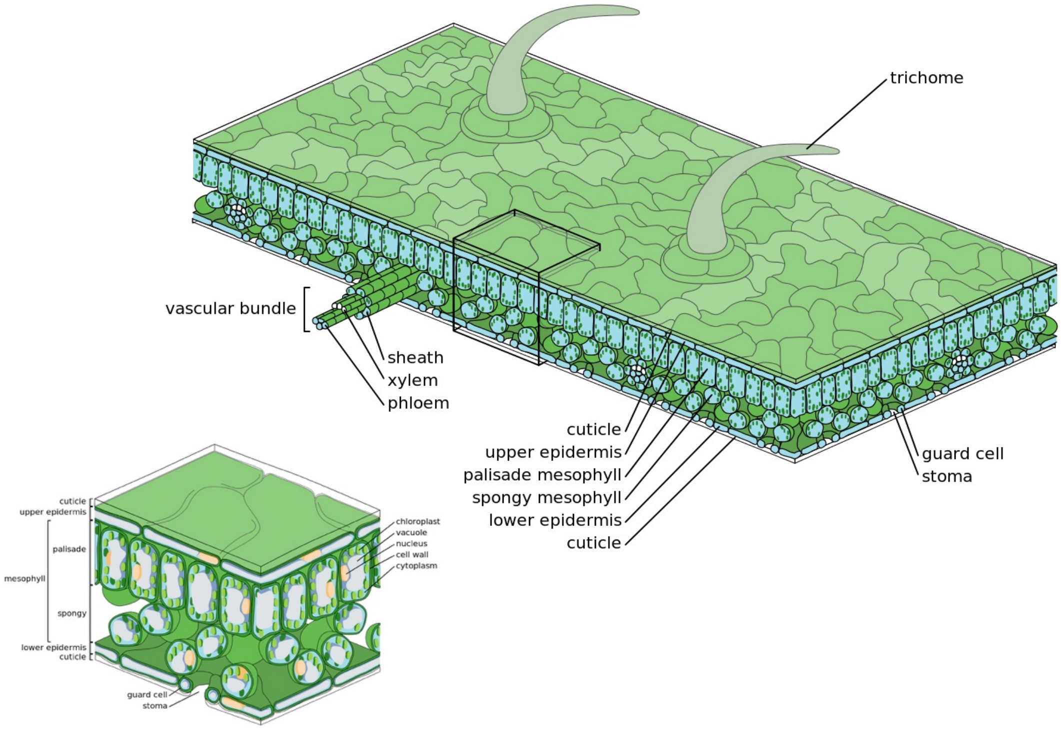


Figure 1. 6: Internal structure of a leaf (Image source: Siyavula, n.d.).

1.10.5 Leaf wetness traits

Traits that influence moisture retention and movement on a leaf can help identify a particular plant species' ability to retain or repel water droplets on leaf surfaces. Natural leaf wetness is caused by precipitation (rain and snow), fog, dew or mist (Wang *et al*., 2015a). Due to heterogeneity of plants and leaves, different species possess different leaf surface characteristics; some are hydrophilic, others have hydrophobic traits. Hydrophobic leaves will repel water and form an ephemeral film, which will eventually retract into small droplets (coalesce into spherical-shaped droplets on the leaf surfaces) and flow along or merge with other previously detained water to form larger droplets (Herwitz, 1987; Sikorska *et al.*, 2017). These droplets will either roll off the leaf surface, or be retained on the surfaces depending on the leaf shape and inclination (Matos and Rosado, 2016). Hydrophilic leaves on the other hand, retain water droplets, or form films of water that are flattened on their surface.

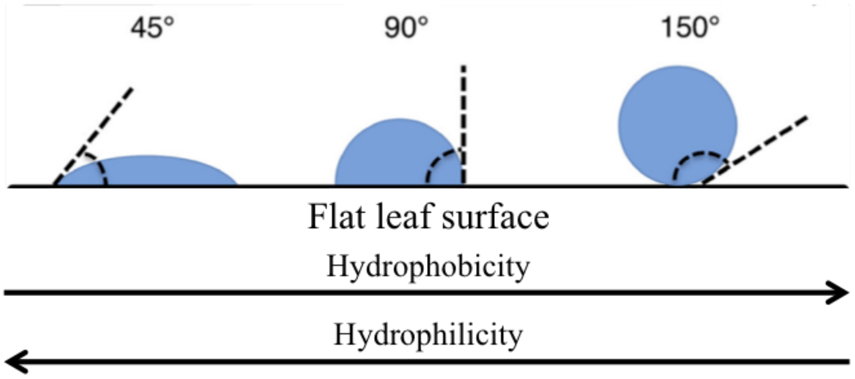


Figure 1. 7: Droplet contact angle of hydrophobic and hydrophilic leaf surfaces; low contact angle represents hydrophilic leaf surface. As contact angle increase, leaf hydrophobicity also increase (Image source: Goldsmith *et al.*, 2017, adapted from Aryal and Neuner, 2010).

Leaf wettability can be determined by measuring the contact angle of water droplet on the leaf surfaces (Figure 1.7) (Sikorska *et al.*, 2017). The physical and chemical properties of a plant species affect their contact angles. The contact angles may also differ between the abaxial and adaxial surfaces as for some species, the hydrophobicity traits between the abaxial and adaxial surfaces vary significantly, which in turn may affect moisture retention on these surfaces (Holder and Gibbes, 2017). Leaf wettability is composed of various characteristics. These include the number, size and pattern of trichomes, stomatal density, epidermal wax layers, and also the shape of epidermal cells (Wang *et al.*, 2015a). Trichomes are outgrowths from the plant epidermis, also known as leaf hairs or leaf pubescence on the plant surface, which increases the roughness / hydrophobicity of the leaf. The presence of either trichomes or wax crystals increases leaf roughness (due to the hydrophobic compounds that they contain), therefore tends to retain less moisture compared to leaves with wax films or glabrous leaves (Wang *et al.*, 2015a). The higher the trichome density, the higher contact angle (higher hydrophobicity), as droplets are held above the trichomes instead of touching and being retained directly on the leaf surface (Brewer and Smith, 1997; Wang *et al.*, 2015a) (refer to Figure 1.8).

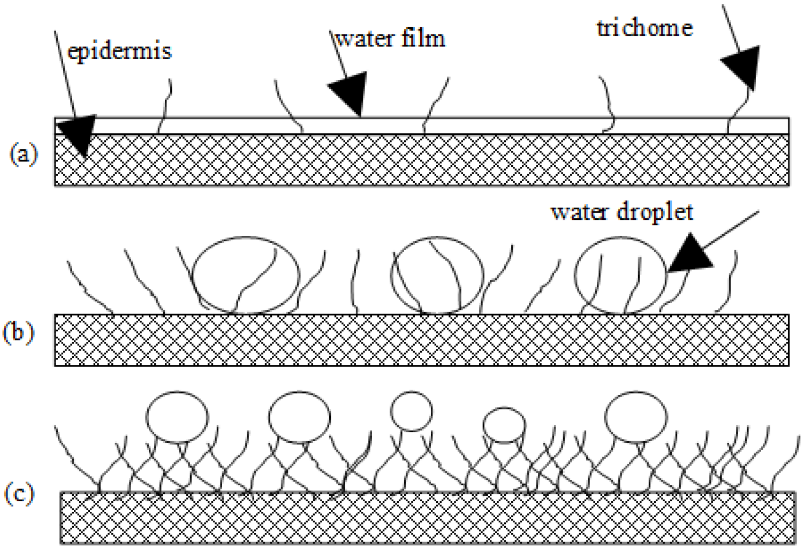


Figure 1. 8: Relationship between different density of trichomes and water droplets; denser trichomes result in higher hydrophobicity therefore higher droplet contact angle (Image source: Wang *et al.*, 2015a).

Epidermal wax is a waxy layer that covers leaf surfaces. These are either thin wax film or highly crystalline epicuticular wax (wax crystals) that determines hydrophobicity and hydrophilicity of leaves (Wang *et al*., 2015a). Similar to trichomes, the presence of epidermal wax result in hydrophobicity of a leaf; the more wax content, the higher the contact angle, although Wang *et al*. (2015a) indicated that the angle of the droplet is dependent on the complexity of the wax rather than just the content or amount. Goldsmith *et al.* (2017) justified an interesting point, that the presence of leaf wax quantity and leaf cuticle properties are influenced by the plant's interactions with the environment; leaves from a tropical rainforest environment may have less leaf wax as a result of being eroded by high amounts of precipitation in tropical regions. This results in a smoother leaf surface, thereby decreasing the hydrophobicity compound. This means that leaves that are subject to dry environments experience less leaf wax erosion, and therefore have higher hydrophobicity characteristics (Goldsmith *et al.*, 2017).

1.10.6 Leaf surface area

According to Aston (1979), moisture storage capacity in plants accounts for the most important parameter in influencing rainfall interception, while Keim *et al.* (2006) indicated leaf area to be the best predictor of moisture storage capacity. Furthermore, Klaassen *et al.* (1996) found high retention capabilities by tree crowns to be associated with higher leaf area index (LAI). Leaf surface areas are dependent upon age, species, growing conditions etc., however, in theory, the more leaves that are present on a plant, the higher the overall leaf surface area of the plant. The comparisons of leaf area between different leaf characteristics (needle-leaved vs. broad-leaved) have been previously studied, where many researchers generally agree that conifers or needle-leaved species tends to have higher total leaf area, mainly due to higher number of leaves compared to broad-leaved species; hence are often associated with higher interception and more moisture storage capacity (Aston, 1979; Keim *et al.*, 2006; Li *et al.*, 2016). However, this is assuming interception on a per leaf area unit, per plant, where needle-leaved trees are often associated with higher moisture storage capacity due to having higher LAI. In general theory, broad-leaved trees may actually have larger surface area (wider in diameter), and larger individual leaf area due to its broad leaf surface. Therefore, the effectiveness of interception and retention by these two contrasting leaf characteristics on an individual leaf basis would probably offer different results, which is explored in this research.

1.10.7 Crown structure and vegetation arrangement

Crown structural features, size and density are factors that help determine the amount of moisture captured and retained within a tree. According to Monson *et al.* (1992), crown architecture of different species are structured in ways that result in significant differences in the amounts of moisture retention. Monson *et al.* (1992) also indicated that the larger the crown, the more water the plant would hold. This is because leaf dry mass accounts for the most important variable in the retention of water in the crown, and that a crown’s surface area and the distribution of leaves and sizes (small leaves or leaflets) effectively determines rainfall capture (Monson *et al.*, 1992). Domingo *et al.* (1998) attributed differences in interception due to differences in canopy structures between two shrub species to be influenced by canopy drainage rates and boundary layer conductance. He concluded that plants with denser canopies with more overlapping leaves may have lower drainage rates than plants with more open canopies and sparse leaves. As for canopy boundary layer conductance, Domingo *et al.* (1998) found that plants with open canopies allow for better wind penetration through the canopy, which resulted in higher evaporation rates from leaf / branch surfaces. The wind effect may also result in movement of leaves that causes water droplets on leaves to drip off, resulting in less water retention. Gómez *et al.* (2001) implied that the arrangement of trees and density of tree stands have significantly affected water capture, and found interception was 7% of annual rainfall for sparsely arranged trees but increased to 25% for trees that were densely arranged. He concluded that this was the effect of the high-density plantings, which increases water demands due to higher interception losses.

1.11 Moisture loss / evapotranspiration from plants and soil

The importance of vegetation for SuDS does not only depend on the plants' capacity to intercept and retain rainwater, as moisture storage capacity of plant canopies *per se*, may be small compared to moisture storage capacity of soil. However, plants have the ability to regenerate the retention capacity via evapotranspiration (ET) and transpiration, and these processes therefore affect the response of SuDS to subsequent rainfall events (Poë *et al.*, 2015). The antecedent moisture content (water availability) in the plant and soil before a rainfall occurrence strongly influences the rate and capacity of a plant to capture and retain rainwater. This is controlled by transpiration by plant and evaporation by soil surface, or the combination of both processes (evapotranspiration (ET)), in which these processes together with drainage recharges the water storage capacity during dry periods (Voyde *et al.*, 2010a; Berretta *et al.*, 2014). Zhang *et al.* (2016) estimated that a large amount of global ET is due to transpiration by vegetation (65%), whereas 25% is due to evaporation from the soil and 10% by vaporization of intercepted rainfall from vegetation. Therefore, the abilities of different plants to transpire under different environmental conditions, and whether leaf morphological traits affect moisture loss rates, would be an interesting observation. This could identify which plant type would be more effective at recharging moisture storage capacity, thereby helping to reduce runoff volumes by increasing the storage capacity for higher retention.

Depending on the plant's physiological attributes, some plants have deeper roots that can access water that is deeper in the soil horizon. A study by Domingo *et al.* (1999) found shrub species (*Retama sphaerocarpa*) to have higher ET (ca. 76 mm) than the volume of rainfall that was recorded. He attributed this to the plant's ability to access water from sources (via roots) other than the rainfall. Wang *et al.* (2012) implied that moisture loss via transpiration is usually higher by taller plants with deeper root systems (e.g. woody plants) than evaporation by soil. This is due to constant water uptake by the plant for daily usage, which therefore emphasizes the importance of vegetation in ET, as plants constantly transpire moisture in order to grow (photosynthesize). Factors leading to higher ET are often associated with higher leaf area index, larger crown cover and deeper roots (which are all attributes of larger vegetation, i.e. trees), however, smaller plants / groundcover plants can also be beneficial in that they shade the soil less, therefore the soil under smaller plants is more exposed to direct solar radiation, inducing higher evaporation rates from the soil (Wang *et al.*, 2012).

Some previous studies of ET by smaller vegetation indicated that mean daily ET can account for up to 12.36 mm d^{-1} (*Stachys byzantine*) during conditions of high available moisture (and decreased in ET rate as moisture content decreased) (Kemp *et al.*, 2019). Meadow flowers had daily ET rate of 2.7 mm d^{-1} compared to *Sedum* with 2.4 mm d^{-1} during summer periods, with relatively lower values in spring (Poë *et al.*, 2015). Wang *et al.* (2012) found daily ET by a sub-shrub site (*Artemisia scoparia*) ranged from 0.7 mm d^{-1} to 2.6 mm d^{-1}, which was higher than those in forest and shrub sites (daily ET rates of 1.7 mm d^{-1} and 1.8 mm d^{-1} respectively). Gao *et al.* (2016) observed the highest daily ET rate of a xerophyte shrubs to be 3.76 mm d^{-1}, with mean daily ET of 0.59 mm d^{-1}. Similar to studies on interception, these studies are also more focused on ET performance of arid / semi-arid plant species or green roof plants, which often uses xerophytes or CAM plants (Crassulacean Acid Metabolism) due to their drought tolerance characteristics. The extent of ET by herbaceous and groundcover urban plants, and the influence of different morphological traits on ET is still unclear.

Moisture loss via ET is promoted by microclimatic factors, namely high temperatures, solar irradiance, low humidity and higher wind velocity (Gerosa *et al.*, 2012; Duffková, 2013; Poë *et al.*, 2015). Positive soil water potentials (moist soil rather than dry soil) also significantly affect ET rate (Poë *et al.*, 2015; Kemp *et al.*, 2019), while plant leaf characteristics such as leaf surface areas and well-distributed leaves within the canopy allows sunlight in and air movement over them (Domingo *et al.*, 1998), thereby affecting the rates of ET. Most moisture is lost through the plant stomata and their capacity to transpire is also affected by hormonal and hydraulic signals within the plant (Giorio *et al.*, 1999; Christmann *et al.*, 2007; Araújo *et al.*, 2011). Background concentration of CO_2 may also influence stomatal aperture (Coupel-Ledru *et al.*, 2016). These factors though, vary with species and their strategies to deal with moisture deficits and surpluses.

1.11.1 Plant characteristics

The heterogeneity of plants is important as a plant's physical and physiological attributes function differently according to the plant's needs. Evapotranspiration accounts for vaporized water of the retained rainfall from plant canopies and soil surface, and also transpiration, which is the capacity of plants to replenish the leaf tissues with water from the roots, which moves through the xylem (Gerosa *et al.*, 2012) (Figure 1.9). However, the capacity of plants to evapotranspire and rates depend on the plant species, and the way they use moisture and regulate their stomata. Even in the same location under the same meteorological conditions, ET rates may present high spatial variability due to different functions of vegetation and land covers (Liu *et al.*, 2010).

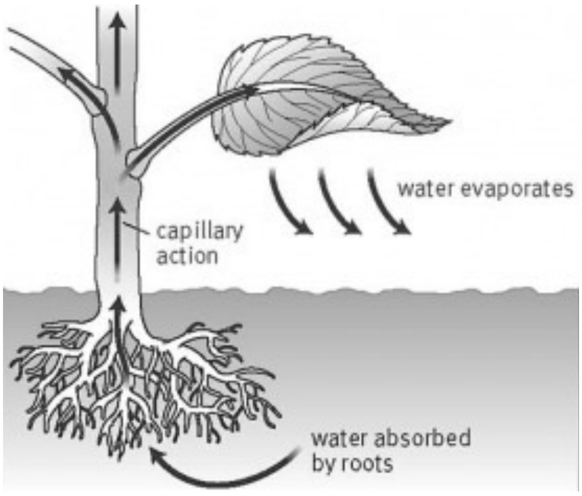


Figure 1. 9: The process of transpiration by a plant (Image source: Morales, 2018).

Factors such as leaf area, number of leaves, plant surface reflectivity and the overall vegetative cover also affect the rate of ET as they do interception losses. In terms of the morphological traits of leaf and canopy types, researchers have encountered conflicting findings as to which type of leaf characteristics are most effective at evapotranspiring rainwater, thereby affecting runoff volume (Komatsu *et al.*, 2011). Many studies compared the obvious contrasting leaf shape (i.e. needle-leaved conifers and broad-leaved / deciduous species) to identify their effectiveness in ET, although again, most were focused on the larger scale vegetation such as forests. However, the information from this research is still relevant in the context of this study, as the focus of this research aims to observe the effectiveness of leaf traits on the hydrological performance including the capacity of different plants to evapotranspire.

Earlier works found ET rates of coniferous forests to be higher than broad-leaf forests (Swift *et al.*, 1975; Calder *et al.*, 2003; Komatsu *et al.*, 2008). Other studies found conifers to have either similar range or lower ET rates than broadleaf forests (Fahey and Jackson, 1997; Pizarro *et al.*, 2006; Komatsu *et al.*, 2007). Conceptually, higher transpiration by needle-leaved species may be attributed to the general theory of needle-leaved trees being mostly evergreen and remaining physiologically active all year round, while deciduous broad-leaved trees shed their leaves during the colder months and can only actively transpire during midsummer (Givnish, 2002; Rahmat *et al.*, 2019). Coniferous trees also tend to have higher surface area due to greater number of leaves (Xiao *et al.*, 2000; Li *et al.*, 2016). This increases the opportunity for higher rainfall interception, which will then be lost via ET (higher intercepted water result in higher ET rate as more water is available for ET). Furthermore, higher leaf surface area and number of leaves may also result in higher ET due to the presence of more stomata pores.

In contrast, the potential for broad-leaved species to evapotranspire at a higher rate may be attributed to their eco-physiology, in that they are usually adapted to warmer climates (e.g. tropical regions with high summer rainfall) compared to conifers, which are often found at higher latitudes. Therefore, this type of leaf morphology (broad-leaved) may tend to lose their moisture more effectively, due to frequent access to available moisture. Moreover, on a per unit leaf area, broad-leaved species tend to have larger leaf surface area, therefore higher stomatal density (more stomatal pores per leaf) to enhance ET rates (Wang *et al.*, 2015b). The conflicting evidence by previous studies raises the interest of this research to investigate ET performance with regards to different leaf morphology, including needle-leaved species and broad-leaved species of smaller scale plants.

Land use types, arrangements of trees, geography and site location as well as the surrounding environment are also determining factors of ET. Hagishima *et al.* (2007) found trees that are densely planted have significantly lower ET rates than sparsely planted trees. Kjelgren and Montague (1998) found trees that are grown over asphalt or impervious surfaces in urban areas have higher ET rates compared to trees planted over turfgrass. This is because the microclimate tends to be warmer due to heat arising from the hard surfaces, thus driving higher ET rates (Kjelgren and Montague, 1998). Furthermore, grass can technically compete for water with the trees, so as moisture decrease in the soil, the capacity for the tree to maintain high ET is limited by competition.

1.11.2 Stomatal response

Stomata are small pores in the leaf lamina (generally on the underside of the leaves), which function as pathways to allow gas exchange by releasing oxygen that the plant produces, and allowing carbon dioxide (CO_2) in for photosynthesis (Gerosa *et al.*, 2012). Stomata are made from two guard cells, which regulate transpiration through the opening and closing of the stomata (Araûjo *et al.*, 2011), and the patterns (shapes, sizes, numbers and density) in which stomata form differ across plant species (Bertolino *et al.*, 2019). The stomata are the main mechanism that controls the rate and amount of water loss from a leaf's surface (Sterling, 2004; Grant *et al.*, 2010). Stomatal opening and closing are dependent on various factors, including air temperature, radiation, humidity, vapour pressure difference, concentration of CO_2, moisture availability and leaf water potential (Sterling, 2004; Giorio *et al.*, 1999; Lin *et al.*, 2015; Urban *et al.*, 2017). Most plants open their stomata (active stomatal conductance) during the day when heat energy and radiation is higher, but some plants (e.g. CAM plants (Crassulacean Acid Metabolism)) open their stomata at night when the climatic conditions tend to be cooler (Poë *et al.*, 2015). Stomata tends to close during moisture deficit conditions (decreased stomatal conductance), which in turn decreases transpiration rates because there is not enough water to be evaporated (Giorio *et al.*, 1999). The pattern in which the stomata opens and closes and at what point of moisture deficit condition the stomata starts to close depends on the plant species, as affected by the plants being efficient in water use (EWU). For some species, stomatal conductance decreases (stomata closes) during midday corresponding to ambient climate (i.e. temperature and humidity), thereby limiting transpiration during this time (Schulze *et al.*, 1974; Gao *et al.*, 2016). These types of plants are usually associated with drought tolerant species, in that they tend to conserve available moisture by regulating their stomatal conductance (Blanken and Rouse, 1996).

1.11.3 Plant growth stage

Evapotranspiration rate is also affected by the different growth stages of the plants. Realistically, mature plants may evapotranspire more compared to younger plants due to relatively higher number of leaves, larger surface area and thus more stomatal pores for the gas exchange process. This was evident in a study by Grant *et al.* (2010), where ET was lower when plants were younger and smaller in size, and increased as plants became taller and height range was wider. Moreover, mature plants have more established root systems that take up a large portion of water storage in the soil through root suction force (Duffková, 2013). However, on an individual leaf basis, young plants with smaller number of leaves (and smaller leaf size) may evapotranspire more efficiently as they require more resources (for photosynthetic activities) to grow quickly. This research seeks to explore this factor and gain further understanding by investigating ET performance between two different canopy sizes.

1.11.4 Soil characteristics and soil moisture content

As ET accounts for the transpiration from plants and also evaporation from the soil surface, soil properties and characteristics as well as moisture availability in the soil are important determinants of ET. Soil types can be characterized by pore spaces between the soils that are determined by the grain size distribution and structure (Duffková, 2013). This can influence ET rate due to water movement through the pores of the soil. For example, coarse-textured sandy soils are the most porous, and have the most drainable porosity (United States Department of Agriculture, 2008). They are made up of large numbers of macropores and tend to drain water to sub-surface aquifers and out of reach of plant roots. This means that sandy soils begin to dry out more quickly and it is increasingly difficult for roots to access what limited moisture is left. In contrast, fine-textured soils such as clay have a high number of micropores, of which water is held in by capillary action, that do not drain by gravity. Under this soil condition, water can be pulled out of the soil by the plant roots using water potential gradients within the soil-plant-atmosphere continuum (Gerosa *et al.*, 2012) (Figure 1.10), which means plants can continue to transpire for a longer period than for example on sandy soils.

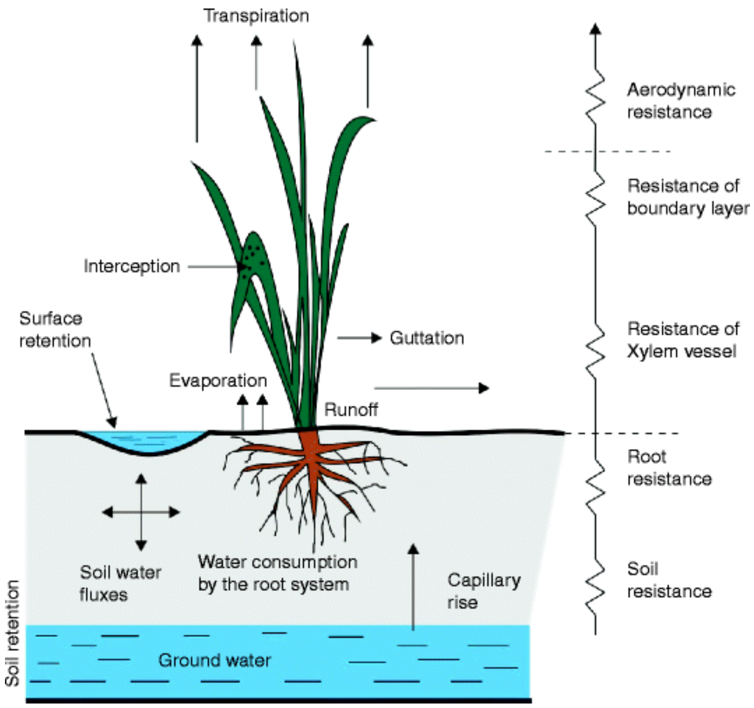


Figure 1. 10: Soil–plant–atmosphere Continuum (Image source: Sławiński and Sobczuk, 2014).

These physical properties of soil and spatial distribution of soil types and textures are important in determining suitable plants with respect to their water consumption and effective ET rates (Duffková, 2013). It is also important to note that ET is limited by moisture availability in the soil and is driven by the atmospheric evaporative demand. Evapotranspiration was reported to be highest when residual moisture content in the soil was abundant, and low ET rate when moisture content decreased (Poë *et al.*, 2015; Kemp *et al.*, 2019). Poë *et al.* (2015) found daily ET rate rapidly declined during summer due to reduction in moisture availability in the soil (in shallow green roof systems), and had a more gradual reduction in ET rate during spring. With regards to smaller plants, an interesting point was made by Wang *et al.* (2012), where shrubs / sub-shrubs may have higher throughfall (less canopy interception compared to trees / forests), therefore leading to higher moisture content in the soil, hence resulting in higher moisture loss / ET; however, this is only applicable for short duration rainfall.

1.11.5 Atmospheric condition / microclimate

The evaporative efficiency is highly dependent on the available energy and the drying potential of the surrounding air, i.e. climatic factors and meteorological parameters, such as precipitation, radiation energy, water saturation deficit and wind speed (Gerosa *et al.*, 2012; Duffková, 2013). These parameters can be considered to be a source of potential energy for ET (Poë *et al.*, 2015). Evapotranspiration is also influenced by the geographical location and the environmental ecosystem. For example, in areas where precipitation is limited (i.e. arid / semi-arid environment), ET can account for up to 90% of annual precipitation and can sometimes exceed precipitation amount (Gao *et al.*, 2016). However, in conditions where moisture content in the soil is sufficient, ET will then be affected by weather factors where upward water movement through the plant tissues (transpiration) is more efficient than upward water movement in the soil via evaporation only (Duffková, 2013).

Atmospheric humidity (RH) and air temperature directly influence ET by governing stomatal regulations (stomata opening and closing based on the atmospheric conditions). In general, the force of water movement is conceptually drawn to areas with less water (Sterling, 2004). Therefore, dry air condition drives water movement towards the atmosphere resulting in increased transpiration rates, while high RH in the atmosphere reduces potential for ET because the air already has sufficient moisture (Sterling, 2004). Higher temperature also enhances ET rates compared to lower temperature due to the increased level of heat energy that can remove moisture from the soil (Poë *et al.*, 2015). Wind speed influences ET rate by moving water vapour from the ground or removing water from the leaf boundary layer by penetrating through plant canopies (Sterling, 2004).

1.12 Plant stress tolerance

Flooding events and drought caused by the impacts of climate change and unpredictable weather changes induce plant stress. Moderate stress affects ET rates and reduced growth, but excessive stress injures plants and can ultimately kill them. Naturally, plants can adapt well to moderate levels of stress and can employ physiological and hormonal changes to tolerate or even escape low levels or short periods of stress (Blanken and Rouse, 1996; Basu *et al.*, 2016; Tewari and Mishra, 2018). Prolonged periods or more extreme levels of water deficit / surplus, however are challenging and even if they do not kill plants outright, may induce secondary problems such as pathogen infection, or reduced productivity e.g. result in the abscission of leaves or flowers (Bashar *et al.*, 2019).

1.12.1 Plant stress due to excessive water

Excessive water can be more damaging to plants than water deficit (drought) as it can restrict root development, thus reducing plant's ability for water and nutrient uptake (Setter and Waters, 2003; Herrera, 2013; Bashar *et al.*, 2019). According to Tewari and Mishra (2018), excess water can also impedes gas exchange, thereby affecting the soil microbiome, which leads to hypoxia (oxygen deficiency) and anoxia (absence of oxygen), as oxygen diffusion through water-saturated soils is much less effective than when the pores are filled with air. Not only is oxygen unable to reach the roots that require it for respiration, it is also utilized by soil micro-organisms, which then compete with the roots for the little oxygen that is available. Moreover, as these micro-organisms (and plant roots) attempt to continue to respire in oxygen deficit systems (anoxia / anaerobic respiration), they produce by-products (e.g. ethylene) that can be toxic to plant roots, especially as concentrations increase near the roots (Basu *et al.*, 2016; Tewari and Mishra, 2018). Furthermore, with deeper flooding, the submergence of plant stems and leaves hinders the photosynthesis process due to lack of light that will eventually halt plant growth (Voesenek and Bailey-Serres, 2013). Although some plant species have adaptive strategies to survive in flooded conditions (e.g. riparian / wetland plants grown in floodplain that can sometimes grow under water), the potential of urban plantings to survive in conditions of excess water can still be explored.

1.12.2 Plant stress due to drought

Inadequate moisture availability (drought) can also disturb plant growth. Due to the unpredictability of weather conditions, scarcity of water resources is equally a cause of global concern. While flooding occurs in some regions, others face lack of rainfall, which greatly affect the growth of plants (Basu *et al.*, 2016; Toscano *et al.*, 2019). However, the severity of drought depends on various factors including natural rainfall occurrence and distribution (thus the duration of stress period), evaporative demands and soil moisture storage capacity (Wery *et al.*, 1994). Essentially, drought stress affects plants physically and physiologically, and its water cycle significantly. Among the most significant effects are on growth, water and nutrient demands, photosynthetic and respiration activities (e.g. stomatal resistance and rate of transpiration) (Farooq *et al.*, 2009).

Some plants have lower total water content and water use efficiency under drought stress than those that are not under stress condition; though this is highly species dependent (Farooq *et al.*, 2009). According to Gao *et al.* (2016), limited water availability in plants decreases transpiration rate, as well as stomatal conductance, which hinders plant growth. DeLucia and Heckathorn (1989) found increased water use efficiency for some pine trees and sagebrush species (*Pinus ponderosa* and *Artemisia tridentate*) due to decrease in stomatal conductance during drought stress condition. This is because some plants close their stomata to reduce or limit transpiration (hence lower moisture loss) during low water supply. Farooq *et al.* (2009) also concluded that drought stress affects plants' stomatal activities (opening and closing) more significantly than water availability, and that drought-tolerant species use their moisture more efficiently by controlling the amount of moisture loss.

1.13 Conclusion

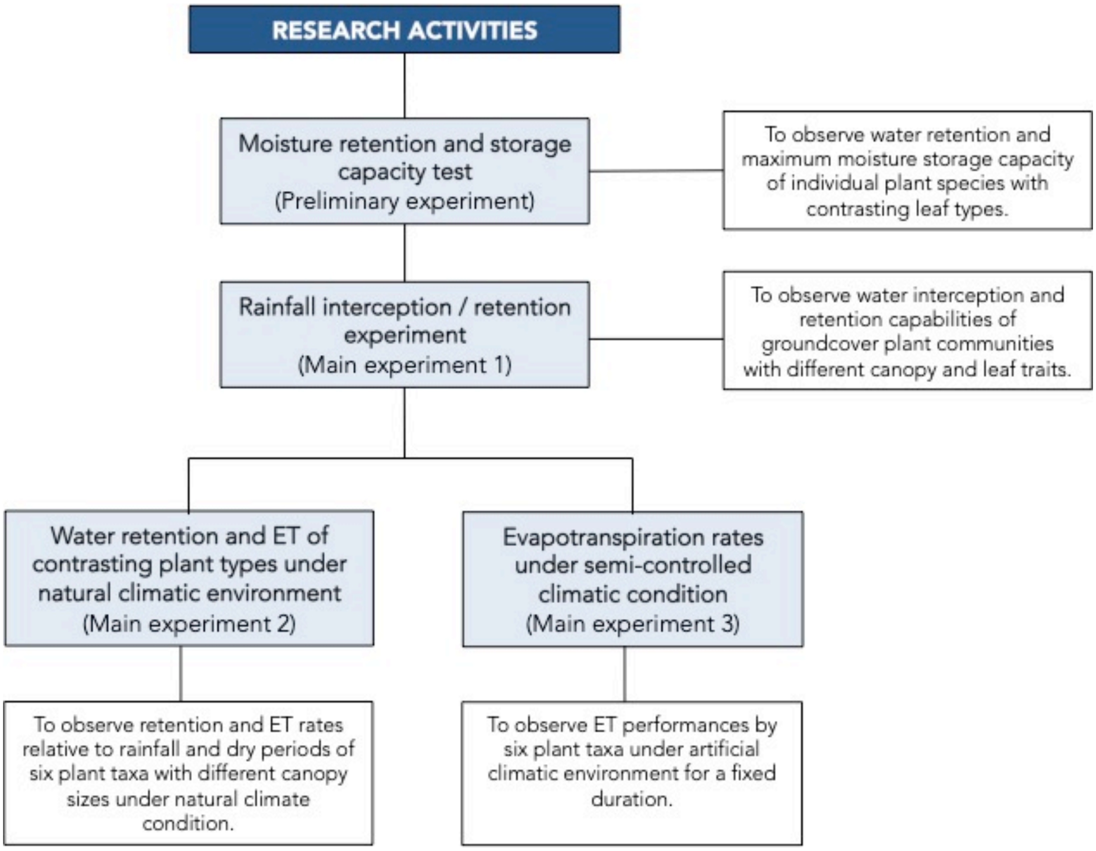
The importance of plants and the benefits of having vegetation in urban areas to reduce stormwater flows has been highlighted, through the ability of plants to intercept rainwater, retain it on their foliage and re-distribute it back into the atmosphere via evapotranspiration (ET). These processes are affected by various factors, namely climatic conditions (e.g. rainfall, temperature, wind, humidity), as well as the physical and physiological characteristics of the vegetation, thus the effectiveness and efficiencies of different plants varies depending on these factors. It is understood from previous studies that forests and trees are important in influencing the hydrological cycle. However, the role of smaller plants such as shrubs and groundcovers in influencing hydrological cycles at local level is less well determined, and indeed the extent to which this is affected by different morphological traits is largely un-researched. It is this gap in the literature that this research aims to address.

CHAPTER 2

GENERAL MATERIALS AND METHODS

2.1 Research activities

In this research, one small-scale preliminary experiment and three main experiments were conducted to observe different aspects of hydrological performance associated with different plant canopy traits. This chapter briefly introduces the different experimental methodologies that were used (Figure 2.1). Detailed methodological approaches are elaborated upon in their respective experimental chapters (Chapter 3, 4 and 5).



To observe water retention and maximum moisture storage capacity of individual plant species with contrasting leaf types.

To observe water interception and retention capabilities of groundcover plant communities with different canopy and leaf traits.

To observe retention and ET rates relative to rainfall and dry periods of six plant taxa with different canopy sizes under natural climate condition.

To observe ET performances by six plant taxa under artificial climatic environment for a fixed duration.

Figure 2. 1: Overview of key research experiments

2.1.1 Preliminary experiment: Water retention and moisture storage capacity test by different plant species

A small-scale indoor experiment was conducted to identify the retention capabilities and maximum moisture storage capacities of individual plant species with contrasting canopy types. The aim of this was to gain understanding and gauge feasibility of the study in order to develop further relevant research methods. Three contrasting plant species were chosen to test and compare 'rain-water' interception / retention capacities between the different traits, using two methods of water application; fine spraying and full submergence in water. Differences in plant weight before and after water was applied were used to determine water retention values. A detailed methodological description of this experiment is provided in Chapter 3.

2.1.2 Experiment 1: Determining rainfall interception and retention by different plant species

Rainfall interception and retention capacities of different plant species were investigated through an experiment conducted outdoors. Initial testing aimed to determine how quickly growing media reached 'field-capacity / container capacity' (i.e. maximum water absorbance, whilst the major pores in the media drained off water). Then, interception and retention experiments were conducted using an artificial rainfall application, and retention associated with different plant species was determined by measuring volume of runoff water in each case. Detailed experimental methodologies are elaborated upon in Chapter 3.

2.1.3 Experiment 2: Quantification of water retention and ET rates under natural climate conditions

The capacity to trap / capture and retain rainwater is dependent on a number of factors including the amount of pre-existing moisture on the plant and in the soil (growing media), and relative ET rates. High ET rates allow the soil's water holding capacity to increase (recharge) as more water is removed from the soil between consecutive rainfall events. In essence, some plants have a greater ability to 're-dry' the soil before the next rainfall occurs. Plants themselves, also have different capacities to store water on their branches and leaves (total surface area). These aspects were explored by measuring plant / pot systems under natural conditions, and monitoring weight changes when plants of different species were exposed to a range of weather scenarios (Chapter 4).

2.1.4 Experiment 3: Determining ET rates under artificial semi-controlled climatic conditions

Concurrent with the outdoor weighing experiment, an experiment was conducted in a laboratory, under semi-controlled climatic conditions, to reduce natural climatic variation. Daily ET rates for the same six plant species were recorded when grown under constant controlled conditions. A lighting rig was constructed to provide radiance and heat (to imitate artificial daylight). Evapotranspiration rates of each plant species were obtained using compression load cells that recorded continuous weight loss (inferred as moisture loss). A detailed methodological description of this experiment is provided in Chapter 5.

2.2 Plant materials

Overall, six species of groundcover plants were chosen to investigate their abilities in water capture and water use (Table 2.1); three of the species were used to test their interception capacities (Chapter 3); and all six species to observe evaporative losses with regards to their interception behavior (Chapter 4 and 5). The experiments in this research were conducted in stages and different time periods during the study, therefore the plants arrived in batches for specific experiments. Plant materials were supplied by Coles Nurseries (James Coles and Sons Limited) and Crocus Nursery (Crocus.co.uk Ltd). The plants were potted in three types of growing media, depending on the experimental purposes (as described in the experimental chapters). The growing media that were used contained a mixture of materials such as compost, peat, loam and fertilizers. Two sizes of plant pots were used for different experiments, which were ~0.3 litre pots (9 cm) and 3.5 litre pots (20 cm). During the experimental periods, the ~0.3 litre plants were placed near windows where natural light was accessible, while the 3.5 litre plants were placed outdoors, on an accessible roof space that also houses green roof test beds (Stovin et al., 2015) until needed for the experiments. Plants were hand watered as required.

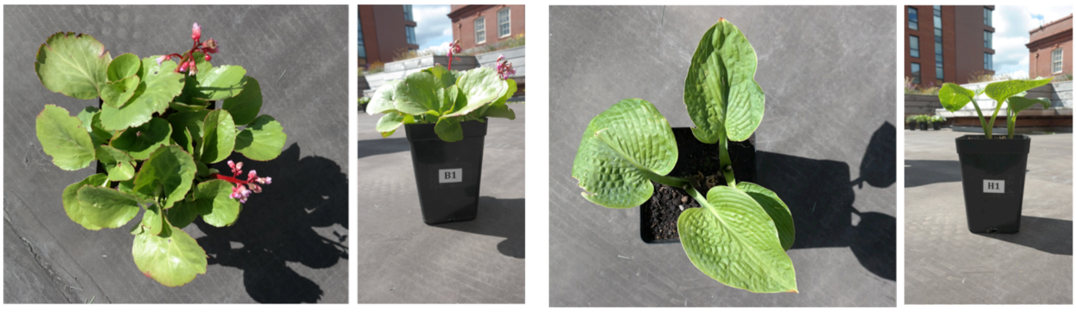
Table 2. 1: List of the plant species that were used in this research.

Botanical name	**Common name**	**Family & plant type**	**Leaves & canopy morphology**
Dianthus ‘Haytor White’	Perennial pink / carnation ‘Haytor White’	*Caryophyllaceae* Evergreen perennials / sub-shrubs	Mounds of greyish, narrow, rough and thick leaves. Quite bushy canopy. Evergreen foliage Hardiness: Very cold winter
Bergenia cordifolia ‘Purpurea’	Elephant’s ear	*Saxifragaceae* Evergreen rhizomatous perennial	Dense canopy. Glossy, leathery leaf surface, thorny edges. Rounded, broad and umbrella-shaped leaves. Bushy. Evergreen foliage Hardiness: Very hardy
Vinca minor	Periwinkle	*Apocynaceae* Herbaceous evergreen perennial	Small leaves with glossy leaf surface. Horizontal leaf orientation. Dense canopy. Mat-forming. Evergreen foliage Hardiness: Very cold winter
Festuca glauca ‘Elijah Blue’	Blue fescue 'Elijah Blue'	*Poaceae* Herbaceous or evergreen	Rhizomatous grasses with very fine linear leaves. Green to bluish colour and

			forms very dense cushion. Tufted. Evergreen foliage Hardiness: Cold winter
Hosta sieboldiana	*Hosta sieboldiana* Green	*Asparagaceae* Herbaceous perennials	Broad, ovate shaped leaf. Blue-green in colour with prominent veining and wavy edge. Clump-forming. Deciduous foliage. Hardiness: Very hardy
Pachysandra terminalis	Japanese spurge	*Buxaceae* Evergreen perennials	Sub-shrubs with creeping stems. Leathery and glossy leaves with toothed edges. Mat-forming. Evergreen foliage Hardiness: Cold winter

Plants of low-growing habit were chosen to represent groundcover plant species often used in urban areas. The plant species had contrasting canopy structures and leaf traits, and the purpose was to investigate whether different leaf types and form; namely broad-leaved, narrow-leaved and small-leaved, as well as the structure of canopy growth, had an effect on EUW. Plant leaf wetness traits were also considered to observe the effect of moisture drops on leaf surfaces. Species may have different leaf wetness traits, which affects how the canopies capture, retain and utilize the moisture within their system.

The chosen plants in this study are categorized into three types of leaf shapes / physical form (Figure 2.2). *Bergenia cordifolia* and *H. sieboldiana* are both clump forming species with large, broad leaves, though their surface leaf texture and canopy structure differ. *Bergenia cordifolia* have smooth leathery and glossy surface that are easily wetted, with wavy and saw-toothed edges. While *H. sieboldiana* have highly hydrophobic leaves with glacuous waxy coating that tends to shed water. Varying surface texture and canopy structure was chosen purposely to identify whether the specific leaf shape and texture themselves affect the hydrologic impact. *Festuca glauca* and *D.* 'Hayto*r* White' have linear and narrow (needle-like / grass-like) leaves with upward facing angles / orientation. While the leaves of *F. glauca* are glacuous, and are very densely clumped together, the foliage of *D. 'Haytor* White' is a little sparser. *Vinca minor* and *P. terminalis* have more similar traits rather than contrasting as they both have a small and simple leaf shape with dense canopy coverage and mat-forming growth habit. The reason for choosing a variety of plant physical traits (i.e. leaf shape and orientation, surface texture, canopy architecture, leaf wettability) was to help identify factors (and parameters) affecting the impact of moisture and how efficiently moisture is utilized within the plant systems.

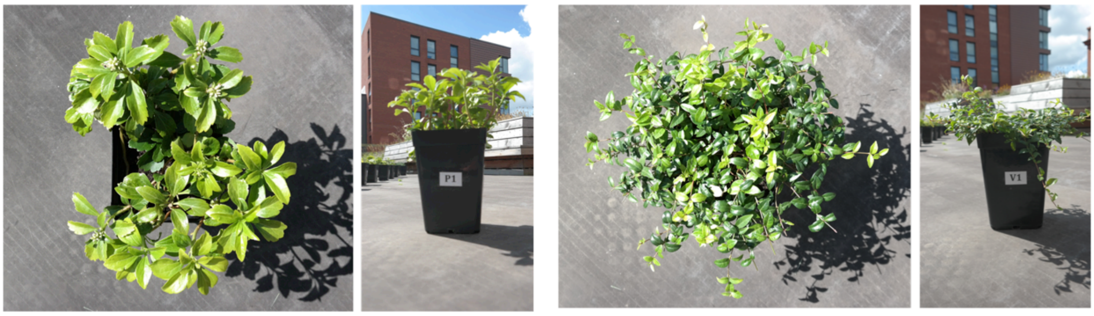


a) *Bergenia cordifolia*
(Broad-leaved)

b) *Hosta sieboldiana*
(Broad-leaved)

c) *Festuca glauca*
(Narrow-leaved)

d) *Dianthus* 'Haytor White'
(Narrow-leaved)



e) *Pachysandra terminalis*
(Simple-leaved)

f) *Vinca minor*
(Simple-leaved)

Figure 2. 2: Images of the plant species used in experimental activities.

Plants leaf wetness traits were assessed by physically observing the shape of water droplets on leaf surfaces. Increased droplet angle (droplet turns into spherical shape) indicates higher hydrophobicity of the leaf surface (see Figure 1.7). Matos and Rosado (2016) suggested that droplets from 1 to 10μL are the most commonly used to measure leaf wetness traits. However, water droplet size and angle were not measured in this study. Based on physical observation of each plant (Figure 2.3), the leaves of *B. cordifolia* have relatively low hydrophobicity. This is due to the formation of filmstrips of water (flattened water droplet) when water was applied on leaf surfaces indicating hydrophilic characteristics. On the other hand, *H. sieboldiana* have high hydrophobicity as droplets coalesce together and form a more spherical shape. *Dianthus* 'Haytor White' also has high hydrophobic character, while *F. glauca* have medium to high hydrophobicity. The leaves of *F. glauca* that are fine and narrow resulted in droplets being retained on the leaf surfaces in high droplet angle (spherical shaped droplets). *Vinca minor* has relatively low contact angle, indicating low hydrophobicity. As for *P. terminalis,* droplets form spherical-shapes with medium contact angle, but these do not easily roll off (medium hydrophobicity).

a) *B. cordifolia* b) *V. minor* c) *D.* 'Haytor White'

e) *F. glauca* e) *H. sieboldiana* f) *P. terminalis*

Figure 2. 3: Moisture droplets on different leaf surfaces based on physical observation.

2.3 Materials and instruments

A range of key instruments used in the research and their functions are outlined in Table 2.2.

Table 2. 2: List of instruments and devices used in the experimental activities.

Instruments	Manufacturer / supplier	Functions
ARG-100 tipping bucket rain gauges	Environmental Measures Ltd.	Measured rainfall depth at 1-minute interval.
Handy Plant Efficiency Analyzer	Hansatech Instruments	Measured chlorophyll fluorescence.
Haws Deluxe watering can	Haws Watering Cans Ltd.	Distributed artificial rainfall (capacity of 5-litres).
LCD temperature thermometer	Duragadget	Displayed indoor room temperature.
600 Watt High Pressure Sodium lamps	Installed by technicians, Civil and Structural Engineering, UoS	Provided artificial radiance and heat that simulates daylight condition.
Marsden B-100 Waterproof Bench Scale	Marsden Weighing Group	Weighed sample treatments - LCD display for weight reading.
Modular 600 Data Logger	RDP Electronics	Logged the data / output from load cells.
PDCR 1830 pressure transducer	Druck PDCR	Measured and recorded runoff data (from test bed) at 1-minute interval.
Rainfall simulator	Assembled by Dr. Simon DeVille, Civil and Structural Engineering, UoS	Distributed artificial rainfall using a dripper network.
RLS010 single-point compression load cell	RDP Electronics Ltd.	Continuously recorded weight changes.

Salter Battery-powered Digital Kitchen Scale (max 5000g x 1g)	Salter	Weighed sample treatment and measuring water quantities with LCD display for weight reading.
SM150T moisture sensors & GP data loggers	Delta-T Devices	Continuous measurement of moisture content (%) in soil at 1-minute interval and logged output in General Purpose (GP) data loggers.
Sartorius balance scale (1403 MP 5500,0 g)	Sartorius	Weighed sample treatments - LCD display for weight reading.
TinyTag Ultra 2 Sensor	Gemini Data Loggers	Recorded air temperature and relative humidity for indoor environment (laboratory).
Weather station	Campbell Scientific	Recorded solar radiation, air temperature, relative humidity, wind speed, atmospheric pressure in an outdoor environment.
24hr/7 Day Electronic Timeswitch	Time Guard Limited	Electronic time controller programmed to automatically turn on / off lighting systems.

2.3.1 Rainfall simulator

A rainfall simulator that has been designed for research in the Department of Civil and Structural Engineering, University of Sheffield was used to fully saturate treatment samples during the experiment, by distributing water using a high flow dripper network (5.5 mm/min) for 30-minutes. The simulator was attached to the monitoring test bed during experimentation and removed when not in use for safety purposes (Figure 2.4). The dripper networks were connected to a valve using a watering hosepipe for water supply. The height of the simulator frame, which was 70 cm was used as the equivalent height to distribute water onto treatments using a watering can (see Chapter 3).

Figure 2. 4: Rainfall simulator attached on the test bed and connected to valve for water supply.

2.3.2 Climate data

A Campbell Scientific weather station recorded air temperature, relative humidity (RH), solar radiation, wind speed and barometric pressure at hourly intervals (Figure 2.5; *Left*). Temperature and RH were recorded using CS215 probe. Solar radiation levels (W/m^2) were recorded using a pyranometer (SP LITE) that was located on a tripod accessible to direct sunlight. Wind speed data was recorded using a 05103 Wind Monitor (Campbell Scientific), which recorded horizontal wind speed by producing AC sine wave signal with frequencies proportional to wind speed. A CS100 barometric pressure sensor recorded atmospheric pressure. Three ARG tipping bucket rain gauges on site recorded rainfall depth at 0.2 mm resolution at 1-minute interval (Figure 2.5; *Right*). The rain gauges were located at the same height as the experimental test bed. Data was recorded through a Campbell Scientific CR3000 data logger and collected every two weeks.

Figure 2. 5: (*Left*) Campbell Scientific weather station; (*Right*) ARG tipping bucket rain gauge.

2.3.3 SM150T moisture sensors

SM150T moisture sensors from Delta-T Devices were used to continuously measure moisture content of treatment samples during the whole experimental period, at 1-minute interval (Chapter 4). A total of 13 moisture sensors were installed vertically in the growing media of one sample for each species (Figure 2.6; *Left*). The sensors were connected to two multipurpose data loggers; four into GP1 and nine into GP2 (Figure 2.6; *Right*). Each sensor was wired as a differential, powered sensor. The GP loggers were placed close to the sensors and were covered with a plastic cover to avoid wind and rain disturbance.

Figure 2. 6: (*Left*) SM150T moisture sensors were installed in the soil of one plant sample of each species; (*Right*) Moisture sensors were connected to GP data loggers.

Prior to the start of the experiment, soil-specific sensor calibrations were conducted in the Plant Laboratory on Floor 19, the Arts Tower, University of Sheffield. The purpose of the calibration was to obtain two coefficients a_0 and a_1, which parameterizes the dielectric properties in the soil that allows the output from the sensor to be converted from mV (millivolts) into percentage of moisture content (%) using a linear equation formula ($\sqrt{\varepsilon} = a_0 + a_1 \times \theta$).

For the soil-specific calibration (for non-clay soils), the growing media soils were first wetted to full saturation and allowed to drain for 3 days for the soil to be moist enough (over the weekend 07/07/2017 to 10/07/2017). Approximately 1.5 litres of the wet soil was poured into a square pot (11 x 11 x 13 cm), with total volume of 1573 ml. The volume occupied by the soil was measured and weighed including the pot. A SM150T moisture sensor was then inserted into the soil and the output was recorded in mV (millivolts) for 10 minutes. The output was taken as the average of recorded output within the 10-minutes duration. The soil sample was then laid on a tray and oven-dried for 2 days at 70°C. The dry soil sample was then poured back into the square pot, and weighed again. The moisture sensor was re-inserted into the dry soil and reading was recorded again for 10 minutes, and the output was determined by taking the average reading of the 10-minutes measurement. As the two coefficients were obtained; a_0= 1.19 and a_1 =10.84, they were logged into the DeltaLINK software program (Ver. 3.6) that automatically converts the sensor readings into volumetric water content (θ) in percentage (%), using the equation below:

$$\sqrt{\varepsilon} = a_0 + a_1 \times \theta$$

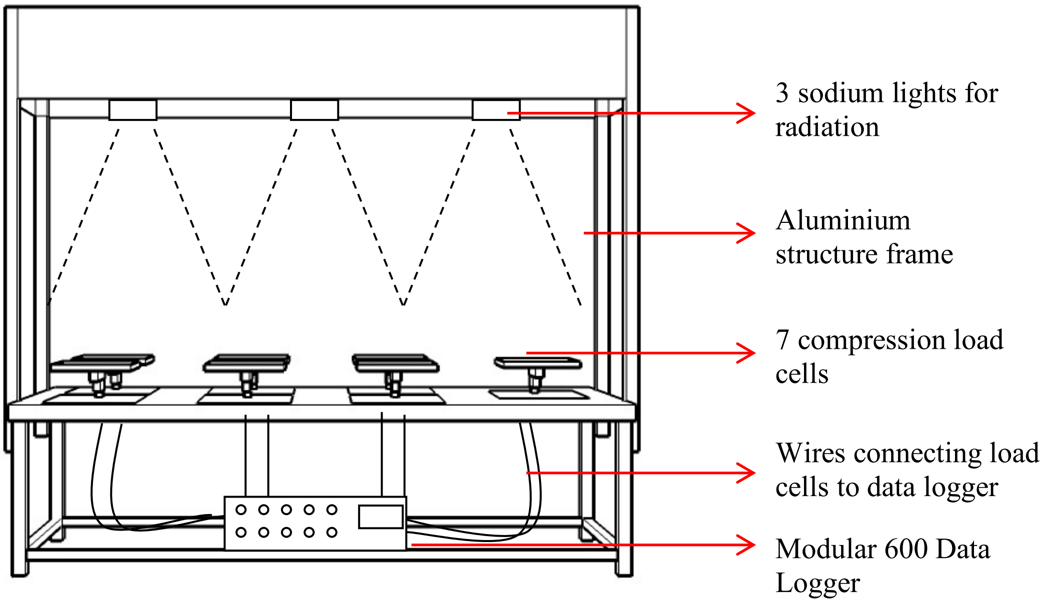
2.3.4 Chlorophyll fluorescence meter

Chlorophyll fluorescence was measured on three consecutive days after the outdoor weighing experiment was completed, to assess signs of stress in the plants (Chapter 4). However, due to inability to attach leaf clips on the leaves of *D.* 'Haytor White' and *F. glauca*, measurements were only taken on four species; *B. cordifolia*, *H. sieboldiana*, *V. minor* and *P. terminalis*. Readings were taken in the morning at 9:00 am which took approximately 1.5 hours to complete all four species with six replicates, and two canopy sizes of each species. Leaf clips were placed on one random leaf sample of each plant species (Figure 2.7). The shutters on the clips were closed for the leaves to adapt to the darkness. Measurements of chlorophyll fluorescence were taken between 10 to 30 minutes after the dark adaptation period using the Handy PEA instrument. In the dark-adapted state, the Fv/Fm ratio result that was displayed enabled estimation of photosynthetic activities. Healthy plants generically exhibit a consistent Fv/Fm value of ~0.8, while stressed plants result in a low level of Fv/Fm (<0.7) (Murchie and Lawson, 2013).

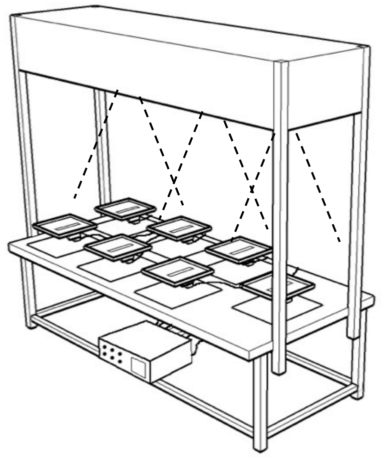
Figure 2. 7: Leaf clip attached to random leaf sample with the shutter closed for darkness adaptation to measure chlorophyll fluorescence.

2.3.5 Bench rig

For the indoor ET experiment (Chapter 5), a bench rig at 186 cm high x 200 cm length x 90 cm width was installed in the Civil Engineering Water Lab, University of Sheffield. The bench was supported by aluminum structure frames, and three sodium lights were mounted for artificial radiation (Figure 2.8). Seven load cells were placed 20 cm from each other, which were used to monitor continuous weights of the treatments. The load cells were connected to the Modular 600 Multi-Channel Signal Conditioning System that logged the output of the load cells at 1-minute intervals.



a) Front view



b) Perspective view

Figure 2. 8: Diagram of the experimental bench and lighting rig, where load cells were placed throughout the entire experiment (diagram not to scale).

2.3.6 Lighting system

Three High-Pressure Sodium lamps (600 Watt) were fitted to provide artificial radiance and heat for plant growth in an indoor laboratory environment (Chapter 5). The lights were fitted with reflectors to spread the lights across all plants located on a bench rig (Figure 2.9), and each lamp provided an output of 90,000 lumens. The lights were installed 1.3 m above the surface of the bench, which provided a reasonably even distribution of radiance onto 7 plants (and growing media) samples during the experimentation.

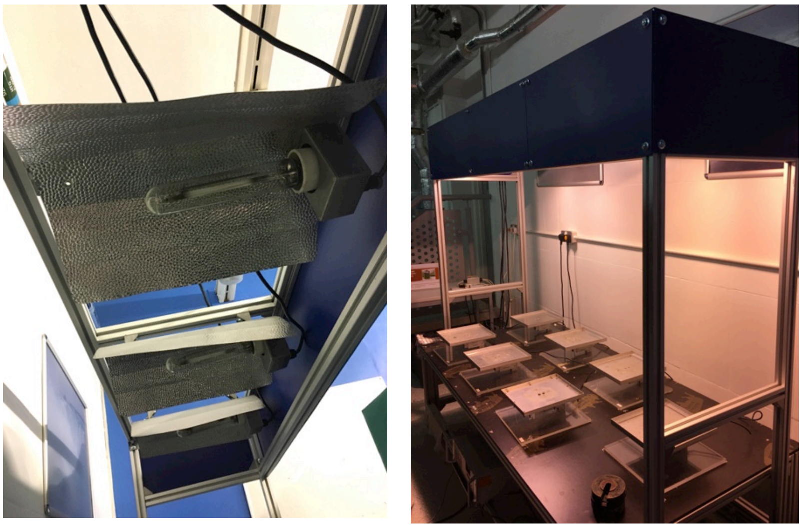
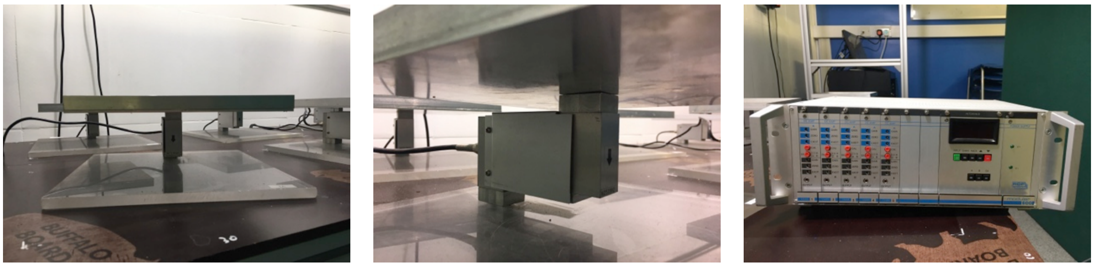


Figure 2. 9: (*Left*) Three sodium lights for artificial daylight effect; (*Right*) The effect of the lightings above the load cells.

2.3.7 Load cells

Seven aluminium single-point compression load cells (Model: RLS010 by RDP Electronics) with working capacity of 10 kg were used to continuously monitor the weights of treatment samples, to determine daily moisture loss (ET) rates (Chapter 5). Each load cell was connected to a Modular 600 data logger (Figure 2.10) and data was recorded at 1-minute interval (refer to Poë *et al*., 2015).



a) Load cell platform

b) Single point compression load cell located beneath the platform

c) Modular 600 Data logger

Figure 2. 10: Load cells and data logger that records and logs continuous weight of the treatments.

Prior to the tests, the load cells were calibrated by adding masses at 0.5 kg intervals up to maximum value of 6 kg, using the RDP calibration program. The signal from the load cells was recorded in volts, thereby enabling the signal to be converted to mass (kg) using a simple linear regression equation with an accuracy of $R^2 = 1.0$ (see example on Figure 5.4). The load cells calibrations were done prior to the first test (Test 1), after Test 2, after Test 3 and finally after the whole experiment was complete (after Test 4), to confirm that the recorded weights were consistent throughout the whole experiment.

2.4 General data management and statistical analysis

The data in this study were managed using Microsoft excel software package (Microsoft Corporation). Statistical support was sought from CiCS (Corporate Information and Computing Services) Statistical Support, University of Sheffield. All statistical analyses were performed using IBM SPSS Statistics software version 24. One-way, two-way and repeated measures analysis of variance (ANOVA) were used to determine if there were significant differences in moisture behaviour (interception, retention and ET rates) by the different plant species. Parameters are considered to be significantly correlated at or above the 95% confidence level ($p \leq 0.05$). An image processing software, ImageJ software (Version 1.46r, National Institutes of Health, USA) was used to calculate total leaf areas of plants.

2.5 Chapter summary

This chapter has outlined the methodologies and general approaches to this research by first presenting the experimental framework that is divided into four experiments; a preliminary experiment and three main experiments to investigate the hydrological performance of six selected plant species with contrasting leaf and canopy characteristics. Plant materials that were used in the overall research have been introduced, and finally the functions of main equipment used have been highlighted. The following chapters present the detailed methodology pertaining to each experiment, and results of each of these experimental components.

CHAPTER 3

WATER INTERCEPTION AND RETENTION BY PLANT SPECIES OF CONTRASTING LEAF FORM

3.1 Introduction

The first vegetated surfaces that rainfall encounters are plant canopies. Although canopy cover may not be entire, the foliage effectively filters the amount of rainfall that passes through the space, either by not touching any plant parts and hitting the ground directly, or by hitting leaves, stems and branches (i.e. the canopy interception process). Different areas and forms of canopy can intercept different proportions of the rain. As heavy rainfall occurs, interception by the canopy can reduce surface runoff over impervious surfaces, though the efficiencies depend on vegetation and foliage types (Nagase and Dunnett, 2012; Kemp *et al.*, 2019).

The precise relationship between rainfall dynamics and plants depends on species, due to variation in the physical and physiological traits of plants. This chapter explores how different plant species with contrasting leaf characteristics influence rainfall capture and subsequent retention on an individual scale and also in groups / community. A variety of experimental approaches were used, including small-scale water application in a domestic situation (i.e. submerging and fine spraying) and a relatively larger scale study using an artificial rainfall application on an experimental test site. These were done at various times of year, and comparisons were made between the two approaches. To investigate the volume of water held on plant canopies and not within the growing media *per se*, plant pots were brought to container (field) capacity prior to applying water to the canopies. Thus, any additional water was either retained on the canopy or percolated / drained through the plant-pot system. Weights of plant pots were recorded before and after water were applied to determine how much water was retained through gravimetric means, and the volume of water that drained through was also measured. The proportion of water on canopies and that which drained through was measured for different plant species.

3.2 Key objectives and questions of experiment

The objectives of the experiments were:

1. To identify whether different leaf traits influence rainfall interception, retention and moisture storage capacity.

2. To investigate which of the leaf traits intercept and / or retain water more effectively.

This chapter aims to answer the following research questions:

1. How do different leaf traits affect moisture capture / interception?
2. Which plant types respond best at capturing and retaining water?
3. What are the key influences in moisture interception and retention by vegetation?

3.3 Hypothesis

- Plants with a higher number of small leaves and denser leaf coverage will intercept and retain more water than plants with fewer, but larger leaves.

3.4 Chapter structure

This chapter consists of four different experimental approaches (Figure 3.1) that are designed around the main and sub research questions framework. There are two main experiments, which are presented in Experiment 1 (Section 3.5) and Experiment 4 (Section 3.8) that were designed to address the main questions. Two small-scale tests and assessments were conducted to address two sub-questions, which are presented in Experiment 2 (Section 3.6) and Experiment 3 (Section 3.7). Experiment 2 and Experiment 3 are generally artifacts to the process to help support the methods used to evaluate key questions and driving hypothesis of this chapter.

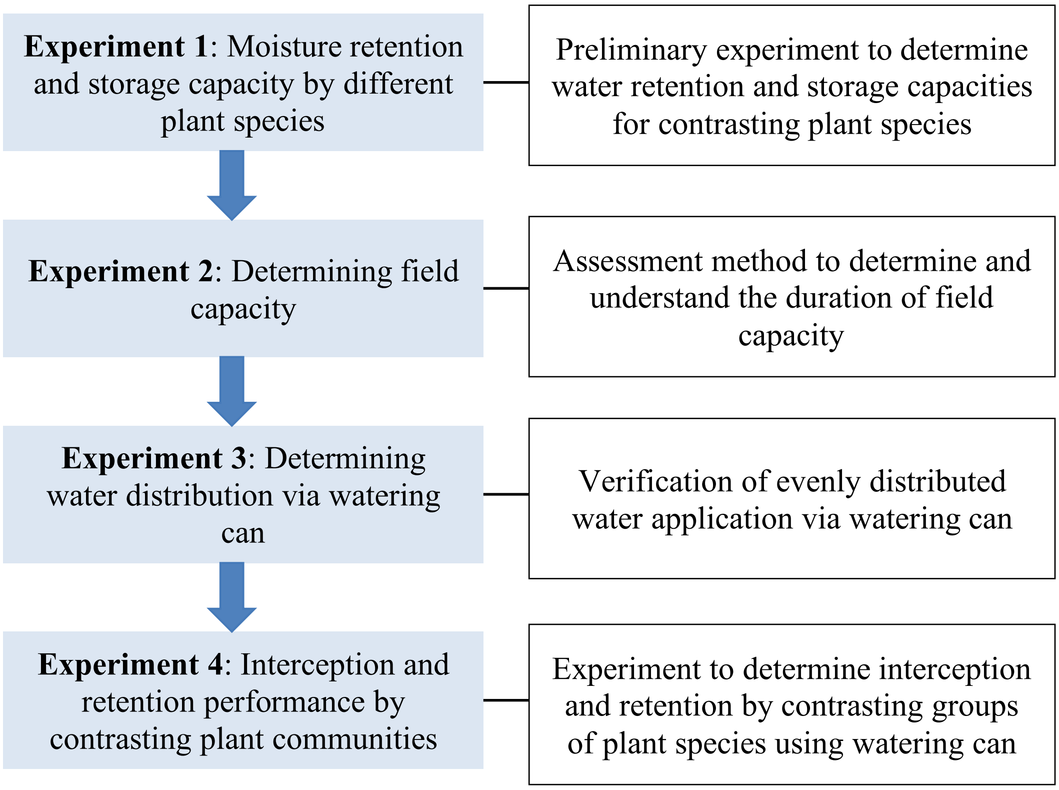


Figure 3. 1: Chapter structure of the four experiments conducted to determine water interception and retention by model plant species.

3.5 Experiment 1: Moisture retention and storage capacity by different plant species

3.5.1 Experimental setup

Three plant taxa, *Dianthus* 'Haytor White' (many small, needle-like leaves), *Bergenia cordifolia* (few, large, thick leaves) and *Vinca minor* (intermediate numbers of small-medium sized leaves) were chosen to compare their interception and retention characteristics. Each plant taxa had three replicates, which were potted in ~0.3 litre round pots (9 cm diameter, 6.8 cm deep) using *Verve* multipurpose compost. A Salter battery-powered digital scale was used to measure the weight of the pots. Buckets 280 mm deep were used to submerge the whole plant into water, and a 140 mm deep container was used to submerge the pot, to saturate the growing media. A 1-litre handheld spray was used as a spraying device. Room temperature was recorded using an indoor LCD temperature thermometer.

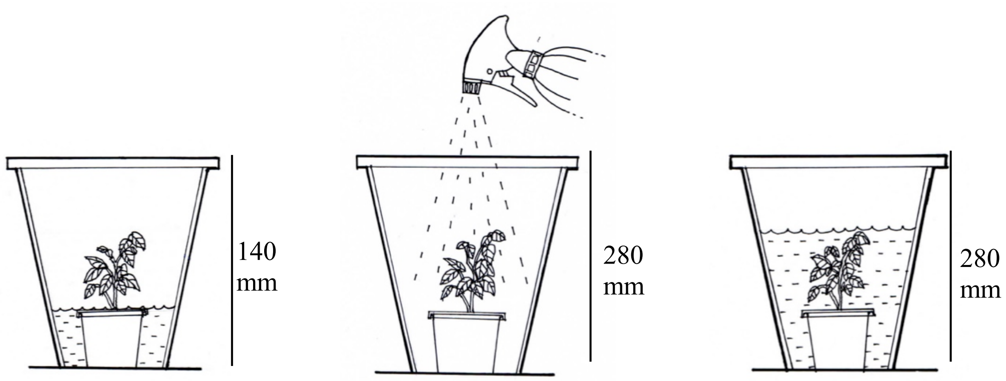
3.5.2 Methods

Due to the requirement for frequent recordings, this experiment was done in the author's domestic apartment in Sheffield, UK. Tests were conducted between 22/11/2016 and 24/03/2017 in a heated indoor environment. Temperature during the experimental period ranged between 12.7°C and 21.4°C. Two methods of water application onto plant canopies were applied; 1) spraying; and 2) submerging (Figure 3.2). The purpose of the spraying was to observe how plant leaves respond to moisture when application mimicked rainfall, i.e. when applied vertically as discrete droplets, and representing the natural wetting process (Wohlfahrt *et al.*, 2006). The second, submerging method allowed the plant canopies to be exposed to water from all directions and saturate all the possible surface area of the foliage, in essence, the maximum potential capacity for the canopy to hold water.

Each plant pot was initially submerged in a 140 mm depth of water (up to the lip of the pot) for 10 minutes to saturate the growing media (Figure 3.2 (a)). After 10 minutes, the pots were allowed to drain naturally above the bucket for 1 minute, to remove any excess water. The pots were then placed on a balance and weight recorded every 5 minutes (removing any excess moisture on the balance with paper towels). Once the weights of the pots remained constant for 15 minutes, the growing media was assumed to have reached 'field capacity state' (technically 'container capacity' in this instance). Field capacity is defined as the maximum amount of moisture held within the soil / growing media after excess water has drained from the macropores, i.e. not held in place by capillary action or hydrostatic forces. The time to reach field capacity here varied between 35 to 60 minutes; varying according to the plant species, pots and different days of experimentation.

Subsequently, for the spraying method, the pots (held at container capacity) were placed in an empty bucket. 100 ml of water was sprayed from directly above onto the plant canopies (Figure 3.2 (b)). After spraying, the pots were lifted from the container (taking care not to tilt the plant and induce any run-off from the wet leaves), and once again, drained for 1 minute to allow draining of any excess water from the pots. The pots were then placed onto the balance to record change of weights every 5 minutes until a stabilized weight value was observed. The difference in weight between before and after the canopies was wetted was assumed to be moisture held in the plant canopies, which is the retention capacity.

Similarly, for the submerging method, the growing media was wetted and pots were brought to field capacity. The pots were then fully submerged into a bucket containing 6000 ml of water for 5 minutes (Figure 3.2 (c)), extracted and drained for 1 minute before being placed onto the scale again. The pots were then continuously weighed every 5 minutes allowing stabilization of weights, as per the spraying method. The weight difference was assumed to be the value of maximum moisture storage in the plant canopies.



a) Pot submerged up to pot lip to saturate the growing media.

b) Plant sprayed with 100 ml of water from above.

c) The whole plant submerged in water to ensure full saturation of the canopy.

Figure 3. 2: Diagram of growing media wetting and two water application methods (diagram not to scale).

A total of six sprays / immersions was conducted on each plant, and the tests between the two methods were done in alternate order. After the experiments were completed, leaves from each plant were removed and placed against a white background (white paper) and photographed. The photos were then analysed using ImageJ software, which calculated green area (green pixels) of each individual leaf against a scale bar, to obtain the total leaf area data for each plant (in cm^2), to give a value per unit of leaf area.

3.5.3 Results

The result of moisture retention here is presented in depth of water unit (mm), which was obtained by dividing moisture retention in (litres) to the pot surface area (0.00785 m^2), for comparisons of moisture retention with different experiments in this research. For both methods, mean retention values were obtained from six repeated trials and three plant replicates for each of the plant species (*D.* 'Haytor White, *V. minor* and *B. cordifolia*). A two-way analysis of variance (ANOVA) was used to analyse whether there were significant differences between the species using the two methods.

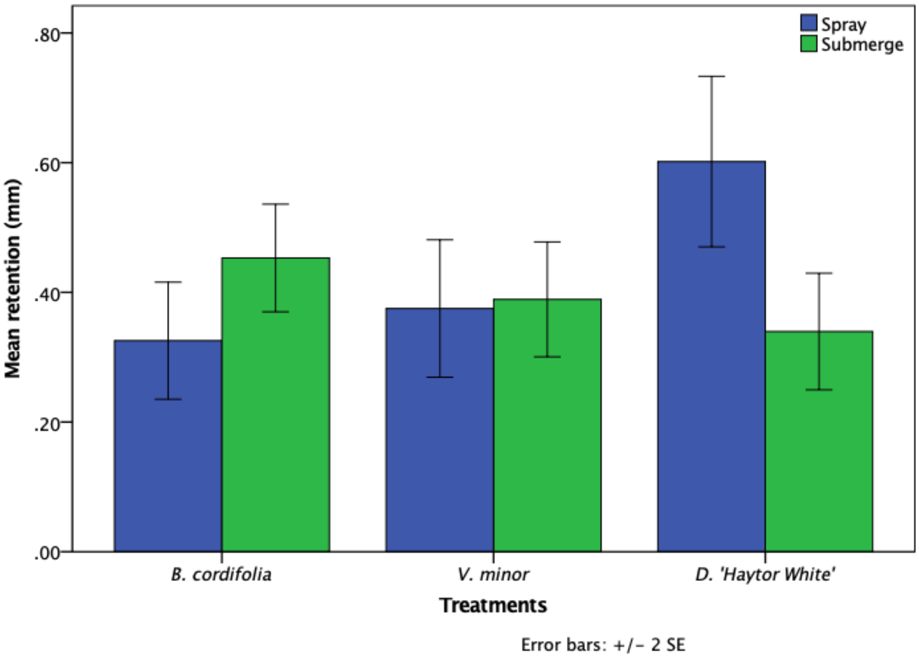


Figure 3. 3: Mean moisture retention by three plant species using spraying and submerging methods.

The results showed contrasting pattern between the two methods (Figure 3.3). When sprayed, *D.* 'Haytor White' intercepted and retained the highest amount of moisture (0.60 mm), followed by *V. minor* (0.38 mm) and finally *B. cordifolia* (0.33 mm). *Dianthus* 'Haytor White' was statistically different from the other two species ($p < 0.05$), but *V. minor* and *B. cordifolia* were not statistically distinct from each other ($p = 0.80$). In contrast, when the canopies were fully submerged in water, *B. cordifolia* retained the highest amount of moisture (0.45 mm), while *D.* 'Haytor White' retained the least (0.34 mm). Again, *V. minor* retained a moderate amount compared to the other two species (0.40 mm). There were no significant differences between the species when they were submerged (p = 0.19). Overall, *D.* 'Haytor White' showed significant difference and retained higher amount of moisture when sprayed compared to situations where it was submerged (p = 0.002), while *V. minor* showed the least difference between the two methods (p = 0.84).

Table 3. 1: Mean retention value by the plant species on a per unit of leaf area basis.

Plant species	**Total leaf area (m^2)**	**Retention per unit of leaf area ($mm\ m^{-2}$)**	
		Spray	**Submerge**
B. cordifolia	3.58	0.09	0.13
V. minor	1.36	0.26	0.30
D. 'Haytor White'	3.82	0.16	0.09

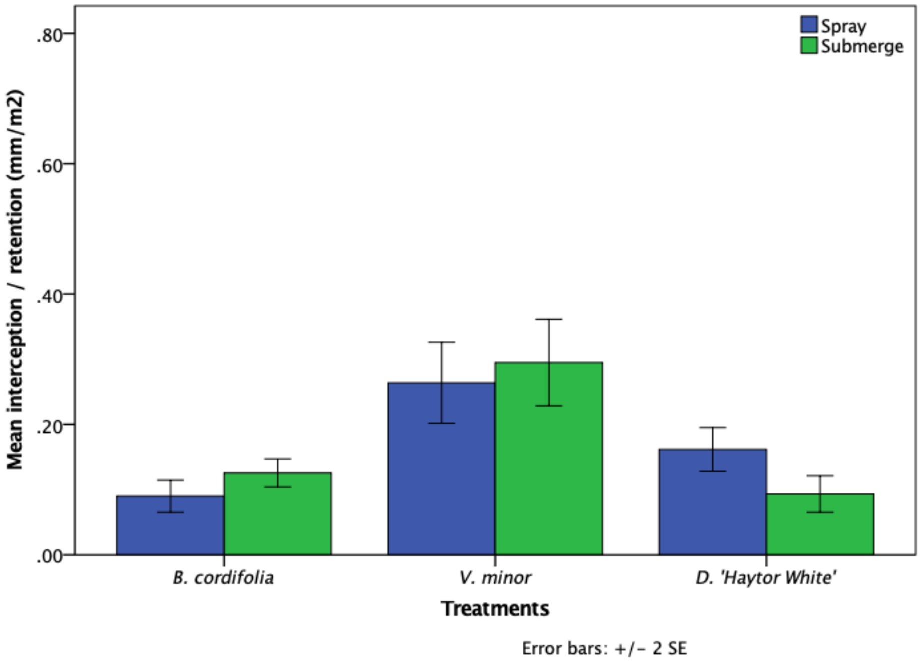


Figure 3. 4: Mean moisture retention by three plant species using spraying and submerging methods calculated on a per unit of leaf area basis.

On a per unit of leaf area basis, *V. minor* intercepted the highest amount of moisture for both methods (0.26 mm m^{-2} when sprayed and 0.30 mm m^{-2} when submerged), which was statistically distinct from both *D.* 'Haytor White' and *B. cordifolia* ($p < 0.05$) (Figure 3.4). *Dianthus* 'Haytor White' retained the second highest when sprayed (0.16 mm m^{-2}) and *B. cordifolia* retained the least (0.09 mm m^{-2}) on a per unit of leaf area. When submerged, *B. cordifolia* retained the second highest amount of water (0.13 mm m^{-2}) and *D.* 'Haytor White' retained the least (0.09 mm m^{-2}) per unit of leaf area. No statistical differences were observed between *D.* 'Haytor White' and *B. cordifolia* for both methods.

3.5.4 Conclusion

As the main purpose of this preliminary experiment was to gather initial understanding on the principles of water interception and retention by different leaf types, based on the results of the experiment, it may be concluded that canopy structures and species variation does influence moisture capture and retention capacities. Although significant differences between the two methods were only seen on *D.* 'Haytor White', for the other two species, it generally suggests that vertically applied water (i.e. rainfall) does not fully utilize the moisture storage capacity in plant canopies because as water drops on leaf surfaces, only the upper surface are in contact with water and temporarily retain water droplets. Some leaves that are covered by upper layers of foliage and undersides (abaxial) of leaves stays dry and do not contribute to moisture retention. The result by *B. cordifolia* and *V. minor* contradicts with a study by Wohlfahrt *et al.* (2014), who found that moisture storage capacities obtained using the spraying method were significantly higher compared to submerging method (on nine species of graminoids and forbs), which therefore suggested that spraying is more effective in optimal wetting of leaf surfaces due to droplets formation. These differences, however, may be associated with species-specific moisture storage capacity as well as leaf characteristics, as Wohlfahrt *et al.* (2014) used mountain species, which are used to medium to high moisture condition, with relatively low temperature.

In this experiment, it typically took between 35 to 60 minutes for a ~0.3 litre pot to reach a stabilized pot weight (container / field capacity) after wetting. This variability may be due to various factors, such as hydrophobicity within the pots, individual plant species and size, time and surrounding factors when the experiments were conducted. Due to this inconsistency, which posed a risk of errors due to lack of understanding field capacity, a test was conducted to verify a standardized duration in which field capacity is reached.

3.6 Experiment 2: Determining field capacity

A laboratory test was conducted to determine a consistent time that ensures the growing media is at field capacity. The new standardized time was used in Experiment 4 (Section 3.8).

3.6.1 Methods

The tests were conducted in the Analytical Laboratory in the Department of Civil and Structural Engineering, University of Sheffield, with air-conditioned room temperature of 20ºC. One random sample of each species (*D.* 'Haytor White', *V. minor* and *B. cordifolia*) was selected to conduct this experiment. Each plant was potted in a 3.5 litre square pot (15 x 15 x 20 cm). The pots were submerged in a bucket of water up to just above the level of growing media for 24 hours. The water level was maintained above the growing media but below the lip of the pot to keep them saturated and to avoid lightweight particles (i.e. perlite) from floating off (Figure 3.5; *Left*). Plant canopies remained dry at this point. After 24 hours, the pots were lifted and drained by placing them for 1 minute on a metal grid, thus avoiding water droplets from accumulating below the pots. The top surfaces of the pots were wrapped in cling film to avoid any moisture losses via ET, evaporation and transpiration (Figure 3.5; *Centre*), and then repeatedly weighed using a Sartorius balance every 30 minutes to monitor change of weight due to moisture draining (Figure 3.5; *Right*). When there were no weight changes detected for 1 hour, it was assumed that the pots had reached field capacity state. The weights were monitored for an overall duration of 3 hours.

Figure 3. 5: (*Left*) Growing media fully submerged up to pot surface height; (*Centre*) Top surface of the treatments were covered in cling wrap; (*Right*) Treatments' weights were continuously monitored.

3.6.2 Results

Although the starting weight and the actual weight of the treatments varied (time 0:00) (Figure 3.6), this only affected the saturation point of the growing media and does not affect the field capacity state. Variation in the starting weight may have been caused by human error, and variation in the actual weights may be due to different plant size and biomass. The growing media had relatively low overall weight, which may be associated with absence of plant biomass. Figure 3.6 presents the result of the field capacity test in weight differences relative to the final field capacity weight for all treatments.

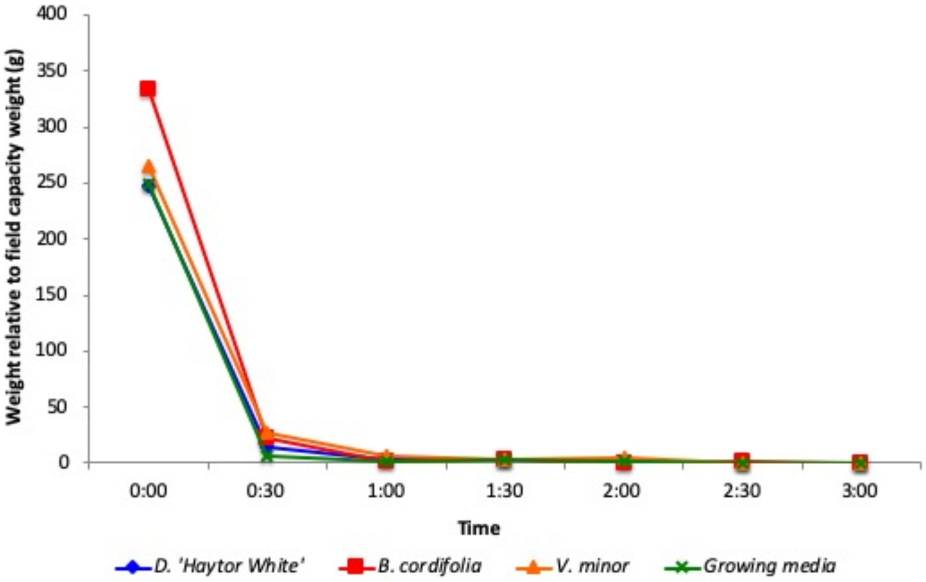


Figure 3. 6: Weight changes of all treatments relative to the final weight (field capacity weight).

It was found that after water had drained from the pots (time: 0:00 to 0:30), the weight of the treatments started to become stable after one hour. This was consistent with all of the treatments. As the weights were continuously monitored for another 2 hours, the treatments showed 'flat line', indicating that draining had stopped and the weights have become stabilized. The stabilized weights were solely as a result of draining of the excess water, on the assumption that evaporation, transpiration and ET did not take place because of the covered surface. This determined the duration for field capacity; which was 2 hours.

3.6.3 Conclusion

It is therefore concluded that the weights of the treatments became constant, and reached field capacity state after 2 hours of draining. Interestingly, this finding is consistent with the laboratory tests for the determination of field capacity for green roof substrates by FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau; German Landscape Research, Development and Construction Society) (FLL, 2008). This duration was then applied in Experiment 4 to ensure the pots had reached container capacity before artificial rainfall was applied (see Section 3.8).

3.7 Experiment 3: Determining water distribution via watering can

To imitate rainfall, a watering can was used to apply water across treatments on a 1 m x 1 m test bed, which is described in Section 3.8 of this chapter. In order to verify whether the 'rainfall' (water) distribution was evenly applied or not, a spatial distribution assessment was conducted. This work was undertaken in collaboration with a visiting student at the Civil and Structural Engineering Department, University of Sheffield.

3.7.1 Methods

For this assessment, 10 aluminium containers were placed randomly on the test bed (Figure 3.7; *Left*). Three litres of water was applied onto the test bed using a watering can with medium fine oval plastic rose that has densely distributed holes (Haws Watering Cans Ltd. Smethwick, Birmingham, UK). Water was applied across the test bed as evenly as possible within an average time of 1 min 30 seconds from a height of 70 cm (equivalent to the height of the rainfall simulator) (see Section 2.3.1, Chapter 2). The applied water was passed through a diffraction mesh for the droplets to spread more evenly before they reached the test bed surface (Figure 3.7; *Right*). The test was conducted three times to reduce chances of errors and anomalies. Water collected in the containers was measured in a graduated cylinder. The containers were placed at the same location for all three repeated tests.

Figure 3. 7: (*Left*) Containers were randomly placed on the test bed; (*Right*) Water applied from rainfall simulator frame height, through a diffraction mesh to test spatial distribution of water.

The purpose of this test was to investigate the spatial distribution of water when applied using the watering can. An even spatial distribution is determined when each of the containers contained the same or similar volume of water when measured in the graduated cylinder. However, this was not achieved. Therefore, the quality of the spatial distribution was determined using the Christiansen's Uniformity Coefficient (CU), which is expressed in percentage (%). The formula is stated below:

$$CU = 100 * \left(1.0 - \frac{\sum |z - m|}{\sum z} \right)$$

Where:

CU = Equal distribution coefficient developed by Christiansen (%)

Z = The amount of water measured in each container while testing uniformity (ml)

x = |z-m| = The total absolute value of deviations from average of the amount of water measured in all accumulation containers (ml)

m = (Σz) / n = Average amount of water (ml)

n = The number of water accumulation containers

3.7.2 Result and conclusion

A CU higher than 70% follows a normal distribution (Abdulrazzaq and Jahad, 2014), however, result of 84% is desirable. Any lesser value is considered uneven spatial distribution (Kara *et al.*, 2008). The result from this test showed an average of 82.3% from the three repeated tests (Table 3.2). This therefore concludes that the spatial distribution of water using the watering can is evenly / normally distributed (visiting student's personal communication), thus used in the following experiment as a method of water application

Table 3. 2: Coefficient of uniformity for the three tests.

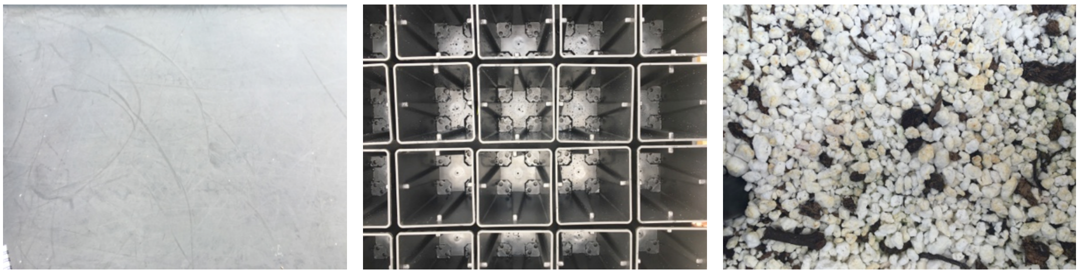
Tests	**Test 1**	**Test 2**	**Test 3**	**Average**
CU (%)	79.5%	84.6%	82.8%	82.3%

3.8 Experiment 4: Interception and retention performance by contrasting plant communities

An outdoor experiment was conducted onto six types of surface covers to determine interception and retention performance by the treatments. Retention values were obtained by collecting runoff that was generated after artificial rainfall was applied onto them using a watering can.

3.8.1 Experimental setup

A total of six Treatment Groups (TG) were used in this experiment. The TG consists of three vegetated treatments; *Dianthus* 'Haytor White', *Vinca minor* and *Bergenia cordifolia*; and three non-vegetated treatments; empty test bed, empty pots and the pots with growing media only (Figure 3.8). The three plant species were chosen based on their contrasting leaves and canopy characteristics (see Chapter 2), while the pots with growing media only represented bare soil. The empty test bed (empty TB) represented impervious surface, and the empty pots represented impervious surfaces with flexibility in surface roughness. Each TG had 36 samples per group that were placed on the test bed during each test. Plants were potted into a mix of 50% perlite (to increase drainage) and 50% *Verve* multipurpose compost, in 3.5 litre square pots (15 x 15 x 20 cm). Microclimatic data including air temperature, relative humidity, wind speed and atmospheric pressure were recorded and logged into a Campbell Scientific CR3000 data logger at hourly intervals.



a) Empty test bed b) Empty pots c) Growing media

d) *Bergenia cordifolia* e) *Vinca minor* f) *Dianthus* ‘Haytor White’

Figure 3. 8: Three non-vegetated and three vegetated treatments used in the experiment.

3.8.2 Methods

The experiments were conducted on an outdoor experimental site, situated on the fifth floor (Floor E) of Sir Robert Hadfield Building, University of Sheffield. The experiments took place only during dry days to prevent interference of natural rainfall, and to allow accurate readings of the runoff collected. The experiments were carried out between 12/08/16 and 25/10/16.

Before the start of each test, the pots were arranged in 6 x 6 grid form across a 1 m x 1 m test bed. The pots were wetted using a rainfall simulator (as described in Chapter 2) that has an even spatial distribution and high application rates (uniform flow rate of 5.5 mm/min) for 30 minutes. The pots were then drained for 2 hours for the growing media to reach container (field) capacity, and also to allow plant leaves to dry under natural weather condition. After 2 hours of draining, 4 mm of water was applied onto the treatments using a watering can. Water was distributed across the TG as slowly and evenly as possible, which takes an average of 1 minute 30 seconds. Watering height was based on the height of the simulator frame.

After applying water across the TG, they were again left to drain for further 2 hours before data collection was terminated. Runoff generated from the treatments was directed into a gutter at the end of the test bed (test bed sloped at 1.5°). The water was accumulated in a collection tank located underneath the test bed (Figure 3.9). A Druck PDCR 1830 pressure transducer was located inside the collection tank to numerically record runoff depths at 1-minute interval. The runoff data was logged into Campbell Scientific (CR800) data logger.

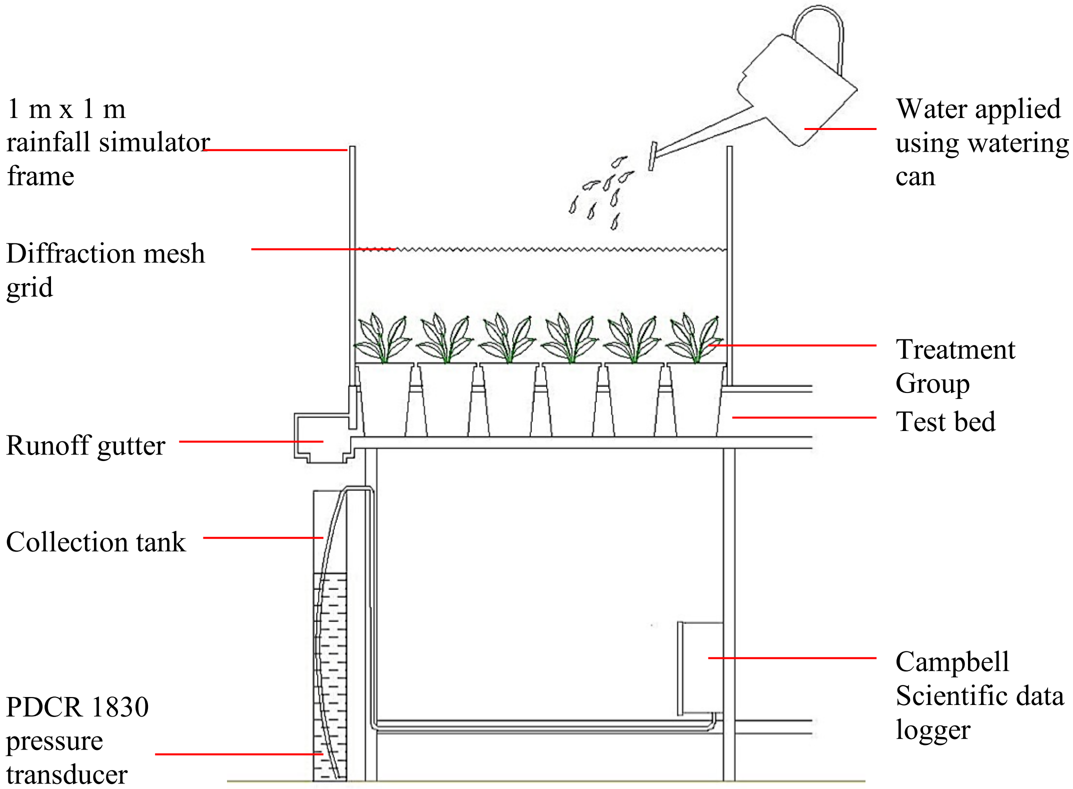


Figure 3. 9: Side elevation diagram of the experimental rig (diagram not to scale).

For the empty TB and empty pots, wetting using the simulator was not applied prior to watering can application; 4 mm of water was directly applied onto the respective surfaces. The drying period for the empty TB was only 1 hour, and 2 hours for the empty pots before runoff data was collected. Eight repeated tests were conducted for each treatment. Slow motion video recorded visual impact of raindrop upon contact with leaf surfaces. However, for this experiment, plant leaves were not harvested to calculate the total leaf area values due to the plants being utilized for different experiments.

3.8.3 Results

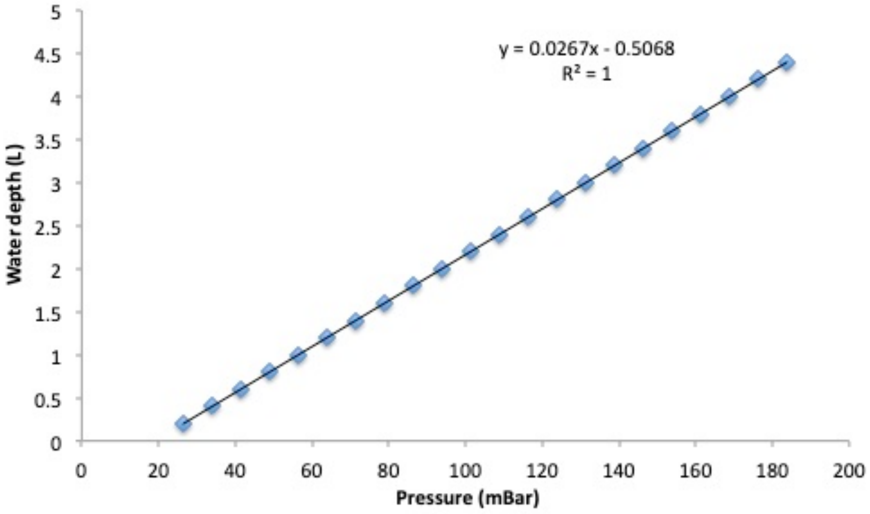


Figure 3. 10: Linear regression equation demonstrating high accuracy ($R^2 = 1$) between the pressure transducer and water volume conversion.

Moisture retention were determined by measuring runoff depths generated from each treatment group, that was collected in a collection tank and measured using a PDCR 1830 pressure transducer installed inside the collection tank. The pressure transducer measured runoff volumetrically at 1-minute interval. Prior to the experiment, the pressure transducer was calibrated by applying 0.2 litres of water at a time into the collection tank. The signal was recorded for each 0.2 litres that was applied, up to 4.4 litres. The purpose of the calibration was to enable the signal to be converted from pressure unit (mBar) to water volume (litres) using a linear regression equation with high accuracy ($R^2 = 1$) (see Figure 3.10).

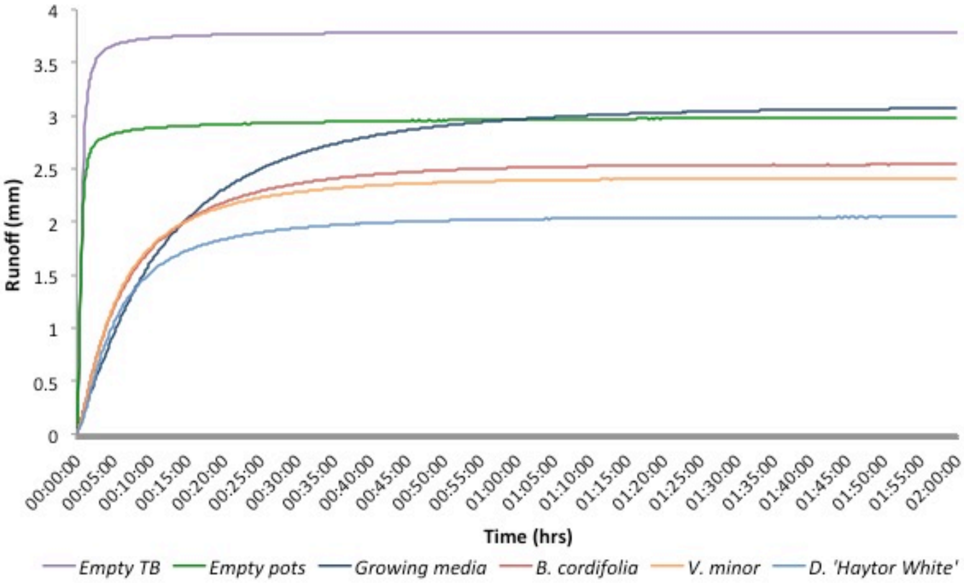


Figure 3. 11: Cumulative mean runoff generated from each TG over a 2-hour duration.

As expected, the non-vegetated treatments generated higher runoff volume and faster runoff rates (steeper slopes) compared to the vegetated treatments (Figure 3.11). The empty TB had the highest runoff volume with the fastest runoff rates. The empty pots also produced relatively faster runoff rates (line starts to flatten within 5 minutes) though the total volume was slightly lower than the growing media. For the vegetated treatments, runoff was detained for a longer period of time (between 0 to 30 minutes) before accumulating the overall runoff depths. However, runoff was detained longer by the non-vegetated growing media which took around 50-minutes to be accumulated (flat line).

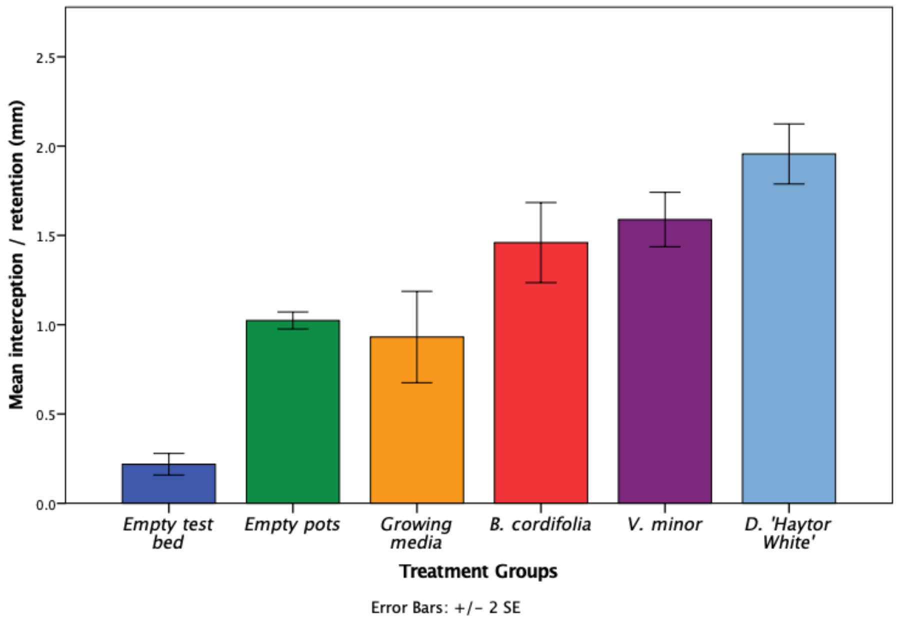


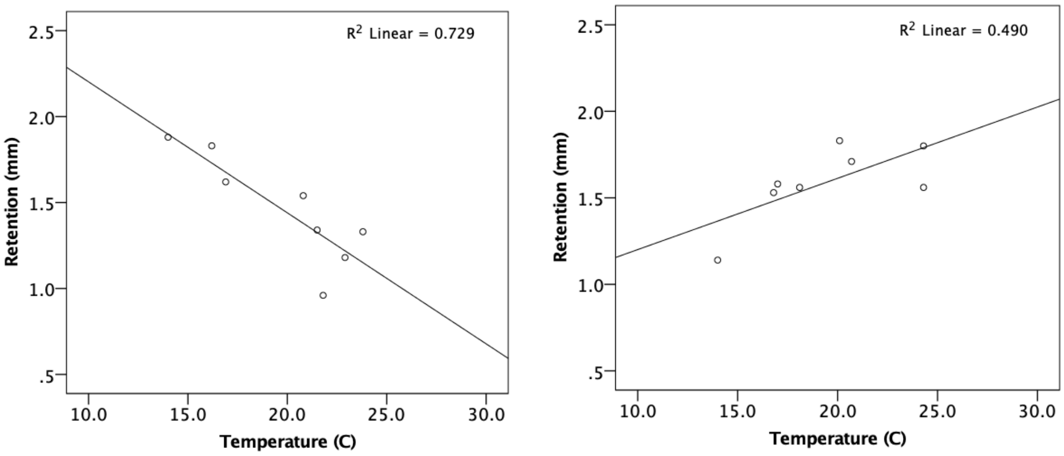
Figure 3. 12: Mean retention by the different surface covers (vegetated and non-vegetated treatments).

It is apparent that the vegetated treatments retained more moisture than the non-vegetated treatments (Figure 3.12). Overall, significant differences were observed between retention by the vegetated treatments and the non-vegetated treatments ($p < 0.05$). Between species, *D.* 'Haytor White' retained a significantly greater amount (1.96 mm) compared to the other two species ($p < 0.05$), however, there were no statistical differences found between *V. minor* (1.59 mm) and *B. cordifolia* (1.46 mm) ($p = 0.29$). As for the non-vegetated treatments, the empty pots retained slightly more water than the growing media (1.02 mm and 0.93 mm respectively), however, this was not statistically significant ($p = 0.45$). The empty TB retained the least amount of water (0.22 mm) and was statistically significantly different from the rest of the treatments ($p < 0.001$).

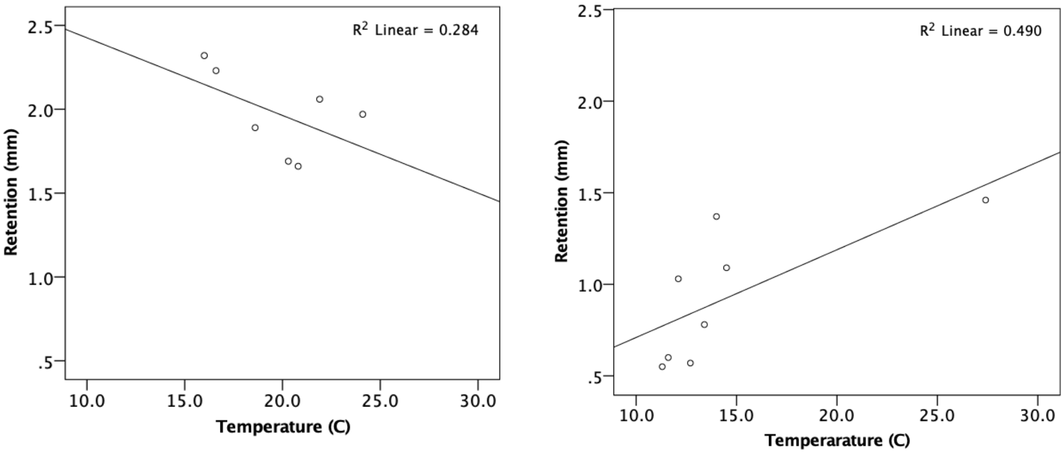
Climatic condition

Due to the experiments being conducted in an outdoor environment, the weather condition during the tests played an important role in influencing interception and retention capacities. Microclimatic data during experiment days were collected from the Campbell Scientific data logger located on site, to identify how climatic condition affects the drying cycles of plants, thus influencing interception and retention performance.

Moisture retention by the vegetated treatments (*D*. 'Haytor White', *V. minor* and *B. cordifolia*) and the growing media, during each repeated tests were correlated with air temperature and relative humidity (RH), to observe the relationships between water retention affected by these climatic variables (Figure 3.13 and Figure 3.14). Unfortunately, there was an error with the climate data collected on one of the monitoring days (02/09/2016), which resulted in missing climate data for *D*. 'Haytor White' on Test Day 5.



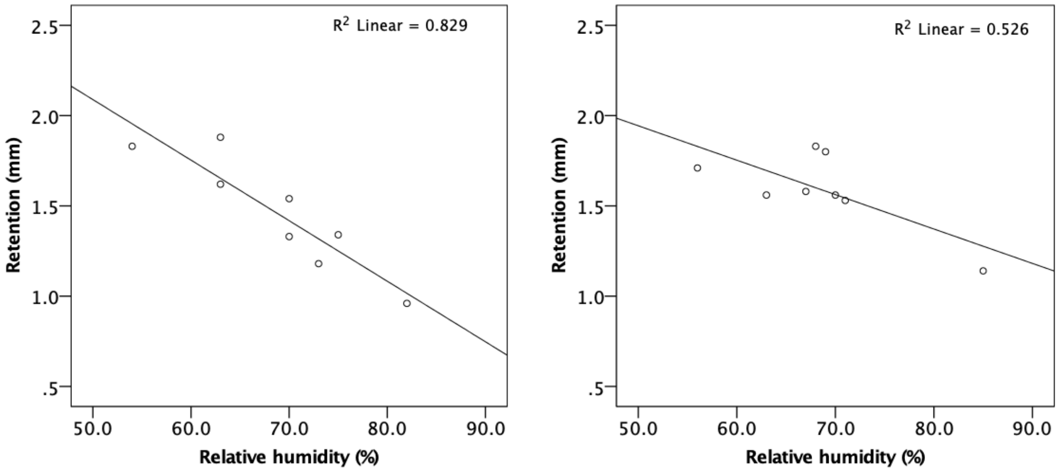
a) *B. cordifolia* b) *V. minor*



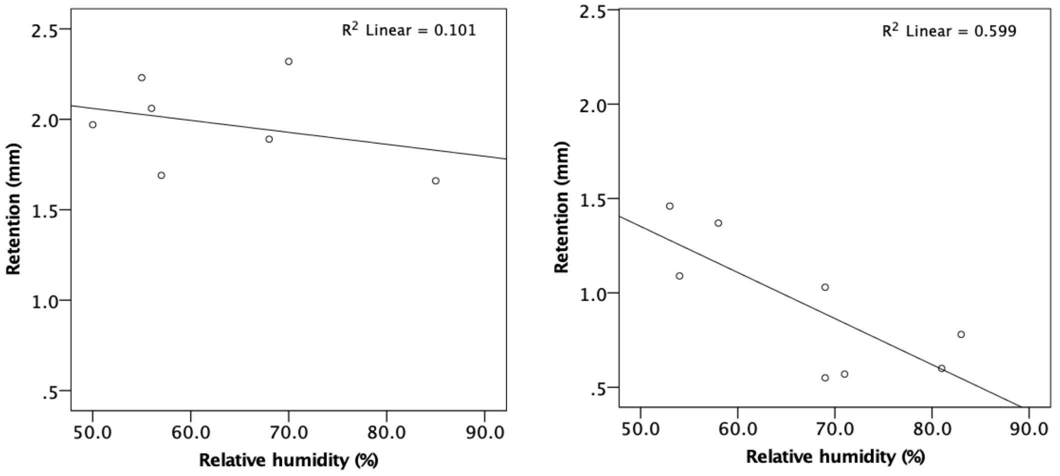
c) *D*. 'Haytor White' d) Growing media

Figure 3. 13: Correlation between retention and air temperature.

Bergenia cordifolia and *D.* 'Haytor White' showed negative correlations with temperature, with *B. cordifolia* having stronger negative correlation ($R^2 = 0.729$) compared to *D*. 'Haytor White' ($R^2 = 0.284$). This indicated that retention was low when temperature was high. In contrast, both *V. minor* and the growing media demonstrated a positive correlation between retention and temperature (R^2 = 0.490), suggesting high retention when temperature was high.



a) *B. cordifolia* b) *V. minor*



c) *D*. 'Haytor White' d) Growing media

Figure 3. 14: Correlation between retention and relative humidity.

The relationship between RH and retention showed negative correlations by all treatments, indicating low retention when RH was high. Again, *B. cordifolia* showed the strongest correlation (R^2 = 0.829). *Vinca minor* and the growing media showed a moderate correlation (R^2 = 0.526 and R^2 = 0.599 respectively), while *D.* 'Haytor White' showed the weakest relationship with RH (R^2 = 0.101). Discussions are provided in Section 3.9.3.

Visual observation of raindrop impact

According to Herwitz (1987), raindrop impact is highly affected by raindrop size and rainfall intensity, and large-sized droplets limit the amount of water retained on leaf surfaces. Although this experiment did not directly measure raindrop size or the intensity of the applied water, a slow-motion video was taken to observe and evaluate how water droplet impacted on the leaves. Based on the visual observation, water that dropped onto the hydrophilic leaves of *B. cordifolia* was detained on the surface until the leaves became heavy and saturated. Due to large leaf surfaces of *B. cordifolia*, when more droplets hits the surface, they merged with the existing droplets and created a pool or 'puddle' especially on leaves that were horizontally angled, which eventually shed off as the leaves became heavier (Figure 3.15). Droplets that fell on vertically angled leaves tend to merge with existing film of water, and as droplets on the leaf surfaces gets bigger, they flowed off along the stem onto the growing media / outside of the pots.

When droplets fell onto the leaves of *V. minor*, due to relatively large droplets impacting on smaller leaf, larger droplets tend to splash and produced smaller droplets (Figure 3.16). The leaves of *V. minor* also deformed and deflected downwards due to heavy droplet impact. Similar to *B. cordifolia*, as smaller droplets that were retained or detained on the leaf surface coalesced and formed relatively larger pool of water, they dripped off from the canopy tip. This process of water flow was faster (dripped more frequently from the leaves) on *V. minor* compared to *B. cordifolia* due to smaller leaf surface area. Furthermore, *V. minor* tends to have more droplets falling in the gaps in between the leaves due to its small leaf size, although droplets that fell in the gaps were either re-intercepted by other leaves or immediately reached the growing media.

Dianthus 'Haytor White' has highly hydrophobic leaf trait. Due to its narrow leaf shape and orientation of the leaves, there was more water splash once droplets hit the leaves. Its hydrophobic character allowed droplets to coalesce into bigger droplets and eventually rolled off once the droplets becomes too big and heavy for the leaf to hold (Figure 3.17). Due to high number of small leaves therefore having more layers of leaves, droplets that fell from a leaf were either intercepted by the lower layers of leaves or got stuck in small angles between the leaves and the stem. Some eventually fell onto the growing media. Figure 3.15, 3.16 and 3.17 presents the still-captured photo of intercepted (and retained) water from the slow-motion videos that were recorded.

Figure 3. 15: Water forming 'puddle' / pooling effect when small droplets merged together on the leaf surface, and dripped off from the leaf when it became too heavy on *B. cordifolia*.

Figure 3. 16: The leaves of *V. minor* were too small and pliable; droplets tend to drop off the leaves as the leaves deformed and deflected due to the droplets impact.

Figure 3. 17: High droplet contact angle formed by droplets coalescence due to high leaf hydrophobicity of *D.* 'Haytor White'.

3.8.4 Conclusion

Vegetated treatments were found to significantly retain more moisture than the non-vegetated treatments. This is attributed to the presence of plant canopies, which helped to capture, retain and detain moisture more effectively compared to the treatments with the absence of plant canopies, with the exception of the growing media which detained longer than the vegetated treatments. It was also found that plant leaf traits played a significant role in reducing runoff more efficiently, as different species respond to water droplets differently, based on their morphology and physiological aspects. Narrow-leaved species (i.e. *D.* 'Haytor White') was found to retain water by the greatest margin than broad-leaved species such as *B. cordifolia*. The planting community was capable of intercepting and retaining almost 2 mm (50%) of the applied 'rainfall' with 1-min 30s duration, depending on the species type.

3.9 Discussion

3.9.1 Moisture storage capacity by different plant species (small scale preliminary experiment)

The two methods of water application (spraying and submerging) showed contrasting results. *Dianthus* 'Haytor White' retained the highest amount of moisture when sprayed (0.60 mm) but the least when submerged in water (0.34 mm). In contrast, *B. cordifolia* retained the least amount of water when sprayed (0.33 mm), but retained the highest when submerged (0.45 mm). *Vinca minor* performed moderately in both cases (0.38 mm when sprayed and 0.40 mm when submerged).

These results may be associated with the leaf morphology, namely leaf shape, size, angle and orientation, as well as leaf surface texture and wettability traits. Depending on the leaf hydrophobic characteristics, when water is sprayed onto plant leaves, they either form a thin layer or film of water on the surfaces and eventually evaporate back into the atmosphere, or coalesce into larger droplets and drop off the leaves when they become heavy. *Dianthus* 'Haytor White' has high hydrophobic leaves, therefore, when moisture droplets fell on their leaves, the droplets coalesced together to form larger droplets. The larger sized droplets either remained as large droplets on the leaves causing heavier pot weights, or fall off the leaves. In the case of *D.* 'Haytor White' those droplets that fall off the leaf tip have a high chance of being re-intercepted by the leaf layers beneath it; this is due to the relatively high number of small leaves present (uncounted) and the overlapping, multi-layers of foliage associated with this species. Furthermore, due to the narrow and upward facing leaves of *D.* 'Haytor White', it allows water droplets to roll deeper into the canopy, and / or retained in the small angles between the leaves and stem.

As stated above, *B. cordifolia* retained the least amount of moisture when sprayed. Its smooth and glossy leaves may have influenced the low moisture retention when sprayed by easily flowing and dripping water droplets off the canopy (including falling away from the pot and not reaching the growing media when the leaves overlap the edge of the pot). Furthermore, the leaf shape formed an 'umbrella effect'; when water was sprayed from above the canopy, the abaxial leaf surface was not in contact with water (most of them remained dry), which reduced the opportunity for more water retention. Although *B. cordifolia* has a broad leaf shape, it has fewer numbers of leaves. Therefore, when droplets fall off from the leaves, instead of being re-intercepted by more leaf layers, it tends to fall directly into the soil / growing media, thereby producing more runoff, or fall outside of the pot and being lost from the plant system.

a) *B. cordifolia* b) *V. minor* c) *D.* 'Haytor White'

Figure 3. 18: Leaf surface wettability showing 'visual' moisture droplet retention on leaf surfaces.

In contrast, submergence of plant canopies in water provides higher apparent retention capacity for different plant species. While it may not work the best for *D.* 'Haytor White', this method works more effectively for *B. cordifolia. Bergenia cordifolia* retained the highest moisture, while *D.* 'Haytor White' with the least amount. Submerging ensures that the canopy is fully saturated with water, both the adaxial and abaxial leaf surfaces. When the plants were pulled out from the submergence, water that was retained within the canopy remained within the leaf surfaces. Here, leaf area may have to some extent, played a role in retaining moisture due to more leaf surfaces being exposed to water during the immergence. *Bergenia cordifolia* has higher total leaf area compared to *V. minor* (Table 3.1), thus it was able to retain more water than *V. minor*. Although leaf area of *D.* 'Haytor White' was only slightly lower than that of *B. cordifolia,* the hydrophobic character of *D.* 'Haytor White' may have resulted in lower retention using this method. When *D.* 'Haytor White' was pulled out from the immergence, due to its angles and orientation of leaves, droplets that coalesced may have immediately rolled off the canopy, thus resulting in less effective retention capabilities. However, even though *V. minor* had the lowest total leaf area, it retained higher moisture than the other two species, per unit of leaf area, for both methods. This was unexpected due to relatively small leaf size of *V. minor*, but the result may be associated with its hydrophilic leaf surface texture.

This study suggests that the submerging method is preferred to determine plants' maximum moisture storage capacity because it ensures complete exposure of plant leaf to water. However, this of course, may not be a representation of what actually occurs in nature, as rainfall may not envelope an entire leaf (i.e. completely cover the adaxial and abaxial surfaces). Interestingly though, for the two species (*B. cordifolia* and *V. minor*), this finding contradicts with a study by Wohlfahrt *et al*. (2006), who found that maximum moisture storage capacities were higher using the spraying method compared to submerging. Their study suggested that spraying was much more effective in wetting leaf surfaces due to formation of individual coherent droplets, which may not be formed through submerging (Wohlfahrt *et al*., 2006), which was the case with *D.* 'Haytor White'. These droplets formation however, is highly dependent on leaf surface roughness, which is also influenced by leaf shape and orientation, as discussed above.

3.9.2 Interception and retention by contrasting plant community (larger scale outdoor experiment)

The effectiveness of canopy interception and retention was further validated by examining retention capabilities on a larger community (group) scale. Variable retention capacity and runoff rates were due to the different species. Although runoff detention was not the primary focus of this experiment, the findings did observe some extent of runoff detention by the vegetated treatments, and between the empty pots and the growing media. The empty pots had higher cumulative runoff than the growing media, but the growing media detained water longer before reaching a 'flat line' (refer to Figure 3.11). This is because water that goes through the growing media (soil) had to go through the small pores in the soil, therefore took longer time to 'release' the excess water and becomes runoff compared to the empty pots and empty test bed (impervious surface). Both the empty test bed and empty pots did not detain any water due to their impervious surfaces, therefore immediately generating runoff at a fast rate. The growing media detained moisture for longer duration compared to the vegetated treatments; runoff was stabilized after around 50 minutes for the growing media compared to around 35 - 40 minutes for the vegetated treatments. This may be because a greater proportion of the water enters the growing media and flows through the pores and takes longer to eventually become runoff, while for the plants, droplets may drop off from the leaf tip (as leaves may extend outside of the pot area) directly onto the test bed, thus immediately became runoff.

As for the vegetated treatments, the presence of the canopy helps capture water and prevents the same volume of water having to progress through the growing media. When the plant canopies became saturated, the water then drips off from leaf surfaces. This water either falls onto the growing media (this tends to be minimal), or directly onto the impervious surface and become runoff, resulting in less opportunities for longer detention periods. Furthermore, any water entering the growing media may have a faster route due to roots creating greater diameter pore spaces within the growing media (McCallum *et al.*, 2004, cited in Yuan *et al.* (2017). However, this result is inconsistent with the findings by (Yuan *et al.*, 2017), who found greater detention by vegetation (forbs) than bare soil, in which he suggested that the plant may have contributed to longer detention due to roots filling in some of the soil macropores, instead of enlarging the pores.

In terms of accumulated runoff depths generated from the treatments, it was obvious that the presence of plant canopy played a significant role in rainfall interception - vegetated treatments retained higher amount of moisture compared to the non-vegetated treatments. This agrees with the general knowledge of canopy interception, and the result is consistent with a number of previous studies (Nagase and Dunnett, 2012; Stovin *et al*., 2015; Kemp *et al*., 2019). Between plant species, *D*. 'Haytor White' intercepted and retained the greatest amount of moisture, followed by *V. minor* and finally *B. cordifolia*. This result is consistent with experiments conducted on the individual plants (Section 3.5), as well as a number of previous studies on the larger-scale planting, that found needle-leaved trees intercepted and retained higher amount of moisture compared to broad-leaved trees (Clark, 1940; Xiao *et al*., 2000; Wang *et al*., 2007; Carlyle-Moses and Gash, 2011; Li *et al*., 2016).

As elaborated above, physical leaf traits of *D*. 'Haytor White' such as small, narrow leaves with upward-facing leaves orientation may have contributed largely to higher moisture retention. In contrast, broad leaves *B. cordifolia* have smaller number of leaves and glossy leaf surfaces that allows droplets to flow easily, resulting in higher canopy drips, therefore less retention on leaf surfaces. However, it was unexpected that the empty pots retained slightly higher amount of water than the growing media. Theoretically, this could be explained by the fact that although the growing media was supposedly at field capacity after the 2 hours of draining, the small amount of moisture retained by the empty pots may be held in between pots and underneath pots, or in the corners of the empty pots instead of directly becoming runoff. While water that goes through the growing media at field capacity state immediately becomes runoff (although takes longer time to generate runoff) as the growing media could no longer retain or hold any more water.

3.9.3 The relationship between retention and climatic conditions

Negative correlations were found between *B. cordifolia* and *D.* 'Haytor White' and temperature and positive correlations between *V. minor* and growing media with temperature. Retention by *B. cordifolia* and *D.* 'Haytor White' was low when temperature was high. This may be associated with decreased stomatal conductance by these species under high temperature, thereby limiting ET rates, which then affects moisture storage capacity for retention. In contrast, *V. minor* and the growing media performed as anticipated; retention was high when temperature was high. This is because at higher temperatures, moisture storage capacity in the plant is restored more rapidly as water is evaporated and transpired between rainfall events (i.e. evapotranspiration (ET)) at a higher rate (Poë *et al.*, 2015). This then provides more 'storage' space for water to be intercepted by the foliage and retained within the canopy.

Negative correlations were found on all treatments with relative humidity (RH), indicating that interception was low when RH was high. This is expected as high humidity in the atmosphere reduces the opportunity for higher ET rate because available moisture in the air is already high (Sterling, 2004). Therefore, when minimal ET takes place, moisture storage capacity in the plant is not fully restored, which then decreases the volume of moisture capture and subsequent retention by the plant canopies.

3.10 Key findings

- Retention from vertically applied water (spray and watering can) was highest with needle-leaved *D.* 'Haytor White' (0.60 mm when sprayed; and 1.96 mm by watering can) compared to broad-leaved *B. cordifolia* (0.33 mm when sprayed; and 1.46 mm by watering can) and small-leaved *V. minor* (0.38 mm when sprayed; 1.59 mm by watering can) when observed in both, individual plant and in groups.
- *Bergenia cordifolia* retained higher moisture when submerged (0.45 mm) in water than when sprayed (0.33 mm), which may be associated with both abaxial and adaxial leaf surfaces being exposed to water, where the abaxial surface may have higher water adhesion potentials (different surface texture than the adaxial).

- Overall, this experiment suggests that groundcover plantings can retain between 1.46 mm and 1.96 mm of rainfall (36.5% and 49% of the applied rainfall with duration of 1 minute and 30 seconds), though proportion varies depending on plant traits.
- Field capacity was achieved within 2-hours of draining after plants were saturated with water. This is consistent with the FLL (German Landscape Research, Development and Construction Society) laboratory test used for determining field capacity for green roof substrate.
- Leaf area value did not play a significant role in water interception. *Dianthus* 'Haytor White' had the highest leaf area, and retained the highest moisture only when sprayed, but retained the least when submerged. While *B. cordifolia* retained the highest moisture when submerged and retained the least when sprayed although it only had slightly lower leaf area than *D.* 'Haytor White'. *Vinca minor* that had the lowest leaf area retained the highest moisture on a per leaf area unit.
- The non-vegetated treatments (empty test bed, growing media and empty pots, respectively) retained less moisture than the vegetated treatments due to the absence of canopy and foliage to help capture and retain water on their surfaces.
- There was no significant pattern between interception and temperature; however, in low relative humidity atmosphere, retention was high.

3.11 Chapter summary

The two scales of experiment in this chapter investigated the efficiencies of interception and retention performance by different plant species with contrasting leaf traits. Findings of the two experiments showed consistent results, which suggest that leaf shape does play a role in influencing interception and retention. Narrow-shaped leaves were found to capture water more effectively compared to plants with fewer large broad leaves and many small leaves. *Dianthus* 'Haytor White' intercepted water by the greatest margin (1.96 mm), while *B. cordifolia* intercepted the least (1.46 mm). Although visually, broad-leaved *B. cordifolia* may be associated with larger leaf surface (not actual unit of leaf area), but its morphological leaf characteristics (e.g. surface texture and foliage angle / orientation) resulted in lower retention compared to narrow-leaved species.

Leaf morphology was found to play a bigger role in rainfall capture and retention than leaf wettability traits (hydrophobicity / hydrophilicity). Apart from plant canopy and leaf traits influencing these processes, different types and characteristics of water application also played a role in influencing retention performance. In the real world, this includes rainfall characteristics. Although rainfall characteristics were not thoroughly observed and measured in this experiment, it does not exclude the possibility of the influence and one of the key parameters determining rainfall interception and retention by plants. Between the two water application methods (spraying and submerging), although not significant, plants that were sprayed with water retained more overall moisture compared to when submerged, however, the retention pattern depends on species. The results and discussion presented here will be brought together with the findings of Chapters 4 and 5, and further discussed with an overall synthesis, along with a final conclusion of the research in Chapter 6.

The next chapter (Chapter 4) discusses an experiment conducted in an outdoor environment. The purpose of the experiment was to observe plants' retention and evapotranspiration (ET) performance through monitoring plant weights relative to rainfall, in which the plants were exposed to natural weather conditions.

CHAPTER 4

RAINFALL RETENTION AND EVAPOTRANSPIRATION BY DIFFERENT PLANT TYPES UNDER NATURAL CLIMATIC CONDITION

4.1 Introduction

The findings from the previous chapter (Chapter 3) relate to experiments to determine the efficiencies of rainfall interception and retention by different plants with contrasting canopy characteristics, through different means of water application. Rainfall interception and retention are influenced by available moisture storage capacity (Herwitz, 1987; Kume *et al.*, 2008; Xiao and McPherson, 2016), which is a function of moisture loss by the plant via transpiration and evapotranspiration (ET) / evaporation (if soil is involved). Plant canopy architecture not only affects the capacity to capture and direct precipitation, but also influences a plant's capacity to remove moisture from the soil. Drying out of soil or other growing media by the action of plants can recharge the capacity of the soil to hold water in between rainfall events (Berghage *et al.*, 2007). Soil that is already saturated by an initial rainfall event can no longer hold any more rainwater, and is likely to lead to surface runoff and potentially flooding. Thus the role of plants may be important in rapidly returning the soil to a state whereby further rainwater can be held. This is particularly important when there are a series of consecutive heavy rainfall events, where ET can return water to the atmosphere and at least partially dry out the soil, before a subsequent rainfall event takes place.

This chapter investigates how the leaf canopy architecture of six different plant taxa affects rainwater retention and ET relative to rainfall and dry periods, under natural climatic conditions. It aims to identify generic traits that could be associated with high ET capacity. Even within the one taxa, the size of the leaf canopy may be important, and this aspect is explored by pruning half the specimens of each species to reduce the size of their canopies, to observe how this impacts on rainfall retention and ET rates. Water use by the plants was recorded gravimetrically by weighing plants on a daily basis and monitoring weight changes with reference to climatic conditions; the experiment being conducted outdoors under natural conditions. Plants' responses to water availability and other climatic variables were recorded by assessing signs of stress in the plants, using visual scoring and chlorophyll fluorescence techniques.

4.2 Key objectives and questions of experiment

The objectives of this experiment were:

1. To determine how moisture loss by different plant taxa is affected by prevalent weather conditions.
2. To identify whether plant canopy size within a particular taxon affects moisture loss and survival.
3. To determine which plants can combine stress tolerance with good ET potential.

The research questions of this experiment were as follows:

1. How do different plant types respond to moisture availability under various climatic conditions?
2. Which plant types intercept moisture, have high ET rates, and thus dry the soil / growing media most effectively?
3. How does plant canopy size affect retention, ET rates, and influence susceptibility to drought stress?

4.3 Hypotheses

For this experiment, two hypotheses were developed:

- Species that possess broad leaves will evapotranspire more water than those that possess narrower, fine leaves.
- Plants with smaller or narrower leaves (i.e. generic traits often associated with greater drought tolerance) will have a higher chance of surviving low moisture conditions compared to species with larger leaves.

4.4 Experimental setup

Six plant taxa were chosen in this experiment (*Dianthus* ‘Haytor White’, *Bergenia cordifolia*, *Vinca minor*, *Festuca glauca*, *Hosta sieboldiana* and *Pachysandra terminalis*), to further investigate their evaporative losses with regards to their interception and retention behaviour. Plants were selected to reflect different leaf types, with two taxa representing each form (Table 4.1). The plants were potted into John Innes compost No. 2; a loam-based compost that is a naturally reduced peat mix (loam, peat, sand, fertilizer), in a 3.5 litre square pot (15 x 15 x 20 cm). Daily microclimatic conditions were recorded using a Campbell Scientific weather station. Two ARG-100 tipping bucket rain gauges recorded rainfall depths on the experimental site and mean rainfall data were taken from the two rain gauges. SM150T moisture sensors recorded moisture contents in each sample treatments, and data were logged in General Purpose data loggers (GP1 and GP2) (see Chapter 2 for detailed instrument specifications). A Marsden B-100 waterproof bench scale was used to monitor pot weight on a daily basis.

Table 4. 1: Leaf shape categories of the six plant taxa that were used in this experiment.

Narrow / linear leaves	**Large, broad leaves**	**Small, simple leaves**
 *Dianthus* 'Haytor White'	 *Bergenia cordifolia*	 *Vinca minor*
 *Festuca glauca*	 *Hosta sieboldiana*	 *Pachysandra terminalis*

4.5 Methods

The experiment was conducted on the roof of the Sir Robert Hadfield Building, University of Sheffield. Each species had two canopy sizes; 'full' and 'half'. The full canopy was left untouched, therefore allowing plants to naturally grow, while for the half canopy, some of the leaves were trimmed for reduction in canopy size / area. Two approaches were used to reduce the canopy size; for *B. cordifolia* and *H. sieboldiana*, which had small number of broad leaves, the leaves were physically counted and half of the number of the leaves were cut and removed to obtain the 'half' canopy sample. For the rest of the species, due to large number of small leaves (therefore posed a difficulty to physically count the leaves), the foliage was trimmed based on the surface area of the pot. (see example in Figure 4.1). The experimental data utilized the full vs. half canopy treatments to determine how much water was funneled from the canopy into the pot, to determine the extent to which this influenced weight data results.

Six plant species with the two canopy sizes, each with six replicates (total 72 plants) and pots with growing media only (control pots) were placed on the roof for daily weight monitoring. Each plant pot was arranged 500 mm between each other (see Figure 4.2). For each species and size, a SM150T soil moisture sensor was placed within the growing media for continuous record of moisture content throughout the monitoring period. Moisture content data was logged into GP1 and GP2 at 1-minute interval and data was collected every 2 weeks.

Full-canopied *V. minor* Half-canopied *V. minor*

Figure 4. 1: Example of full (*left*) and half (*right*) canopy size of *V. minor*.

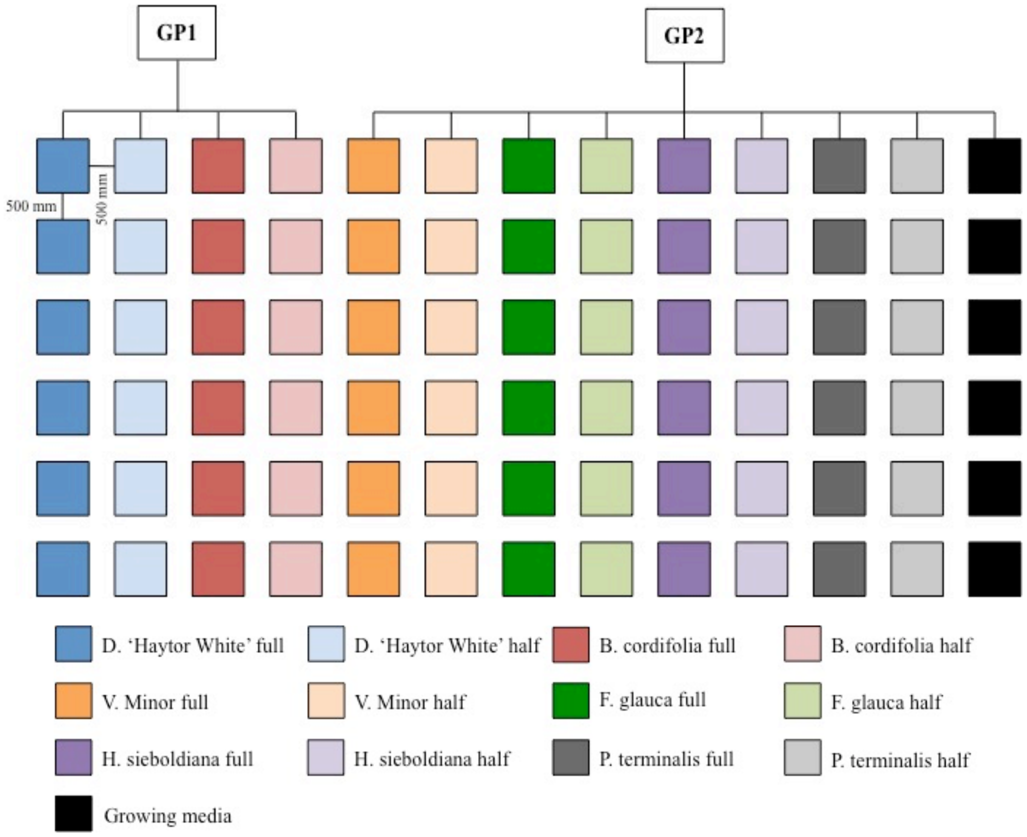


Figure 4. 2: Arrangement of treatments on the experimental site.

At the start of the experiment, all plants were intensely watered for 1 hour (11:00 – 12:00), and then drained to field capacity for further 2 hours. After 2 hours, each plant, except for the plants containing moisture sensors, was weighed using a Marsden B-100 waterproof bench scale at 14:00 to obtain the weight of the plant pot at field capacity. On the subsequent days, each plant was weighed daily at 14:00. The overall weighing process of 60 plants took an average of 30 minutes. The weighing took place for a total of six weeks, between 14/08/17 and 26/09/17. No additional irrigation was given apart from natural rainfall. Due to inability to access the experimental site during non-working hours, weight data were not taken during weekends. However, as the weight changes are expected to follow a linear pattern; data were interpolated by taking the difference between weight on Friday and Monday, and dividing by three, and the mean weight change was used to estimate daily weight change during the weekends. Any natural rainfall events would cause the soil moisture storage to be partly or fully restored, and was evidenced by weight gains in the pots. Pot weight changes in kg were converted into water volume in liters by using the relationship that the density of water is 1000 kg / m^3, and volumes (liters) were converted to water depths (mm) by assuming that the weight changes occurred based on the plan area of the pot, i.e. 0.15 m x 0.15 m = 0.0225 m^2. This allows for the gravimetric data to be understood in terms of conventional precipitation measures, i.e. mm of rainfall.

After the experiment was completed, chlorophyll fluorescence was measured for three consecutive days using a Handy Plant Efficiency Analyzer (Hansatech Handy PEA) to measure plant stress. The purpose was to observe how the physical features of the plants changed and affected the physiological activities throughout the experiment and to identify which species showed stress tolerance or intolerance signs. Dark adaptation leaf clips were placed onto one leaf for each plant for 20 minutes, and measurements were made on each clip. The physical conditions of the plant canopies were also visually assessed by observing and taking photos of each plant at the start of the experiment, every two weeks and on the last day after the experiment was complete, to identify any seasonal changes or stress signs.

Finally, after the experiment was complete, plant leaves of each species were harvested to obtain the total number of fresh leaves, total weight of fresh leaves and total leaf area. The numbers of fresh leaves were obtained by physically counting each leaf, and then weighing to obtain fresh leaf weight. Leaf area values were obtained by taking photographs of the harvested leaves against white background, and then using ImageJ software (an image processing software) to calculate total leaf area by measuring green pixels of each leaf against a scale bar (cm^2). Leaf area data in the thesis are presented in m^2. However, due to large number of leaves by *F. glauca*, total number of leaves and total leaf area could not be obtained using this method. This is because counting and arranging the leaves to measure leaf area values would take too much time, which will cause the leaves to dry / die as they had already been removed from the plant. Therefore, for *F. glauca*, only the weight of fresh leaves was available. In order to obtain leaf area values for *F. glauca*, samples of 20 blades of leaves from three random plant replicates of each canopy sizes (six plant in total) were photographed, and leaf area values were calculated using ImageJ software. The leaves were then weighed, and the average weight and average leaf area of the six plants (three for each canopy size) were taken. Leaf area value of *F. glauca* was estimated by multiplying the leaf area value of the 20 leaves and the 20 fresh weights, by the same multiplication factor with the average fresh weight of the leaves of the whole plant.

4.6 Results

4.6.1 Data interpretation

Actual weight (g)

Each plant pot was weighed daily (Monday to Friday) using a balance scale during the experimentation period. The term 'actual weight' or 'daily weight' used in this thesis refers to the value of the pot weights in unit gram (g). Weight data for the weekends were estimated by interpolating weight differences between Mondays and Fridays.

Weight changes / weight difference (g)

Weight change refers to the difference of weights between two given days. This can either be weight increase or decrease that is attributed to rainfall interception and retention or ET by the plants, depending on the weather conditions. Weight changes of the treatments were calculated by subtracting the weight on any given day from the value of the previous day. E.g. Weight value of *B. cordifolia* on Monday is subtracted from weight value on Tuesday to obtain the weight changes between those two days. Therefore, a positive weight change value indicates moisture gain, while a negative weight change value indicates loss of moisture.

Moisture changes (mm)

Moisture changes of the treatments represent the daily amount of moisture gains and moisture losses with regards to the rainfall data, which is expressed in water depths unit (mm). This is obtained by converting the 'weight difference' from mass unit (kg) to volume (liters) and then to water depth (mm) by dividing the weight difference by the pot surface area (0.0225 m^2) (see method in Section 4.5).

Interception and retention (mm)

Moisture interception and retention is when rainwater is captured (interception) and held (retention) within the plant leaves and canopies. Any gain in weight is assumed to be due to moisture retention. As it is unclear whether moisture gain was due to water being held by the plant canopies or the growing media (or even both), mean daily water retention by the plant canopies was estimated by subtracting the daily moisture change of the growing media from daily moisture change of the plants. Therefore, water retention by the plants referred to in this chapter is an estimation of water retained within the plant canopies only.

Evapotranspiration (mm)

Evapotranspiration (ET) is the moisture loss from the plants and the growing media. Any loss of weight is assumed to be moisture loss due to ET, based on the climatic factors (typically due to warmer / high temperature and lower relative humidity).

Moisture content values (%)

Moisture contents was obtained from readings of SM150T moisture sensors, and expressed in percentage (%) of moisture content, which was obtained through soil-specific calibration that was conducted prior to the experiment (see Section 2.3.4 in Chapter 2).

Moisture content changes (%)

Moisture content changes of the treatments consisted of the difference in moisture content (%) between two given days, which represents the daily amount of moisture gains and moisture losses within the pots with regards to rainfall. This was calculated by subtracting the moisture content on any given day from the value of the previous day. E.g. Moisture content of *B. cordifolia* on Monday is subtracted from moisture content on Tuesday to obtain the moisture content changes between those two days.

4.6.2 Microclimate data

Rain was recorded for 27 days (Figure 4.3), with peak precipitation on Day 23 (11.3 mm). The longest continuous dry period was observed for 11 days, from Day 7 to Day 17, with total rainfall of only 0.9 mm. During the experiment, mean air temperature was 14.4°C (ranged from 11.3°C to 19.3°C), and humidity ranged between 67.5 and 89.6%. The highest temperature was observed on Day 15 with

19.3°C. There was a slight decrease in air temperature from the first half of the monitoring period (Day 1 to Day 23, ranging between 12.6°C and 19.3°C) to the second half (Day 24 to Day 44, ranging between 11.3°C and 14.9°C). This may be due to the transition of season from late summer to early autumn. As rainfall events were higher and more frequent during the second half of the monitoring period, relative humidity (RH) was also proportionally higher during these times.

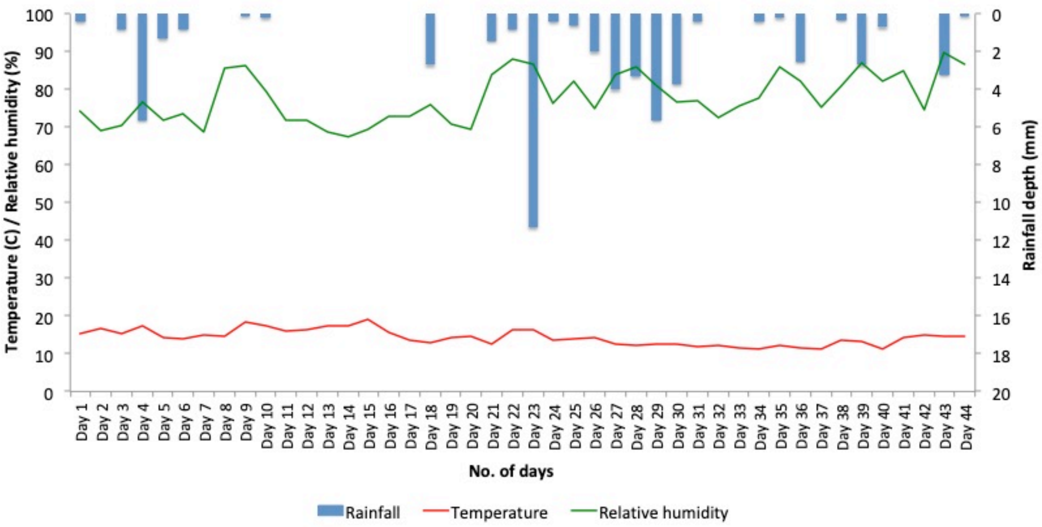


Figure 4. 3: Mean daily rainfall, air temperature and relative humidity throughout the monitoring period.

4.6.3 Plant weight

Mean daily weights of each species were obtained by dividing the total actual weights of each plant species by the number of species replicates (five). Figure 4.4 and Figure 4.5 present the mean weights of each plant species (full and half canopy), in response to rainfall occurrences throughout the monitoring period of 44 days.

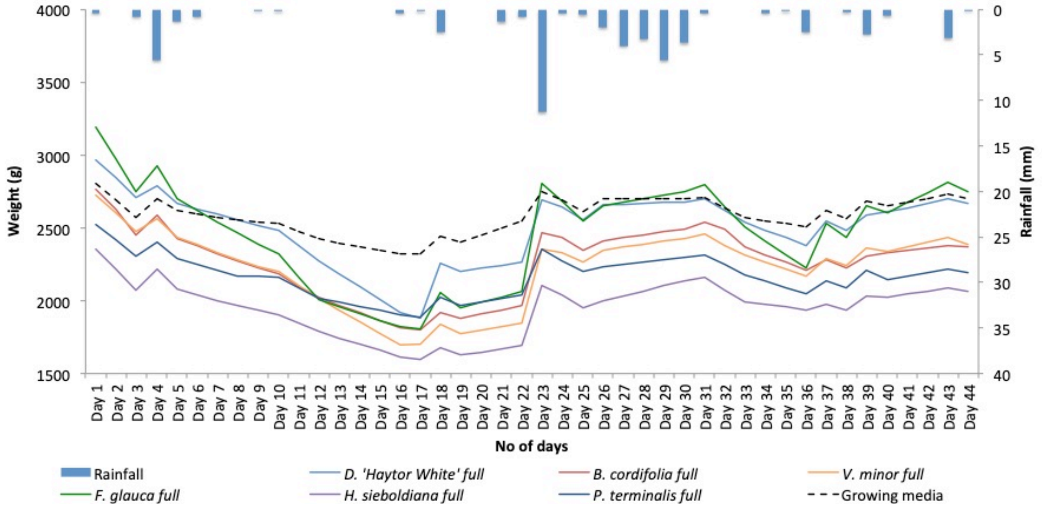


Figure 4. 4: Mean daily weights of the full-canopied plants and the growing media relative to rainfall.

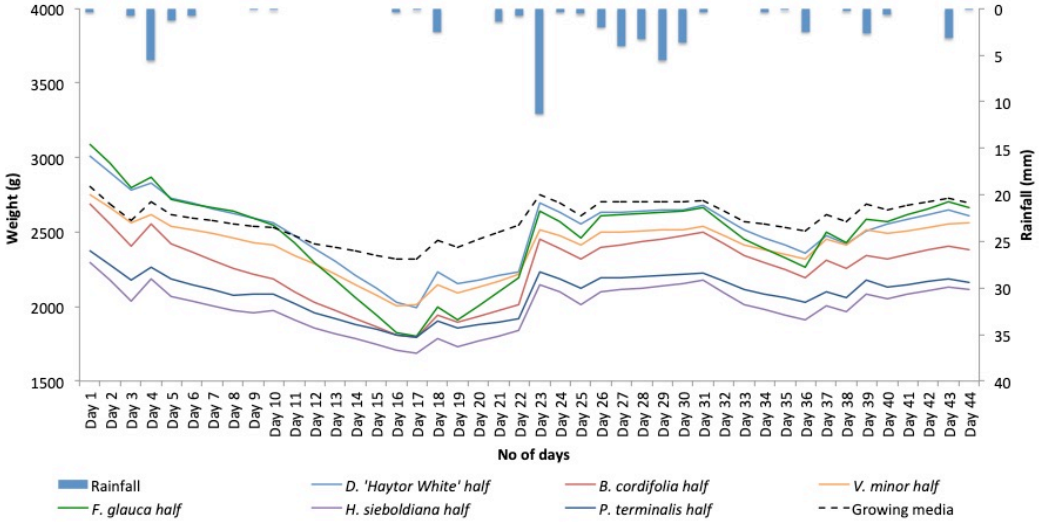


Figure 4. 5: Mean daily weights of the half-canopied plants and the growing media relative to rainfall.

Although all of the treatments started with moisture content at field capacity on Day 1, the starting weights of each treatment were not consistent; some plants started with higher weight at field capacity (e.g. *F. glauca* and *D.* 'Haytor White'), while some with lower starting weight (e.g. *H. sieboldiana* and *P. terminalis*). This variation may be due to the differences in the plants' fresh weights, number of leaves and other morphological features including roots and plant biomass of different species varieties.

Generally, the daily pot weight fluctuations correspond to the rainfall variations; weights increased during / after rainfall occurrences and decreased during dry periods. This is consistent with the natural phenomenon of plants capturing and retaining rainwater during rainfall and evapotranspiring moisture in warmer conditions. A noticeable decrease in weights was observed within all plant taxa, both for the full and the half-canopied plants from Day 7 to Day 17, which corresponds to the longest observed dry period, indicating highest ET losses.

Analysis of variance (ANOVA) with repeated measures were undertaken to observe whether there were statistical differences between the actual weights of each species and the two canopy sizes over the entire experimental period (44 days). For both canopy sizes, *F. glauca* was observed to have the highest variation of weight readings throughout the experiment. It gained the most weight during rainfall events (which may be associated with water retention), and lost the most weight during dry period (likely due to ET), which is further discussed in Section 4.6.8 and 4.6.9. However, between the two canopy sizes, only *F. glauca*, *H. sieboldiana* and *V. minor* showed statistical differences ($p < 0.05$), in which the largest differences between the two canopy sizes were seen on *V. minor* ($p < 0.001$). Canopy size variations of each species are discussed in Section 4.6.11.

4.6.4 Moisture sensor data

Moisture content was recorded for the entire experimental period at 1-minute interval, but unfortunately, there were gaps in the continuity of the data. The data was unable to record for the growing media, full and half-canopied *P. terminalis* and half-canopied *H. sieboldiana* from Day 3 to Day 8, and Day 27 to Day 31. For the rest of the species, data is not available from Day 18 to Day 21 (Figure 4.6 and Figure 4.7). This was due to batteries of the data logger, both GP1 and GP2 inadvertently failing, therefore unable to record some period during the monitoring.

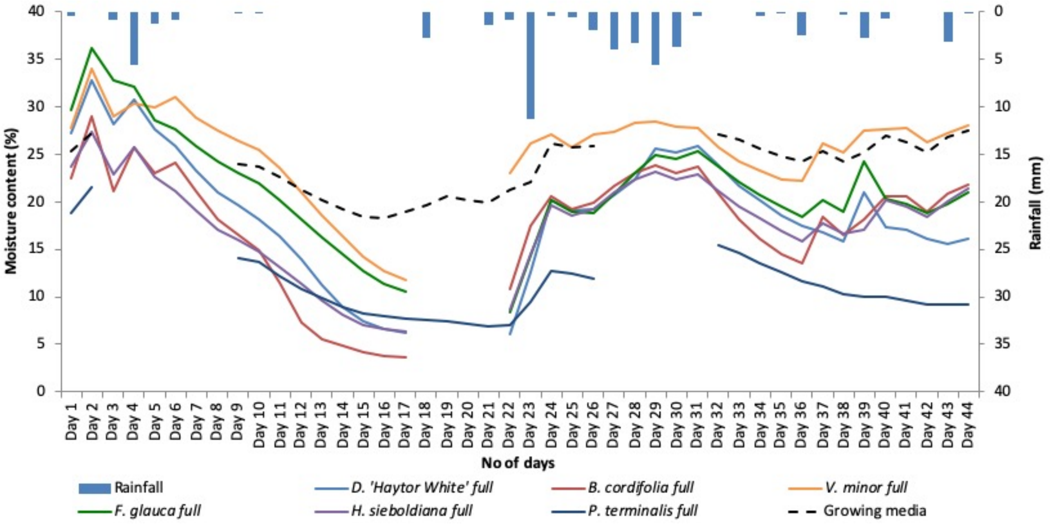


Figure 4. 6: Daily moisture content of the full-canopied plants and the growing media relative to rainfall.

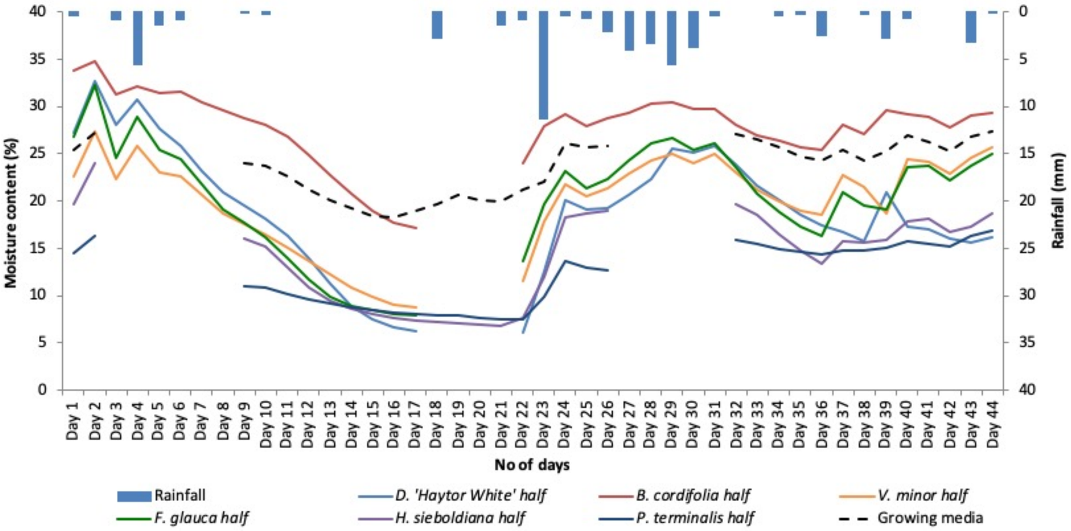


Figure 4. 7: Daily moisture content of the half-canopied plants and the growing media relative to rainfall.

In general, moisture content within the soil increased for all treatments during rainfall occurrences and decreased during dry periods. This is consistent with pot weight gains / losses as demonstrated in Figure 4.4 and Figure 4.5. As moisture contents were continuously recorded at 1-minute intervals, hourly data was available to observe moisture increase in relation to rainfall between Day 33 to Day 37 (Figure 4.8 and 4.9), where total rainfall during this period was 3.1 mm.

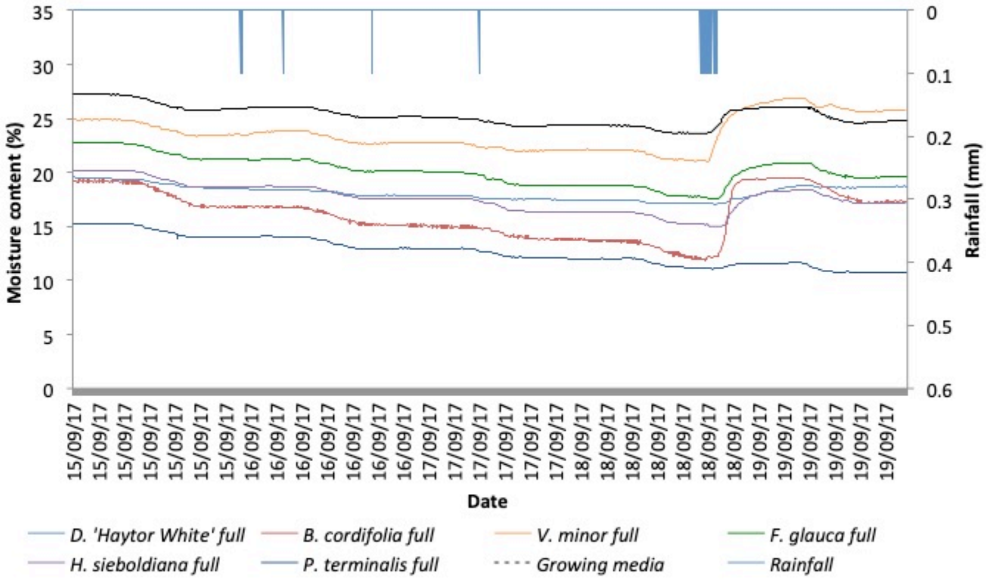


Figure 4. 8: Moisture content behavior of the full-canopied plants and the growing media relative to rainfall between Day 33 (15/09/17) and Day 37 (19/09/17).

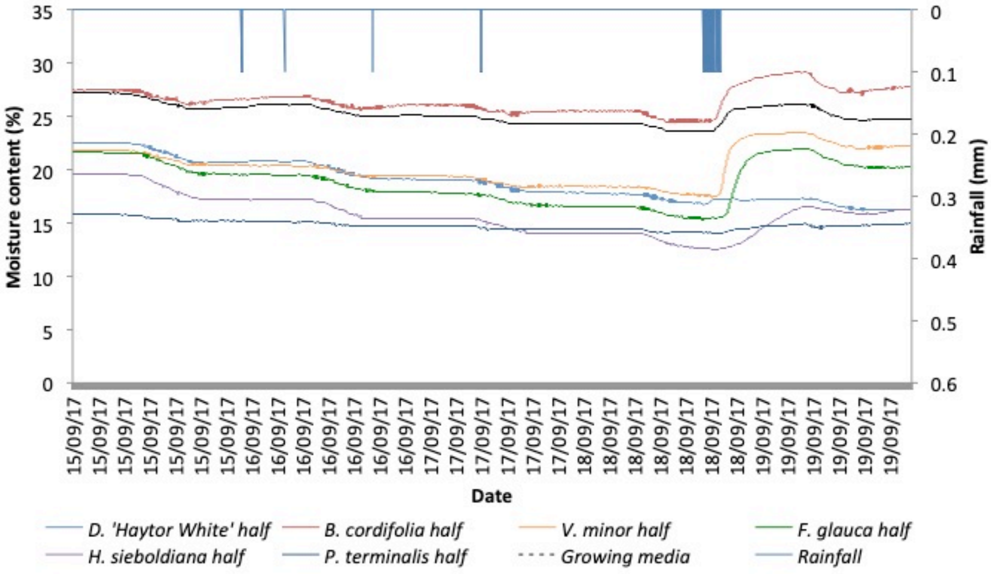


Figure 4. 9: Moisture content behavior of the half-canopied plants and the growing media relative to rainfall between Day 33 (15/09/17) and Day 37 (19/09/17).

During this period, the largest rainfall occurrence was observed on Day 36 (18/09/17) with rainfall depth of 2.5 mm. All treatments saw an observable increase in moisture content during this time. *Vinca minor* (both canopy sizes) and half-canopied *F. glauca* had the largest increase in moisture content (3.7%), while the full-canopied *B. cordifolia* also increased by a relatively large value (3.4%). Both canopy sized *P. terminalis* and the growing media increased the lowest amount (up to 0.4%), while the half-canopied *D.* 'Haytor White' slightly decreased in moisture content during this time.

4.6.5 Moisture content changes

Moisture content changes enable identification of moisture behavior within each plant species. Figure 4.10 and Figure 4.11 presents moisture content changes (increase / decrease in moisture contents) of the full and half canopied plants associated with rainfall occurrences.

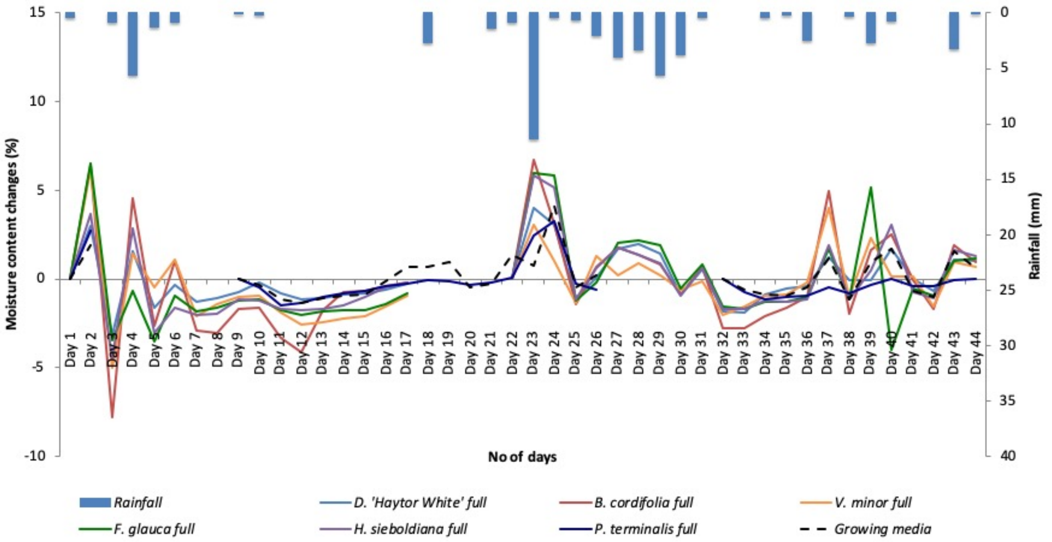


Figure 4. 10: Daily moisture content changes of the full-canopied plants and the growing media relative to rainfall.

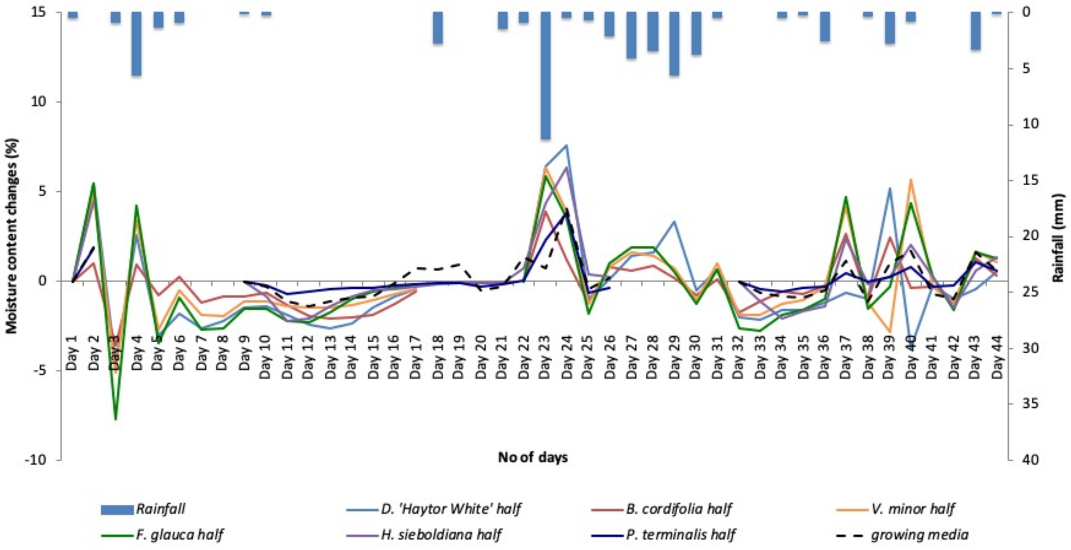
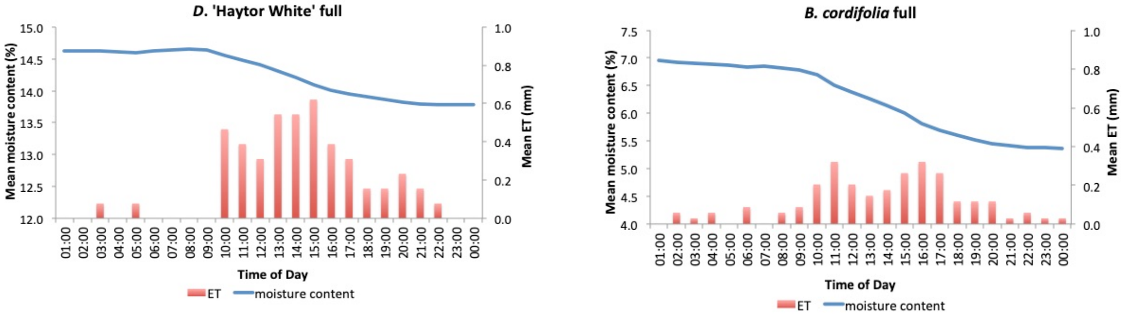


Figure 4. 11: Daily moisture content changes of the half-canopied plants and the growing media relative to rainfall.

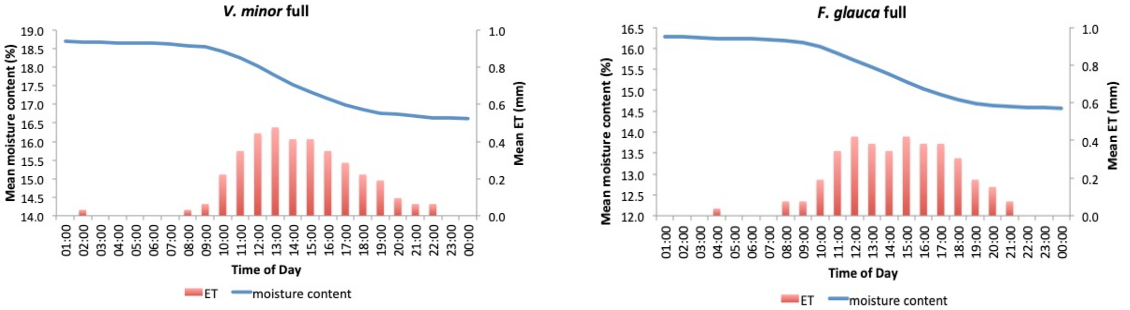
In general, moisture content for all treatments corresponds to rainfall events; moisture content increases as rainfall occurs. The full-canopied *B. cordifolia* was seen to have low moisture content levels during dry period from Day 7 to Day 12, and a noticeable decrease in moisture content was also observed by the full-canopied *F. glauca* on Day 40, which may associate to higher moisture loss (ET). Although rainfall was present on Day 40 (only a small amount of 0.7 mm), this may not have affected the moisture content of *F. glauca,* as its canopy may have intercepted the rainwater, thus preventing it from reaching the growing media. Similarly, moisture contents by the half-canopied plant corresponded to rainfall events.

4.6.6 Diurnal ET patterns

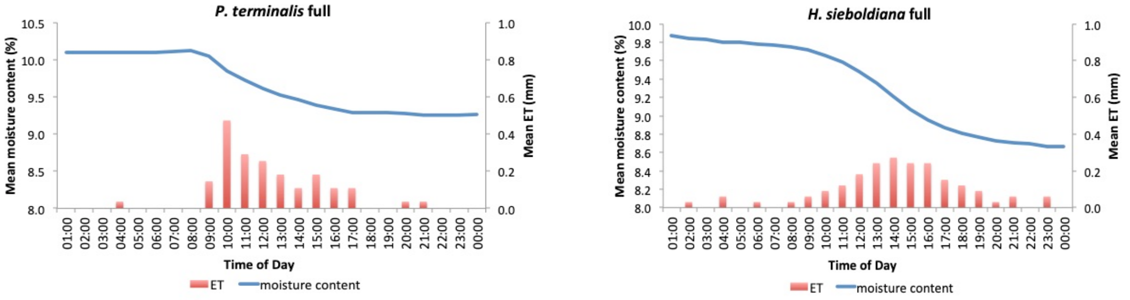
As the moisture sensors data were recorded at 1-minute intervals, hourly data was available to observe ET diurnal patterns of the plants. Mean moisture content of the species was observed on the chosen dry period (Day 11 to Day 16), where moisture content readings from the sensors were available for all plant species. There was no rainfall occurrence during this period. Figure 4.12 and Figure 4.13 presents mean hourly ET rates of the plant species (full and half canopy) for 24 hours over the observed dry period, to identify any diurnal ET patterns. This was calculated from the difference in hourly moisture content (%) (i.e. moisture content decrease) during this period. The diurnal moisture content profile (%) was transformed into ET values (mm) by multiplying each hourly moisture change by the ratio of observed daily moisture loss / ET (mean ET from Day 11 to Day 16 from the weight data), to the observed daily moisture content change (in %).



a) *D*. ‘Haytor White’ full b) *B. cordifolia* full

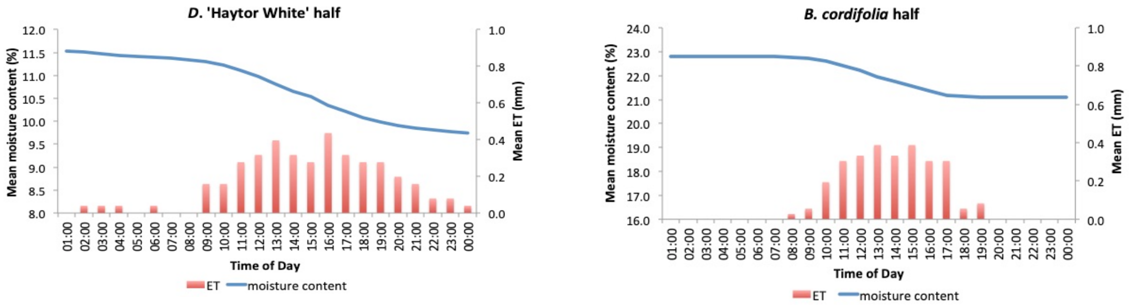


c) *V. minor* full d) *F. glauca* full

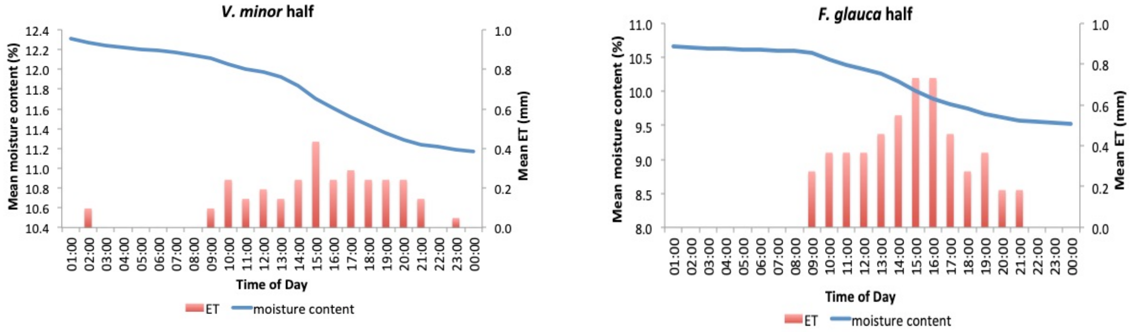


e) *P. terminalis* full f) *H. sieboldiana* full

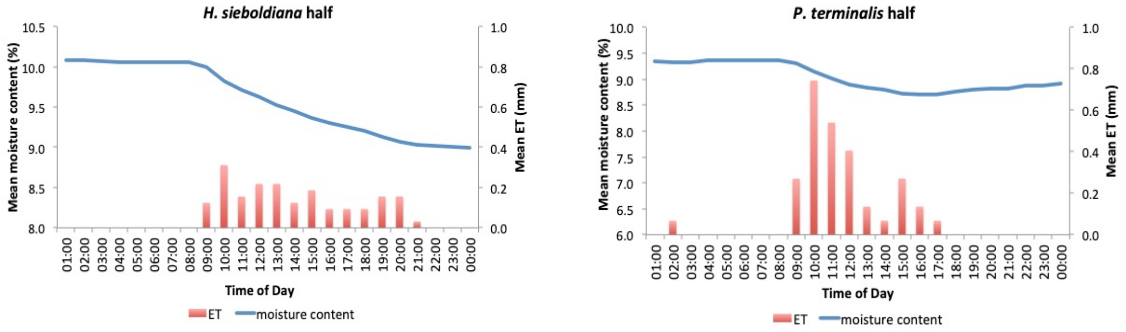
Figure 4. 12: (a – f) Diurnal ET cycles of the full-canopied plants.



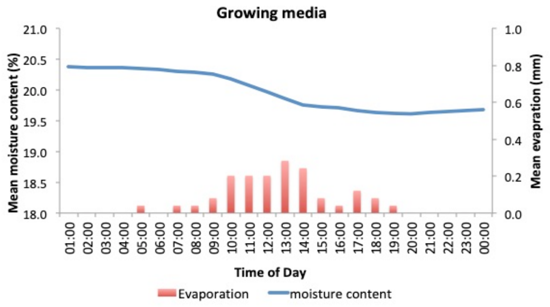
g) *D.* ‘Haytor White’ half h) *B. cordifolia* half



i) *V. minor* half j) *F. glauca* half



k) *H. sieboldiana* half l) *P. terminalis*



m) Growing media

Figure 4. 13: (g – m) Diurnal ET cycles of the half-canopied plants and the growing media.

The highest mean daily ET rate during this period was by the half-canopied *F. glauca* (5.31 mm d^{-1}), followed by *D*. ‘Haytor White’ (4.19 mm d^{-1} for the full canopy and 3.92 mm d^{-1} for the half canopy), while the lowest ET rates (for the vegetated treatments) were associated with *H. sieboldiana* and *P. terminalis*. The growing media had the lowest overall evaporation rate (refer to Table 4.2). It was noticeable that moisture content decreases significantly during midday (typically between 11:00 to 15:00), a period that coincides with maximum / peak ET for all species. Some species (i.e. both canopied *D*. ‘Haytor White’, full-canopied *B. cordifolia* and *F. glauca*) had two peaks ET, in which the first peak typically occurred between 10:00 to 13:00, and the second between 14:00 to 17:00. Evapotranspiration by all species started from 9:00, with the exception of full-canopied *B. cordifolia* and *D.* ‘Haytor White’, where some extent of ET was observed during very early morning (from 2:00). For most of the species, ET stopped between 21:00 to 22:00, but for half-canopied *D*. ‘Haytor White’ and full-canopied *B. cordifolia*, ET extended (but decreasing in rate) until 23:00. However, for both-canopied *P. terminalis*, ET stopped between 16:00 to 17:00.

Table 4. 2: Mean ET rate by each species over dry period from Day 11 to Day 16.

Treatments	**ET rate (mm d^{-1})**
Full canopy	
D. 'Haytor White' full	4.19
B. cordifolia full	2.74
V. minor full	3.71
F. glauca full	3.75
H. sieboldiana full	2.11
P. terminalis full	1.89
Half canopy	
D. 'Haytor White' half	3.92
B. cordifolia half	2.74
V. minor half	3.04
F. glauca half	5.31
H. sieboldiana half	1.96
P. terminalis half	1.96
Growing media	1.58

4.6.7 Moisture changes

Mean moisture changes of the treatments were obtained by converting weight differences of each treatment into moisture depths (refer to Section 4.6.1). Figure 4.14 and 4.15 presents the moisture changes by all treatments (in mm), both for the full and half-canopied plants throughout the whole monitoring period.

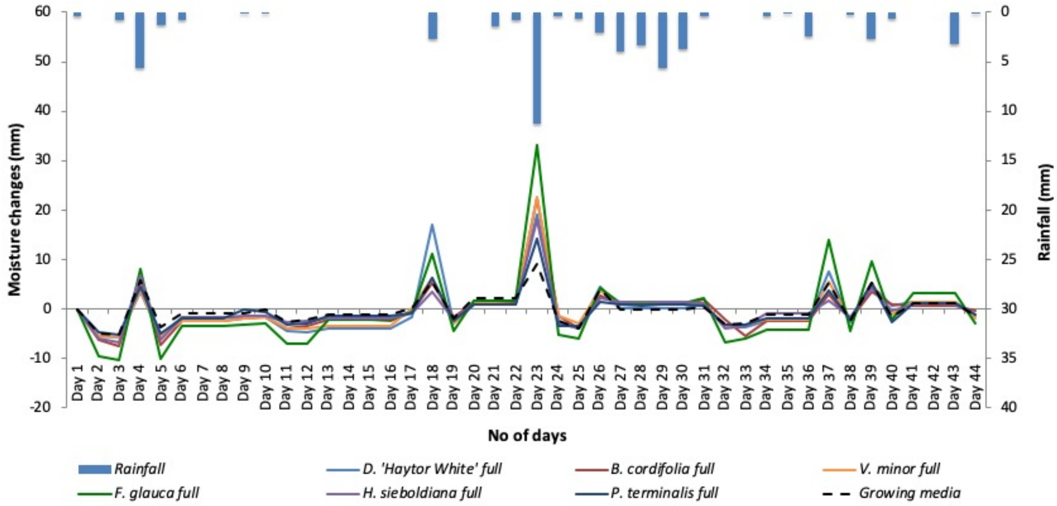


Figure 4. 14: Mean daily moisture changes of the full-canopied plants and the growing media relative to rainfall.

Moisture gains and losses in response to rainfall are clearly demonstrated by all species. For the full-canopied plants, the highest moisture gain for all taxa is seen on Day 23 during peak rainfall period. It was also observable that from Day 1 to Day 12, *F. glauca* consistently lost the most moisture compared to the other species ($p < 0.001$), corresponding to dry periods.

Nonetheless, it was observed that *F. glauca* often gained the most amount of moisture (greatest weight gains) during periods of rainfall and lost the most moisture during dry periods. This is evident during peak rainfall on Day 23, where *F. glauca* gained the greatest amount of moisture (33.1 mm), which was statistically significant compared to *V. minor* ($p = 0.03$) and *B. cordifolia* ($p = 0.03$). Similarly, with the rainfall on Day 18, *F. glauca* also gained a relatively high amount of water (11.2 mm), although in this case not as much as *D.* 'Haytor White' (16.9 mm). During the last three major rainfalls on Day 36, Day 39 and Day 43, again, *F. glauca* captured and retained the highest amount of rainwater compared to other species, although this was only statistically significant to the other species (except for *D.* 'Haytor White) on Day 36 ($p < 0.05$). Of the plant taxa, *P. terminalis* and *H. sieboldiana* consistently gained the least amount of water during rain days. While *H. sieboldiana* often gaining lesser amounts compared to *P. terminalis* during smaller rainfall occurrences (i.e. on Day 18, Day 36, Day 39 and Day 43), on larger rainfall (i.e. Day 4 and Day 23), *H. sieboldiana* intercepted and retained relatively larger amounts than *P. terminalis.*

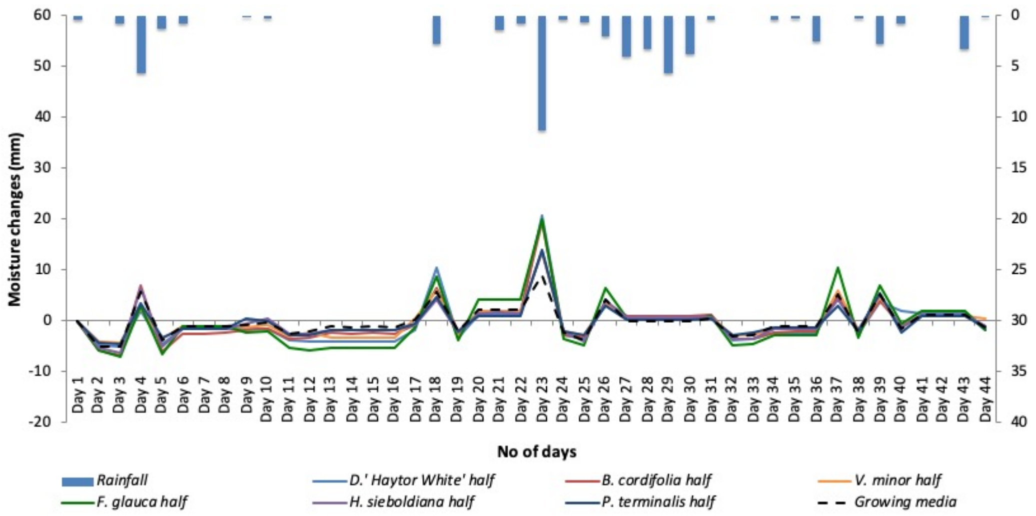


Figure 4. 15: Mean daily moisture changes of the half-canopied plants and the growing media relative to rainfall.

In general, the half-canopied plants captured less water compared to the full-canopied species. This is expected due to smaller amount of leaves, therefore lower leaf surface areas as well as less dense canopy. Similar to the full-canopied plants, *F. glauca* showed the greatest differences by losing moisture by the greatest margin during dry periods and gaining the most moisture during most rainfall days. Although during the first 10 days, the species showed some significant difference between themselves, in terms of moisture changes, it was apparent that from Day 11 to Day 15 (corresponding within the longest dry period on Day 7 to Day 17), *F. glauca* lost the most moisture and was significantly different from the rest of the species ($p < 0.001$), followed by *D.* 'Haytor White', *V. minor* and *B. cordifolia* respectively. During peak rainfall on Day 23, *D.* 'Haytor White' gained the greatest amount of moisture, closely followed by *F. glauca* and *B. cordifolia*. For the consecutive three major rainfall events towards the end of monitoring (Day 36, Day 39 and Day 43), *F. glauca* gained the most moisture on all of these event, followed by *D.* 'Haytor White'.

Over the course of the entire experiment, the greatest differences of moisture changes between the two canopy sizes were seen on *V. minor*, ($p = 0.47$) whereas the smallest variation was seen on *F. glauca* ($p = 0.84$). However, the growing media had the least differences when compared to the overall treatments.

4.6.8 Retention performance during wet period

During a rainfall event, it is difficult to identify whether water that is captured by the plants are retained within the canopy or infiltrated and stored in the soil. Therefore, in a further attempt to determine how the canopy structure *per se*, of different plant species affects rainfall interception, data relating to the capture and retention capacity of the growing media is excluded. Estimates of retention by the plant canopies of each species were calculated by subtracting the mean daily moisture change of the pots with growing media only (control pots) from the mean daily moisture change observed across all species (Table 4.3). Two rainfall days of varied rainfall depths; Day 18 with 2.7 mm; and Day 23 with 11.3 mm are chosen to observe retention capacities by the plant species for both canopy sizes. Figure 4.16 and Figure 4.17 demonstrate a 'close up' portion of the graph, of the moisture changes for the full and half-canopied plants, from Day 17 to Day 24, where rainfall was present on the two days (Day 18 and Day 23). Statistical test repeated measures analysis of variance (ANOVA) was conducted to observe whether there were any significant differences between water retention by the plant species. As the gravimetric data (weight) was converted into depth of water (in mm), for comparison purposes, the original raw data of weight changes (in kg) are also presented. Table 4.3 presents the retention by each species on the two days.

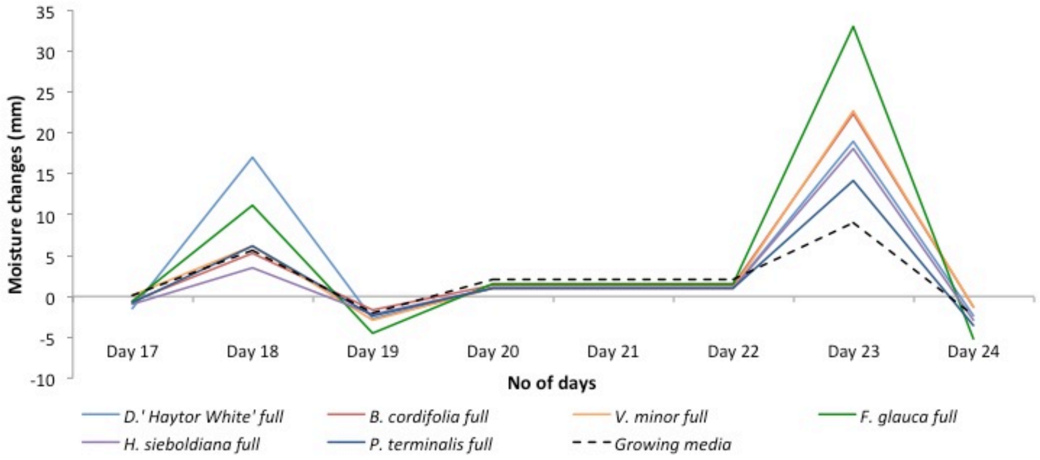


Figure 4. 16: Mean moisture changes of the full-canopied plants and the growing media from Day 17 to Day 24.

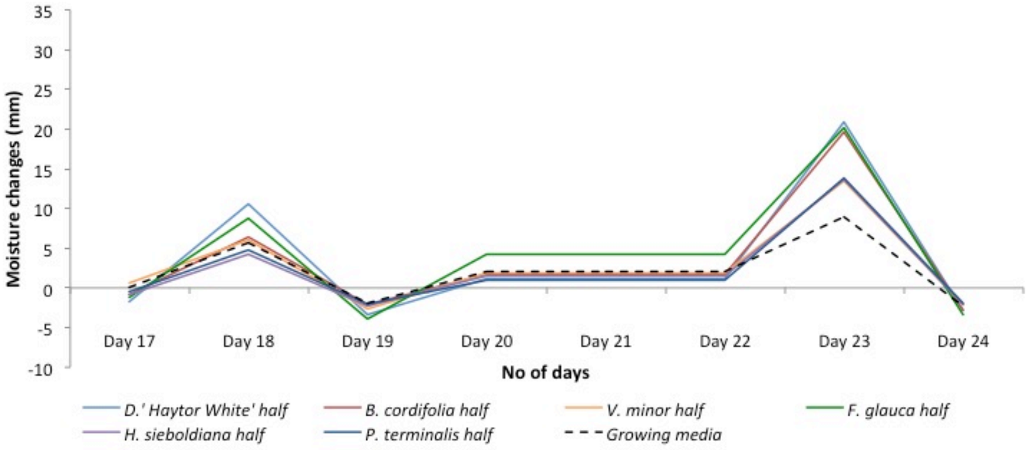


Figure 4. 17: Mean moisture changes of the half-canopied plants and the growing media from Day 17 to Day 24.

Table 4. 3: Mean retention in water depth (mm) by different plant taxa over two rainfall days (Day 18 and Day 23).

Treatments	**Retention Day 18 (mm)**	**Retention Day 23 (mm)**
Full canopy		
D. 'Haytor White' full	11.28	9.94
B. cordifolia full	1.40	13.28
V. minor full	1.44	13.62
F. glauca full	5.58	24.06
H. sieboldiana full	0.34	9.02
P. terminalis full	2.26	5.54
Half canopy		
D. 'Haytor White' half	5.28	11.76
B. cordifolia half	2.42	10.54
V. minor half	0.82	4.62
F. glauca half	3.28	11.04
H. sieboldiana half	0.42	5.18
P. terminalis half	0.80	5.68

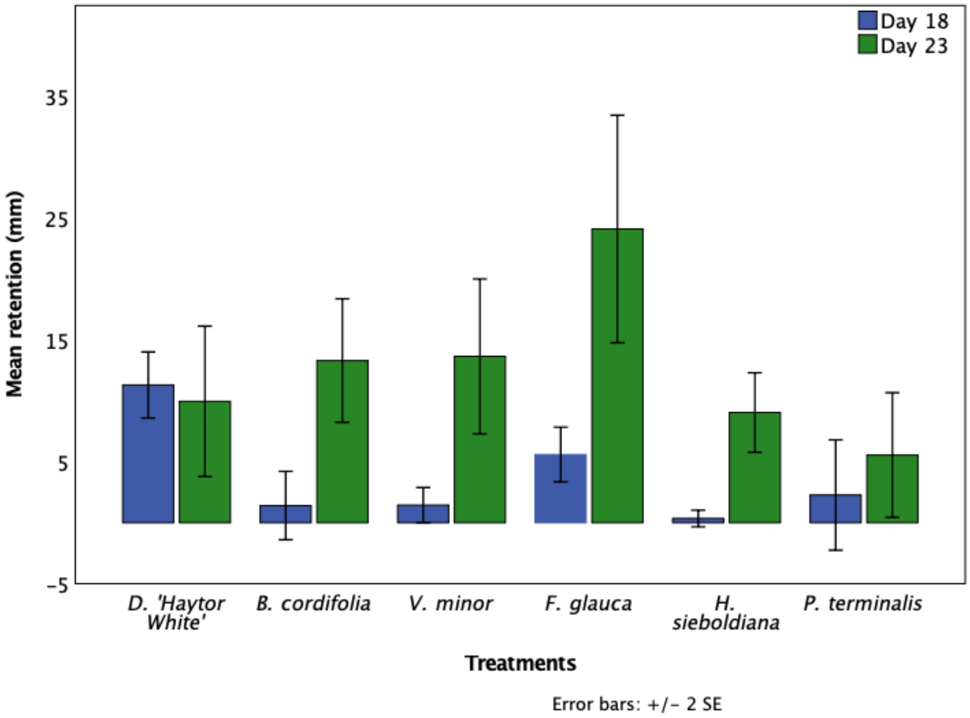


Figure 4. 18: Mean retention by the full-canopied plants on two observed rainfall days (Day 18 and Day 23).

For the full-canopied plants, during rainfall on Day 18, *D.* 'Haytor White' intercepted and retained the highest amount of moisture of 11.28 mm, which was statistically significant compared to the rest of the species, except for *F. glauca* (p = 0.88), which retained the second highest amount (5.58 mm). Other species retained comparable amounts to each other with no significant differences. *Hosta sieboldiana* retained the least amount (0.34 mm). For rainfall on Day 23, *F. glauca* retained a significant amount of rainfall (24.06 mm) that was statistically significant only to *H. sieboldiana* (p = 0.03) and *P. terminalis* (p = 0.004). *Vinca minor* and *B. cordifolia* retained comparable amount of 13.62 mm and 13.28 mm respectively. *Dianthus* 'Haytor White' retained 9.94 mm, closely followed by *H. sieboldiana* with 9.02 mm, and *P. terminalis* retained the least amount of 5.54 mm. There was no statistical difference in retention among the rest of the species on Day 23.

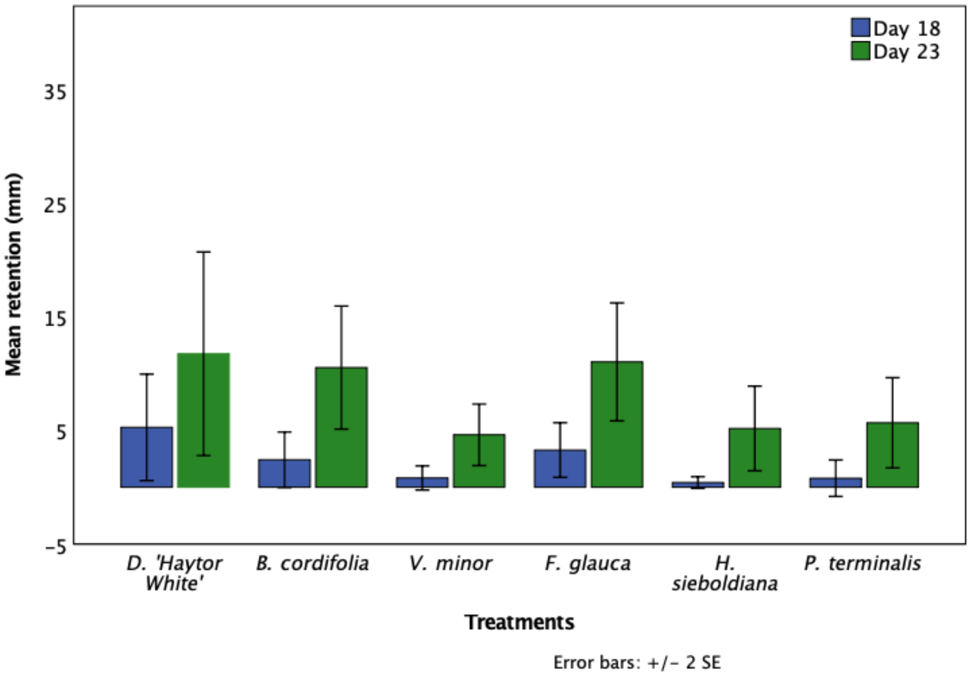


Figure 4. 19: Mean retention by the half-canopied plants on two observed rainfall days (Day 18 and Day 23).

For the half-canopied plants on Day 18, *D.* 'Haytor White' retained the highest amount of rainfall (5.28 mm), however, was not statistically significant from any of the species. *Hosta sieboldiana* retained the least amount of moisture (0.42 mm). The rest of the species did not show significant differences between each other. For rainfall event on Day 23, again, *D.* 'Haytor White' retained the highest amount of moisture (11.76 mm), followed by *F. glauca* (11.04 mm) and *B. cordifolia* (10.54 mm) respectively. There were no statistical differences in the retention by the plant species on Day 23.

In general, the full-canopied plants retained greater amounts of rainwater than the half-canopied, with the exception of *B. cordifolia* and *H. sieboldiana* on Day 18 and *D.* 'Haytor White' and *P. terminalis* on Day 23 (Table 4.4). All species retained greater amounts of water on Day 23 compared to Day 18, except for the full-canopied *D.* 'Haytor White' (peak rainfall was observed on Day 23). *Dianthus* 'Haytor White' and *F. glauca* (both canopy sizes) intercepted and retained rainwater most effectively, with *D.* 'Haytor White' retaining more than *F. glauca* on Day 18, and *F. glauca* retaining a significantly higher amount on Day 23. Both the full and half-canopied *B. cordifolia* also retained a relatively high amount of moisture on rainfall Day 23, while both canopy *H. sieboldiana* and *P. terminalis* generally retained the least amount of rainfall on both days.

4.6.9 Evaporative losses during dry period

The longest dry period was observed for 11 days, which was from Day 7 to Day 17. Total rainfall depth over this period was 0.9 mm. The highest mean daily temperature was observed on Day 15 (19.3ºC); however, weights of the treatments were not taken on this day due to the UK public holiday (and the researcher could not access the building). The second highest temperature was observed on Day 9 (18.3ºC), therefore ET performances by the plant species on Day 9 are presented in Figure 4.22 and 4.23. Figure 4.20 and 4.21 demonstrates the moisture changes / loss during the dry period from Day 7 to Day 17. Table 4.5 and Table 4.6 presents ET data, both in gravimetric data (weight loss in kg) and in depth of water (moisture loss in mm) for comparison purposes.

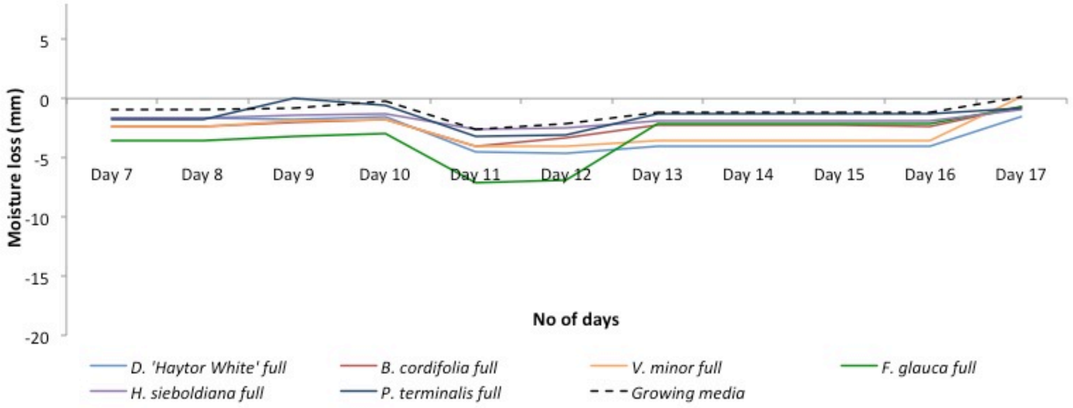


Figure 4. 20: Mean moisture changes of the full-canopied plants and the growing media during the longest continuous dry period (Day 7 to Day 17).

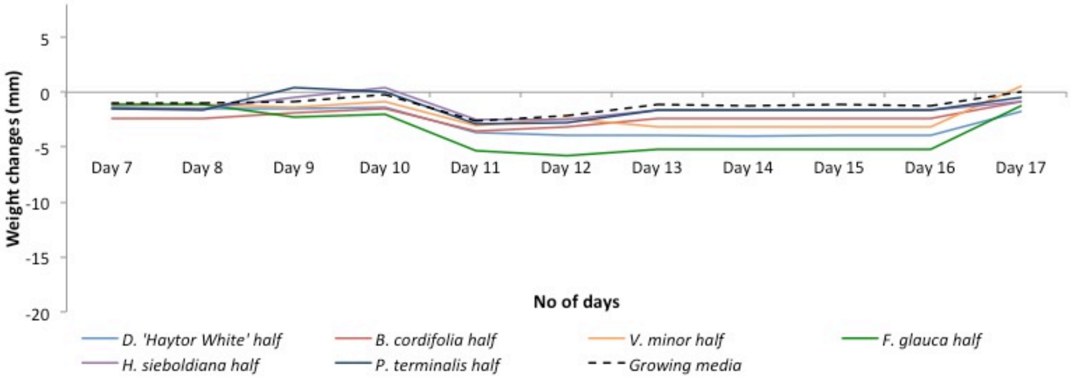


Figure 4. 21: Mean moisture changes of the half-canopied plants and the growing media during the longest continuous dry period (Day 7 to Day 17).

Table 4. 4: Mean weight changes / loss (kg) by different plant taxa on Day 9.

Treatments	**Weight changes on Day 9 (kg)**
Full canopy	
D. 'Haytor White' full	0.039
B. cordifolia full	0.044
V. minor full	0.042
F. glauca full	0.073
H. sieboldiana full	0.033
P. terminalis full	0.000
Half canopy	
D. 'Haytor White' half	0.034
B. cordifolia half	0.042
V. minor half	0.031
F. glauca half	0.051
H. sieboldiana half	0.020
P. terminalis half	0.000
Growing media	0.024

Table 4. 5: Mean ET rates (mm) by different plant taxa on Day 9.

Treatments	ET rates on Day 9 ($mm\ d^{-1}$)
Full canopy	
D. 'Haytor White' full	1.72
B. cordifolia full	1.96
V. minor full	1.88
F. glauca full	3.23
H. sieboldiana full	1.45
P. terminalis full	0.00
Half canopy	
D. 'Haytor White' half	1.51
B. cordifolia half	1.83
V. minor half	1.36
F. glauca half	2.28
H. sieboldiana half	0.93
P. terminalis half	0.00
Growing media	1.06

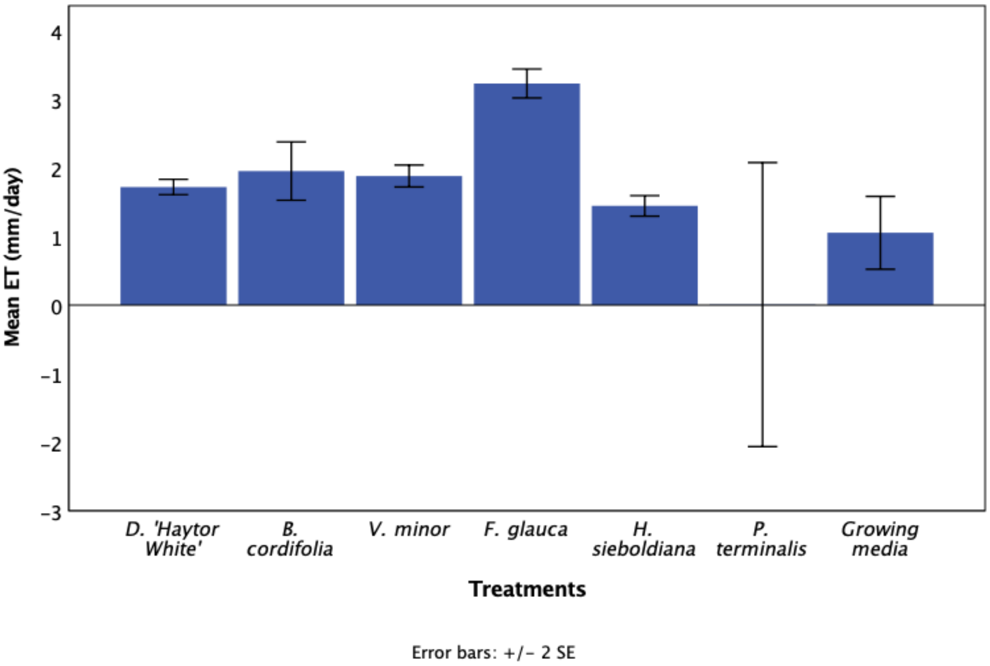


Figure 4. 22: Mean ET rates by the full-canopied plants on Day 9.

**Negative values were recorded for* P. terminalis, *so the mean value was translated to zero. This was because the dataset consisted of two specimens that were dead (completely dysfunctional) during the experiment, and high error value associated with the stress.*

For the full-canopied plants, *F. glauca* had the highest ET rate (3.23 mm d^{-1}), and was statistically significant from all species ($p < 0.05$). The rest of the species did not show significant difference with each other. *Pachysandra terminalis* had 0 mm of ET rate, which was lower than the pots with the growing media alone. This taxon also had large error values reflecting two plants that were extremely stressed, possibly even dead. However, even the remaining viable plants had low ET rates, which suggest that they were effective at conserving water, i.e. little evapotranspiration was taking place.

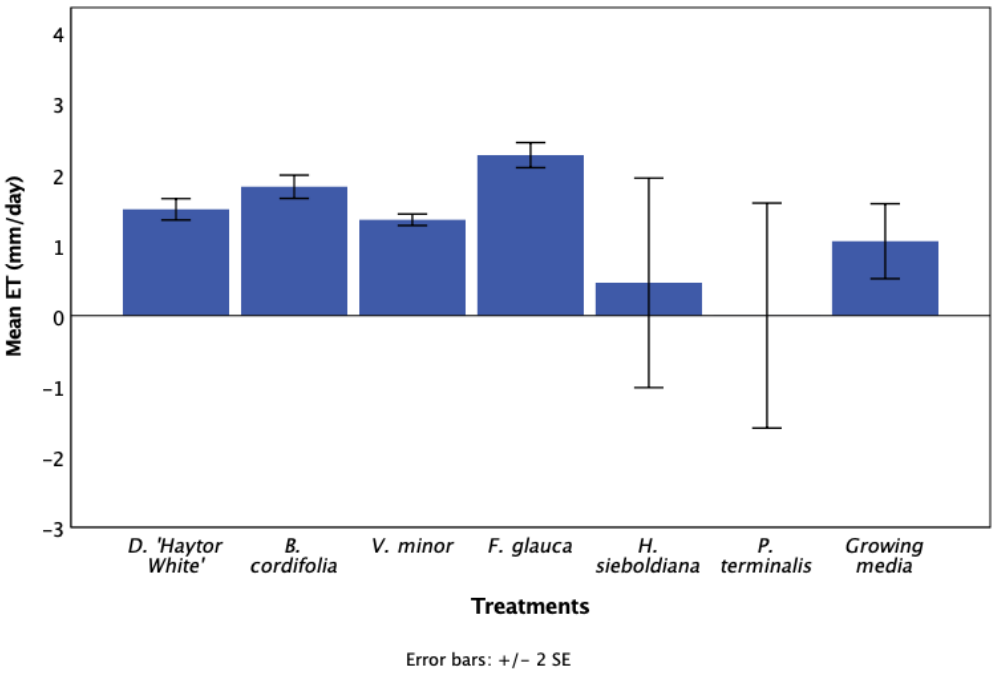


Figure 4. 23: Mean ET rates by the half-canopied plants on Day 9.

**Negative values were recorded for* P. terminalis*, so the mean value was translated to zero. This was because the dataset consisted of two specimens that were dead (completely dysfunctional) during the experiment, and high error value associated with the stress.*

For the half-canopied plants, *F. glauca* lost the highest amount of moisture (2.28 mm d^{-1}) and was statistically significant from *H. sieboldiana*, *P. terminalis* and the growing media ($p < 0.05$). The rest of the species did not show significant difference with each other. *Hosta sieboldiana* and *P. terminalis* had the lowest ET rates and was lower (but not significantly less) than that of the growing media. Similar to the full-canopied plants, some replicates of *P. terminalis* experienced severe stress (thus mean value was translated to zero), but again, suggest that the remaining specimens too, had low ET rates. *Hosta sieboldiana* generally had low ET rates as towards the end of the experiment; it appeared that this species was heavily senescing. As such, any moisture loss could have been just by evaporation, much in the same way as was occurring in the control (growing media alone).

4.6.10 Plants' hydrological performance in relation to leaf area

Retention of rainfall and ET rates by the plants species on the chosen days (Day 23 and Day 9) were expressed relative to leaf area, to identify whether plant leaf area and number of leaves affects the plants' moisture behaviors (water retention and ET rates). Mean of the total leaf area and the numbers of leaves for each plant species are presented in Table 4.7. In general, all of the full-canopied plants had higher total leaf area than the half-canopied. Similarly, in terms of the number of leaves, the mean numbers of leaves of the full-canopied plants were higher than the half, with the exception of *D*. ‘Haytor White’, where the half-canopy had slightly higher number of leaves than the full. The full-canopied *V. minor* and *P. terminalis* had twice the number of leaves than the half-canopied, while the full-canopied *B. cordifolia* and *H. sieboldiana* each had only one extra leaf than the half-canopied. These differences may be due to the fact that the number of leaves are only mean data that was taken at the end of the experiment, therefore some plant replicates of each of the sizes may have either died, dried out or destroyed due to pathogen infections as only number of fresh leaves were counted. Furthermore, the half-canopied plants may have grown new leaves during the experiment, which was then included as fresh leaves when they were counted.

Table 4. 6: Mean leaf area values and number of leaves of the six plant taxa.

Treatments	**Mean total leaf area (m^2)**	**Mean number of fresh leaves**	**Retention (D23) / Unit of leaf area ($mm\ m^{-2}$)**	**ET (D9) / Unit of leaf area ($mm\ d^{-1}\ m^{-2}$)**
Full canopy				
D. ‘Haytor White’ full	6.99	830	2.70	0.26
B. cordifolia full	6.38	18	3.35	0.31
V. minor full	12.87	1003	1.87	0.15
F. glauca full	16.37	-	2.16	0.22
H. sieboldiana full	5.64	5	3.42	0.27
P. terminalis full	14.92	418	2.22	0.00
Half canopy				
D. ‘Haytor White’ half	4.62	858	4.49	0.33
B. cordifolia half	4.06	17	5.45	0.52
V. minor half	5.20	504	2.72	0.27
F. glauca half	5.76	-	3.52	0.40
H. sieboldiana half	3.80	4	3.64	0.25
P. terminalis half	4.00	229	4.12	0.00

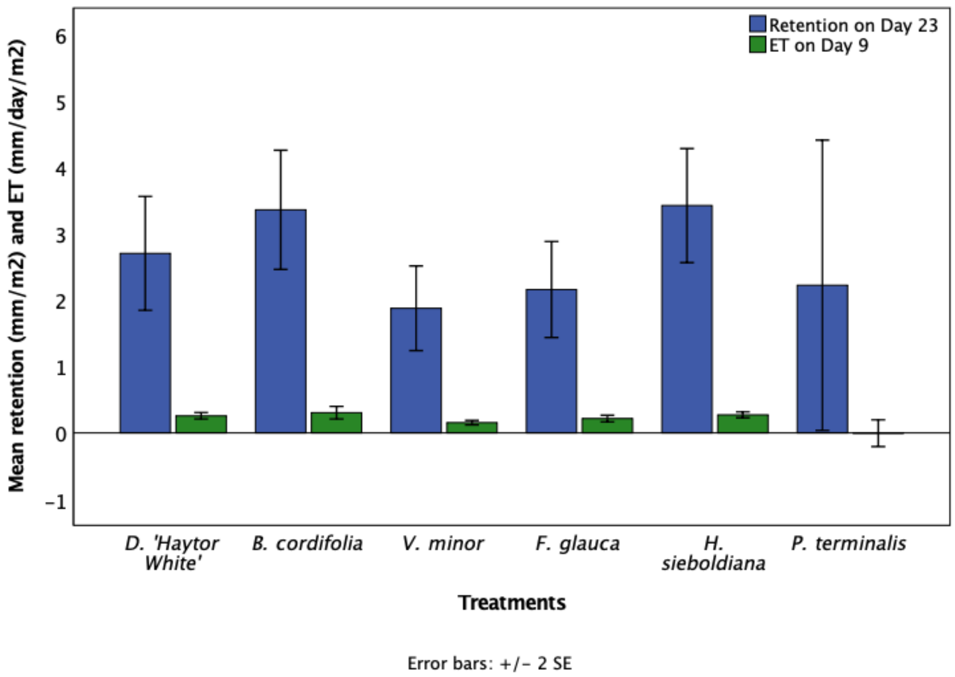


Figure 4. 24: Mean retention and ET rates per unit of leaf area of the full-canopied plants on Day 23 and Day 9.

**Negative values were recorded for* P. terminalis*, so the mean value was translated to zero. This was because the dataset consisted of two specimens that were dead (completely dysfunctional) during the experiment, and high error value associated with the stress.*

Moisture retention on Day 23 was assessed based on their total leaf area to identify which of the plants can capture and retain higher moisture on a per unit of leaf area basis. Overall, for the full-canopied plants, *H. sieboldiana* and *B. cordifolia* retained the highest amount of moisture (3.42 mm m^{-2} and 3.35 mm m^{-2} respectively), while *V. minor* intercepted the least (1.87 mm m^{-2}), per unit of leaf area. In terms of ET rates on Day 9, for the full-canopied plants, *B. cordifolia* had the highest ET rates (0.31 mm d^{-1} m^{-2}), followed by *H. sieboldiana* (0.27 mm d^{-1} m^{-2}) and *D.* 'Haytor White' (0.26 mm d^{-1} m^{-2}), while *P. terminalis* had 0 mm of ET due to plant stress on some specimens (refer to footnote above). No significant difference was found between the full-canopied species for retention on Day 23 and ET on Day 9.

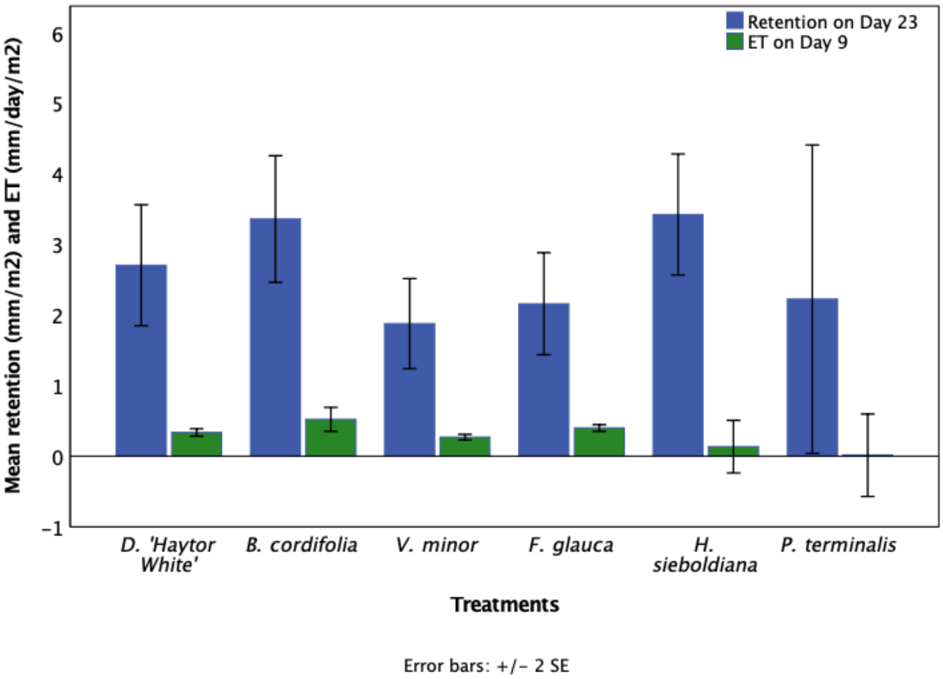


Figure 4. 25: Mean interception and ET rates per unit of leaf area of the half-canopied plants on Day 23 and Day 9.

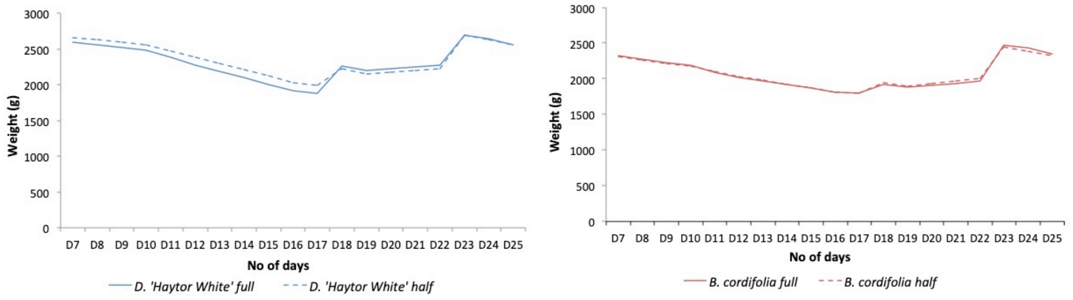
**Negative values were recorded for* P. terminalis*, so the mean value was translated to zero. This was because the dataset consisted of two specimens that were dead (completely dysfunctional) during the experiment, and high error value associated with the stress.*

For the half-canopied plants, again, *B. cordifolia* retained the most moisture per unit of leaf area on Day 23 (5.45 mm m^{-2}), followed by *D.* 'Haytor White' (4.49 mm m^{-2}) and *P. terminalis* (4.12 mm m^{-2}). *Vinca minor* retained the least amount of moisture per unit of leaf area (2.72 mm m^{-2}). For ET rates on Day 9, the half-canopied plants had higher ET rates than the full-canopied plants. *Bergenia cordifolia* had the highest ET rate per unit of leaf area (0.52 mm d^{-1} m^{-2}), followed by *F. glauca* (0.40 mm d^{-1} m^{-2}). *Hosta. sieboldiana* also had among the lowest mean ET rate (0.25 mm d^{-1} m^{-2}), while *P. terminalis* demonstrated 0 mm of ET (refer to footnote above). There was no statistical difference between retention and ET rates by the species.

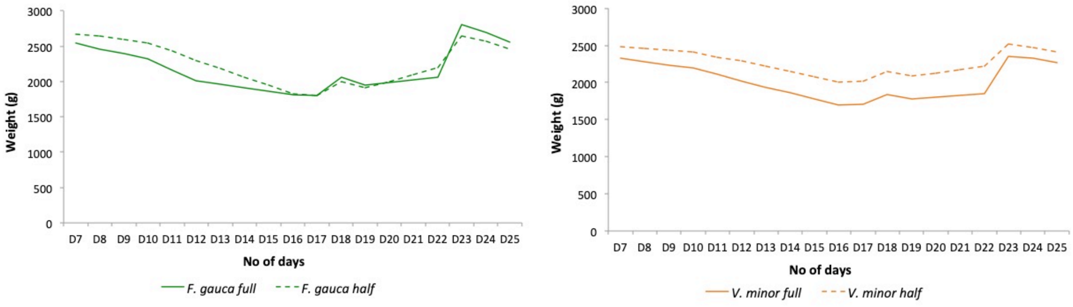
4.6.11 Canopy size variation

The purpose of having two different canopy sizes was to identify whether there would be any significant differences in their effectiveness in retaining or losing water. The effectiveness of canopy size variations was analyzed by looking at the weights during wet and dry periods (Figure 4.26). The period between Day 7 until

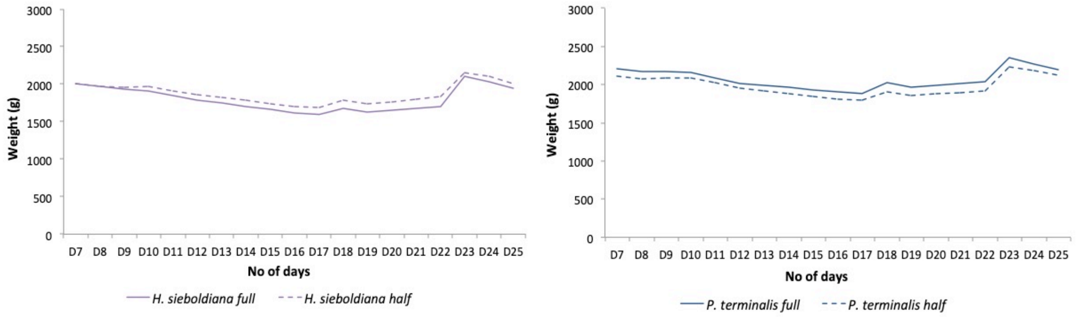
Day 25 was chosen because this period consisted of the longest dry period (Day 7 to Day 17) and also two rainfall days (Day 18 and Day 23), in which weight gains (water retention) and weight loss associated with ET with regards to the different canopy sizes could be verified.



a) *D.* ‘Haytor White’ b) *B. cordifolia*



c) *F. glauca* d) *V. minor*



e) *H. sieboldiana* f) *P. terminalis*

Figure 4. 26: Mean daily weights of the two canopy sizes of each plant species from Day 7 to Day 25.

In general, weight performances for different species varied on different days where weather was associated with weight fluctuations. However, the biggest differences were seen on *V. minor* during both dry period and peak rainfall period, which was statistically significant between the two canopy sizes ($p < 0.05$). The full canopy lost more weight than the half during dry period from Day 7 to Day 17. Although rainfall was present on Day 18 and Day 23, this was not enough for the full-canopied *V. minor* to gain higher than the half-canopied. For *F. glauca*, a significant difference was only found during the first 7 days (Day 7 to Day 14) ($p < 0.05$); after it rained, the full-canopied *F. glauca* exceeded the half by gaining more or similar weight (moisture). *Bergenia cordifolia, D.* 'Haytor White' and *P. terminalis* did not show any significant difference between the two canopy sizes throughout all of the observed days (Day 7 to Day 25).

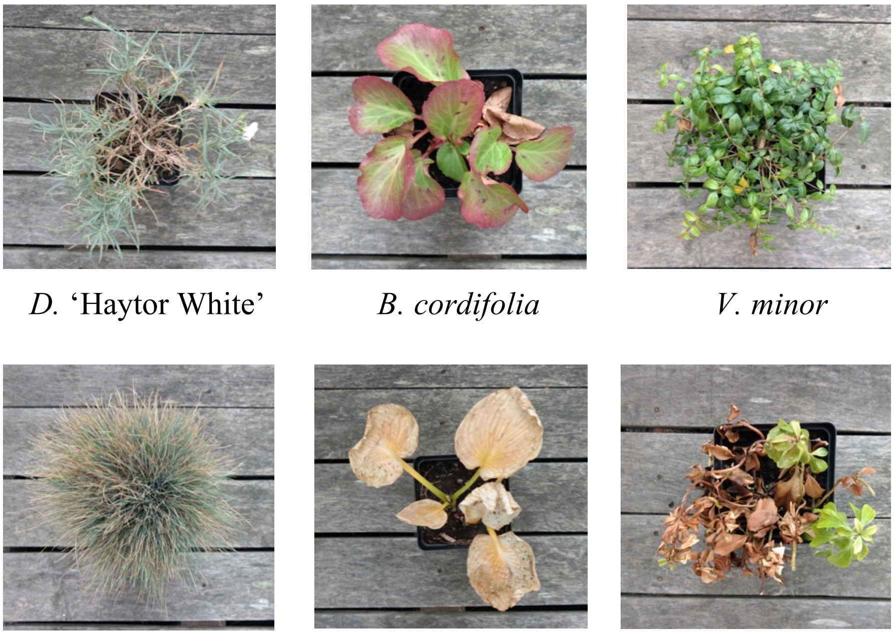
4.6.12 Plant stress tolerance

Chlorophyll fluorescence (Fv/Fm) results can help indicate plants stress level due to photosynthetic activity that is influenced by environmental conditions. While values between 0.7 and 0.8 indicate a healthy plant condition, plants that are stressed are shown in lower value of Fv/Fm (< 0.7). The average result of data taken in three consecutive days at the end of the monitoring period (additional drought test after 44 days) for four plant species on both canopy sizes (*B. cordifolia*, *V. minor*, *H. sieboldiana* and *P. terminalis*) are presented in Table 4.8. Data for *D.* 'Haytor White' and *F. glauca* were not taken due to very small leaf surface, therefore inability to attach leaf clips onto leaf samples.

Table 4. 7: Mean chlorophyll fluorescence value (Fv/Fm) of four plant taxa.

Plant species	**Mean chlorophyll fluorescence (Fv/Fm)**
Full canopy	
B. cordifolia	0.82
V. minor	0.71
H. sieboldiana	0.59
P. terminalis	0.72
Half canopy	
B. cordifolia	0.83
V. minor	0.78
H. sieboldiana	0.66
P. terminalis	0.71

The result from the mean chlorophyll fluorescence measurement indicated that *H. sieboldiana* showed some degree of stress for both the full and half canopy with lower values of Fv/Fm on most replicates. *Bergenia cordifolia* showed the highest fluorescence result, indicating it was in the healthiest condition after the experiment was complete. The other two species (*V. minor* and *P. terminalis*) showed relatively healthy mean result. Statistical analysis conducted using a two-way analysis of variance (ANOVA) indicated that there is a statistical significance between the means of all species ($p < 0.05$) except between *V. minor* and *P. terminalis* ($p = 0.31$). There was no statistical difference between the full and the half canopy size for all species ($p > 0.05$). Plants' physical conditions at the end of the experiment were also observed and photographed to identify changes and physical stress signs. Figure 4.27 demonstrated examples of how each species exhibited their stress signs.



D. 'Haytor White' *B. cordifolia* *V. minor*

F. glauca *H. sieboldiana* *P. terminalis*

Figure 4. 27: Example of stress conditions exhibited by each plant species on the last day of the experiment (Day 44).

Each plant species and their replicates were scored on a scale of 1 to 6 based on their stress conditions; 1 being dead / very stressed and 6 being very healthy at the end of the experiment (1 - severely stressed (dead leaves); 2 - very poor condition (70% dry / dead); 3 – poor condition (50% dry / dead); 4 - unhealthy (20% dry /

dead); 5 – moderately healthy; and 6 - very healthy). The scores were then analyzed to identify whether there was statistical significance in the stress levels using a two-way analysis of variance (ANOVA). This result enables comparisons between all species including *F. glauca* and *D.* 'Haytor White' that were unable to obtain from the chlorophyll fluorescence measurement. Overall, there is statistical difference between species, but not between the two canopy sizes of each species. *Festuca glauca* was statistically significant with *B. cordifolia* ($p = 0.023$) and *H. sieboldiana* ($p = 0.002$) (which had the lowest stress scores), while *H. sieboldiana* was also statistically significant with *V. minor* ($p = 0.023$).

Based on physical observation of each species throughout the experiment, *H. sieboldiana* was observed to experience the most stress, where most of their leaves were either dry or dead (with a possibility of autumn senescence). *Vinca minor* and *P. terminalis* showed some stress signs with a proportion of leaves / stems showing pathogen infections (secondary stress response). *Festuca glauca* and *D.* 'Haytor White' demonstrated some desiccated leaves, however, this may be due to insufficient water, and did not affect their overall performance. As chlorophyll fluorescence data were not taken on both of these species, their photosynthetic / photochemistry activity and heat dissipation remain unquantified. As the season transitioned from late summer to early autumn, most of the leaves of *B. cordifolia* had started to turn red, however this is not necessarily a sign of water stress as they naturally turn brownish / red during winter. Based on the plant stress scores that were given to the plant species, *D.* 'Haytor White' did not show statistical difference with the other species while *F. glauca* was significantly different with *B. cordifolia* and *H. sieboldiana*.

4.7 Discussion

4.7.1 Plant weight and moisture content performance

Weights and moisture content (from moisture sensors) varied with the prevalent climatic conditions and were useful parameters to determine periods when water became short, and when rainfall events replenished supplies within the pots. For example, it was noted that the longest continuous dry period was from Day 7 to Day 17, when plant / pot weight and moisture content slowly decreased, and the single largest rainfall event took place on Day 23.

4.7.2 Plant responses during dry periods

Festuca glauca (both canopy sizes) showed the highest moisture loss during dry periods, especially over Days 7 to 17. *Festuca glauca* (full and half) had the highest ET rates on both days. *Bergenia cordifolia* also consistently had relatively high ET rates compared to the other species (though not as high as *F. glauca*) between the start and end of the main dry spell, suggesting a 'slow and steady' approach to water use. *Hosta sieboldiana* and *P. terminalis* did not perform as well as the other species during the dry periods. Both of these species generally had lower ET rates compared to other species. Towards the end of the experiment, stress signs such as secondary pathogens, drying and dying leaves were observed, especially on *H. sieboldiana* (Figure 4.28) and to a lesser extent *P. terminalis* (Figure 4.29). This, along with low Fv/Fm values suggest that *H. sieboldiana* is not drought-tolerant, and was ineffective at managing its water reserves during the dry periods (although it cannot be totally ruled out that natural autumn senescence in this species was contributing to a decreasing ET / leaf function performance over time).

It was expected that broad-leaved species would have higher ET rates than small, narrow-shaped leaves due to the latter often being associated with more arid or drought prone climates, therefore have the ability to conserve their moisture. However, this was not the case. As pointed out above, both plants with narrow leaf type (*F. glauca* and *D*. 'Haytor White') evapotranspired higher compared to the rest of the species. *Festuca glauca*, which has dense canopy coverage and a high number of leaves (uncounted), and thus presumably greater numbers of stomata overall, results in better capacity to evapotranspire. *Dianthus* 'Haytor White' tends to exhibit water repellence; hydrophobic leaf character is usually associated with minimizing moisture loss due to having waxy cuticles on the leaf surface. However, the relative high number of leaves per plant in this species may have also contributed to a relatively higher overall ET rate.

4.7.3 Evapotranspiration rates based on leaf area and per unit of leaf area

As indicated above, the leaf number and total area of leaves may have affected water use characteristics. This was investigated both by artificially reducing canopy sizes in this experiment, thus estimating the effects due to leaf area and calculating moisture loss on a per unit of leaf basis. When comparing the overall water status (which plants dried out the most), water use between the full and half canopied plants were surprisingly uniform; with the exception being on *V. minor* (Figure 4.26). For this species, the full-canopied plants lost significantly more moisture than the half during dry period, and even when it rained, it was unable to gain more weight than the half due to having lost a substantial amount of moisture during the dry period. This large difference may be attributed to the mean difference of leaf area values and number of leaves of the full and the half canopies of this species, in which the values of the full was ≥ 50% than the half (Table 4.7). This was not the case elsewhere and there was some indication of compensatory growth (and increase in photosynthetic efficiency) after trimming in some of the other species (Table 4.7).

Indeed, the data tended to suggest that half-canopied plants had higher ET rates than their full-canopied equivalents, on a per unit of leaf area basis. This may be due to the fact that when leaves were trimmed, these plants tend to compensate for the loss in photosynthetic potential by promoting higher ET / photosynthetic rates (and grow faster) than undamaged plants. Therefore, when observing ET rate per unit of leaf area *per se* (Table 4.7), ET was higher in many species for the equivalent area of leaf tissue.

Based on this unit of leaf area parameter, *B. cordifolia* had the highest ET rates for both canopy sizes (Table 4.7), while the full-canopied *H. sieboldiana* also had relatively high ET rate per unit of leaf area. Both these species are broad-leaved types and may associate with higher stomatal density per leaf (not measured), therefore contributes to higher ET rates per given area. Plant eco-physiology, however, may also play a part. Both *B. cordifolia* and *H. sieboldiana* appreciate moist and humus rich soils, and presumably are adapted to move water through their stomata readily (and thus can have high rates per unit area). *Bergenia cordifolia*, however, appears to be the better of the two in terms of dealing with higher irradiance and more open, exposed positions, whereas *H. sieboldiana* may be more dependent on shady moist woodland conditions; a point borne out by better leaf conditions in *B. cordifolia* at the end of the experiment.

Pachysandra terminalis (both canopy sizes) had the lowest ET rate, both cumulatively and per unit of leaf area, although it had high overall total leaf area.

This may be because *P. terminalis* are commonly grown in deep shaded areas, and can act as groundcover under other plants / trees. Therefore, they may tend to close their stomata under full direct sunlight, or during times of drought to conserve their moisture, hence evapotranspiring less. This reflects its low ET rate under drought stress condition, and severe signs of pathogen infections found on some replicates of *P. terminalis* during drought condition.

4.7.4 Plant responses during rainfall events

As well as using water at a high rate, *F. glauca* proved to be the best species at harvesting it (Figure 4.17 and 4.18). The full-canopied specimens gained more moisture than their half-canopied equivalents, due to a greater total leaf area, number of leaves and canopy surface area. *Festuca glauca* was most effective at capturing rain; full-canopied *F. glauca* retained a significantly high amount of 24.06 mm. This is attributed to larger canopy surface area (0.0806 m^2) compared to the rest of the species (ranged between 0.0238 and 0.0573 m^2). *Dianthus* 'Haytor White', *V. minor* (full canopy*)* and *B. cordifolia* also proved relatively effective in this respect. In contrast, *P. terminalis* and *H. sieboldiana* often gained the least amount of moisture throughout the entire monitoring period. Growing media alone gained comparable amounts of moisture to the planted pots, but lost less, presumably due to soil evaporation acting alone (i.e. the absence of transpiration).

Most species retained greater amount of water after heavy rainfall (Day 23) compared to a light rainfall event (Day 18), although this was not the case for all species. This contradicts studies by Clark (1940), Gómez *et al.* (2001) and Xiao and McPherson (2011) who found interceptions were generally higher with smaller rainfall (intensity and depth) than larger rainfall characteristics. This anomaly may relate to the previous periods of drought in this experiment rather than the amount of rainfall depth itself. The plants had the longest continuous dry period prior to rainfall on Day 18, therefore, the small amount of rainfall (2.7 mm) may not have been enough to replenish the plants' water requirements (and fill moisture storage within the soil) due to the antecedent dry period. Hence, the next major rainfall (Day 23) with depth of 11.3 mm allowed the plants (and soil) to retain a larger amount of water.

The reasons behind the capacity for *D.* 'Haytor White' and *F. glauca* (both canopy sizes) to have high retention rates is unclear, but may be attributed to leaf morphology, with both species possessing linear, narrow, upward-facing leaves. These factors may contribute to allowing water droplets to access deeper into the canopy, therefore capturing and retaining more moisture. Moreover, when the canopies themselves are saturated, these leaf morphologies tend to direct additional water onto the growing media due to their upward-facing angles, instead of shedding them directly onto the ground (outside of the pot area). *Festuca glauca* have large numbers of leaves (unquantified) and very dense canopy coverage, which helps to store more water in their canopy. The hydrophobic leaf traits and leaf orientation of *D.* 'Haytor White' encourages rain droplets to coalesce immediately and roll down the canopy to the soil rapidly, thus promoting more overall rainfall capture. Comparisons on interception by narrow-leaved species by previous findings are discussed in Chapter 6.

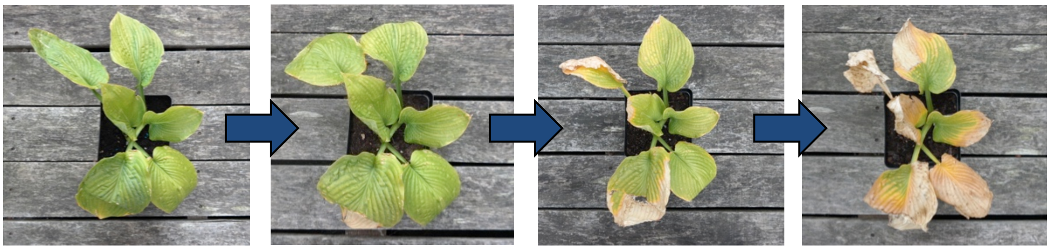
In contrast, both canopied *H. sieboldiana* and *P. terminalis* retained the least amount of moisture. *Hosta sieboldiana* has a broad leaf type that is highly hydrophobic. Its relatively open canopy and limited number of leaves may have caused it to retain little moisture as raindrops coalesce, but which then drop off the leaf tip (in some cases them missing the pot / and the growing media entirely). This rolling effect also means there is less 'splashing' and multi-layer interceptions with again, water lost to the system (i.e. outside the pot). As for *P. terminalis*, although they have a very dense canopy structure with larger numbers of small leaves, mean retention was relatively low for both rainfall days and both canopy sizes. This may be due to a number of reasons; in terms of leaf trait, the leaf surfaces of *P. terminalis* are very glossy, therefore water droplets may easily and immediately slip / drip off the leaves onto the leaf layers below or contribute directly to droplets on soil surfaces / outside of the pots. It was also found that this species did not withstand the experimental stress condition (no additional irrigation added, therefore plants were exposed to continuous dry periods according to weather condition); some replicates showed severe signs of pathogens and drying / dying of leaves (Figure 4.29). This resulted in plants not functioning therefore unable to absorb / intercept moisture.

Retention per unit of leaf area actually showed that *B. cordifolia* and *H. sieboldiana* generally intercepted higher rates than *F. glauca* and *D.* 'Haytor White' (Table 4.7). Interestingly, *H. sieboldiana,* which initially had low overall retention rates for both Days 18 and Day 23, had amongst the highest interception per unit of leaf area (on Day 23). This high interception per unit of leaf area attributed to broad-leaved species, suggests that this type of leaf is able to capture and retain water effectively due to horizontal leaves gathering moisture droplets and 'pooling' these on the leaf surface (as observed in Section 3.8.3, in Chapter 3). Overall, however, this does not seem to compensate for other factors such as total leaf number, angles of orientation and hydrophobicity that may be advantaging the smaller leaves species. More research however, is required to determine where the intercepted water goes (including the use of non-pot systems) to give a better understanding of water movement within a wider landscape scale.

4.7.5 Soil / growing media moisture content during diurnal cycle

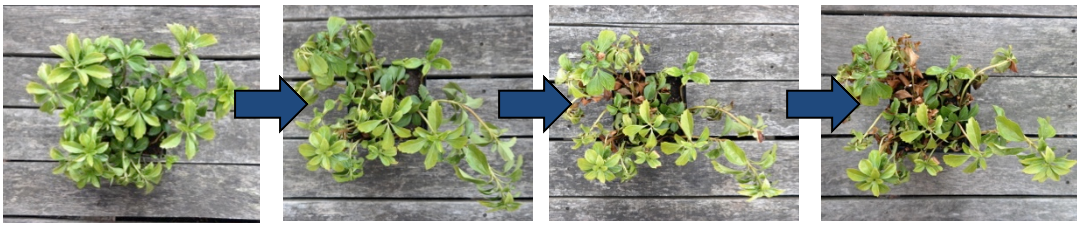
Soil moisture content data was also used to determine mean ET diurnal pattern for a chosen dry period (Day 11 to Day 16). Diurnal cycle was observed for 24 hours for each plant species. In general, ET started at 9:00, except for full-canopied *B. cordifolia,* which started from 2:00 (possibly from guttation or cuticular moisture loss rather than ET (Kerstiens, 2007; Coupel-Ledru *et al.*, 2016). Peak ET occurred between 11:00 to 15:00 (consistent with Voyde *et al.*, 2010a). Interestingly, *D.* 'Haytor White' (both canopy sizes) and the full-canopied *B. cordifolia* and *F. glauca* were observed to have two peaks of ET; one between 10:00 to 13:00, and a second between 14:00 to 17:00. This phenomenon has been observed elsewhere and is thought to be a strategy in some species to avoid excessive moisture loss during the hottest part of the day (Schulze *et al.,* 1974; Gao *et al.*, 2016), This is not uncommon, as stomata can close when the evaporative demand exceeds the capacity of xylem vessels to supply water to the leaves, and can happen due to high temperatures, leaf-to-air vapour pressure deficits (VPD) or wind speed (Gerosa *et al.*, 2012). Cessation of ET typically took place between 21:00 to 22:00, however was much earlier for *P. terminalis* (between 16:00 to 17:00). Why this was the case is unclear, though this was consistent with its overall lower ET rates, and may be an artifact of this being a shade-adapted species, tolerant of dry woodland soils.

4.7.6 Plant stress tolerance



Week 1 Week 3 Week 5 Week 7

Figure 4. 28: Physical condition of *H. sieboldiana* at the start of the experiment, mid-way during the experiment and after the experiment was complete.



Week 1 Week 3 Week 5 Week 7

Figure 4. 29: Physical condition of *P. terminalis* at the start of the experiment, during the experiment and after the experiment was complete.

Overall, *F. glauca, D.* 'Haytor White' and *V. minor* were among the species that performed relatively well in terms of water retention and ET compared to the rest of the species, and *H. sieboldiana* and *P. terminalis* often had lower ET rates and also showed some major stress signs. While *F. glauca* demonstrated a consistent amount of dry leaves, the other two species (*D.* 'Haytor White' and *V. minor*) did not show major signs of due stress at the end of the experiment. There were some dry leaves present on the plants due to the continuous dry period, but these did not affect their overall performances. This further supports the notion that these species were able to withstand drought stress conditions while also functioning well in capturing, retaining and releasing moisture. Such species could be recommended as having potential to tolerate drought, yet still impact on flood avoidance by relatively good water capture and use capabilities.

4.8 Key findings

- *Festuca glauca* was observed to have the most variation in weight changes; *F. glauca* showed the highest weight (moisture) loss during the longest continuous dry period (from Day 7 to Day 17), and it also gained the largest weight (moisture) during peak rainfall on Day 23.
- Overall, *V. minor* showed the largest significant differences in moisture changes between the two canopy sizes (full and half) throughout the monitoring period. This is attributed to the full-canopied having higher total leaf area and number of leaves than the half-canopied.
- In relation to moisture content, diurnal cycle was observed by all plant species where the peak ET was observed between 11:00 to 15:00 and the plants were more dormant at night time. This supports the natural phenomena of no photosynthesis taking place at night; plant stomata pores are closed at night, hence no ET observed.
- In terms of interception and retention performance, the full-canopied plants intercepted and retained more moisture compared to the half-canopied. This was expected due to higher plant leaf biomass, leaf area, number of leaves and total surface areas in general.
- For the two main rainfall events (Day 18 with 2.7 mm and Day 23 with 11.3 mm), *D.* 'Haytor White' and *F. glauca* (both canopy sizes) were among the species that retained greater amount of moisture compared to the other species. *Hosta sieboldiana* and *P. terminalis* often retained the least amount.
- In terms of ET performance, *F. glauca* (3.23 mm d^{-1}), *B. cordifolia* (1.96 mm d^{-1}) and *D.* 'Haytor White' (1.72 mm d^{-1}) had the highest ET. Again, *H. sieboldiana* (up to 1.45 mm d^{-1}) and *P. terminalis* (up to 0.99 mm d^{-1}) had lower ET rates compared to other species.
- *Bergenia cordifolia* (both canopy sizes) intercepted and retained the among highest amount of moisture per unit of leaf area on Day 23 (up to 5.45 mm m^{-2}), while *V. minor* retained the least (up to 2.72 mm m^{-2}) on a per unit of leaf area basis. This may be associated with leaf size, as *B. cordifolia* have large broad leaf to support droplets retention on its leaf surface (e.g. create pooling) as it had low leaf hydrophobicity.
- The half-canopied species had higher ET rates than the full-canopied species, per unit of leaf area, due to the trimmed canopy striving for resources harder

and faster. Again, *B. cordifolia* (both canopy sizes) had the highest ET rate per unit of leaf area on Day 9 (0.31 mm d^{-1} m^{-2}), and *P. terminalis* (both canopy sizes) lost the least / close to zero (0.1 mm d^{-1} m^{-2}).

- At the end of the experiment, *H. sieboldiana* and *P. terminalis* showed more stress signs (physically) compared to the other species, where their leaves were mostly dry, dead or had pathogen infections, which also reflected their low overall performances (retention and ET) due to loss of some leaf functionality.
- The physical stress observation supports the chlorophyll fluorescence data, which indicated *H. sieboldiana* to have lowest chlorophyll fluorescence values, while *B. cordifolia* showed the highest chlorophyll fluorescence values, indicating the healthiest amongst the other species.

4.9 Chapter summary

This chapter discussed different plants' behavior pertinent to moisture conditions with regards to Sheffield's natural weather conditions in late summer / early autumn. Plants' behaviors were associated with relative interception and retention during / after rain days and evapotranspiration (ET) during dry periods. *Festuca glauca* exhibited the best performance in terms of rainfall interception (up to 24.06 mm) and ET (up to 3.23 mm d^{-1}) compared to the rest of the species. *Hosta sieboldiana* and *P. terminalis* were the two species that outperformed in both circumstances. However, *B. cordifolia* performed well in relation to leaf area (interception, 5.45 mm m^{-2}; and ET, 0.52 mm d^{-1} m^{-2}). Moisture content relative to ET during dry period saw the expected diurnal cycle, where peak ET were seen during midday (between 11 am to 3 pm) for all species. Differences in the two canopy sizes (full and half-trimmed) were only significant on some species (i.e. *V. minor*, *F. glauca* and *H. sieboldiana*) and did not affect the rest of the species as significantly. Finally, plant stress observations through measuring chlorophyll fluorescence and visual observation suggested that *H. sieboldiana* showed the most stress signs (low chlorophyll fluorescence value), indicating that not only did it not perform well in the experiment (for both retention and ET), it was also the least tolerable to withstand drought stress conditions. However, an interesting finding suggests that its broad leaf species, was actually quite efficient at intercepting (and retaining) moisture on per unit of leaf area basis.

As ET in this experiment was highly affected by microclimatic conditions (i.e. solar radiation, temperature, relative humidity, wind speed), which is difficult to determine the accurate influencing factors, the next chapter (Chapter 5) will discuss experiments conducted to determine ET performances by the same plant species, in an indoor semi-controlled laboratory environment, thus eliminating the confounding factors such as weather parameters. This will then provide an outlook on the comparison of how ET by the plants is affected by different climatic scenarios (natural and artificial). The results and discussion presented here will be brought together with the findings of Chapters 3 and 5, and further discussed with an overall synthesis, along with a final conclusion of the research in Chapter 6.

CHAPTER 5

EVAPOTRANSPIRATION PERFORMANCE BY DIFFERENT PLANT TYPES UNDER SEMI-CONTROLLED CLIMATIC CONDITION

5.1 Introduction

The previous chapter presents the results and discussions on the weight changes pertinent to rainfall retention and evapotranspiration (ET) by six plant taxa associated with natural weather conditions. The experiments were conducted in an outdoor environment under Sheffield's late summer to early autumn weather conditions. It is known that ET efficiency is highly influenced by the surrounding microclimate, where higher temperature and low relative humidity increases the opportunity for higher ET rates due to capabilities of warm atmospheric conditions to hold more moisture than cool air (Sterling, 2004). Wind speed and direction also affects ET rates, as it moves the evaporated moisture from boundary layers of foliage (above canopy areas) making the atmosphere around the plants drier, thus increasing the opportunity for ET to take place (Domingo *et al.*, 1998). However, the variability and fluctuations of the natural climatic scenarios leads to the difficulty to measure accurate parameters that influence ET. Therefore, this chapter observes daily ET rates of the same plant species, in a semi-controlled laboratory / constant climatic environment. The purpose of the controlled climatic environment is to provide direct measure of moisture loss due to ET, and help to identify parameters that influence ET by reducing the confounding factors of uncontrollable parameters (i.e. climate). Continuous monitoring of weight loss (inferred as moisture loss) from the plant pots signifies ET rates from plants over a 12-day monitoring duration, and ET are also observed on per unit of leaf area basis.

5.2 Key objectives and questions of experiment

The objectives of this experiment were:

1. To identify which leaf type and canopy characteristics evapotranspire moisture more effectively under artificial climatic conditions.
2. To determine daily and overall ET rates of six plant taxa under artificial / semi-controlled climatic conditions.
3. To investigate the factors influencing ET rates by the plant taxa under semi-controlled climatic conditions.

The research questions of this experiment were:

1. Which plant species have the highest ET rates under artificial climatic conditions?
2. What are the key parameters that influence ET by the different plant taxa?
3. Which plants are most stress tolerant and have the capacity to alter ET rates in line with moisture availability, i.e. normally have a high ET rate, but can close this down effectively when experiencing the onset of drought?

5.3 Hypothesis

Broad-leaved species will have higher ET rate compared to plant species with narrow and small leaves.

5.4 Experimental setup

Seven compression load cells were placed on a bench rig that was installed in the Civil Engineering Water Lab, in the Civil and Structural Engineering Department, University of Sheffield (see Section 2.3.6, Chapter 2) (refer to Poë *et al.*, 2015). To normalize the climate condition within the working area, three high-pressure sodium lamps were used for artificial radiation (see Chapter 2 for detailed description and specification of the lights). The lights were switched on and off using a Time Guard Limited timer, set on timed mode. The timer was set to turn on at 10:30 am and turned off at 18:30 (6:30 pm), with a total of 8 hours of artificial daylight. Due to safety reasons based on laboratory risk assessment, the lighting systems were only allowed to be continuously turned on and unattended for a maximum of 8 hours per day. A TinyTag Ultra 2 sensor located on the experimental bench continuously recorded daily air temperature and relative humidity (RH) within the working space. Wind speed was presumably to be zero.

Six plant taxa (*Bergenia cordifolia*, *Dianthus* 'Haytor White', *Vinca minor*, *Festuca glauca*, *Hosta sieboldiana* and *Pachysandra terminalis*) and one growing media pot were examined in this experiment. Plants were potted using John Innes Compost No. 2, into 3.5 litre square pots (15 x 15 x 20 cm), a size that fits on the load cell platform (27 x 27 cm). The plants were kept outdoors (on the green roof of Sir Robert Hadfield Building, University of Sheffield), and brought into the lab at least 24 hours before the experiment took place.

5.5 Methods

Prior to the experiments, photos of each plant were taken to assess the condition of the plants before the start of each test. This was to eliminate the confounding effect of time and replicates, as the tests were repeated four times consecutively, in which the plants' condition may have been affected by seasonal change (time) because they were placed outside prior to tests. At the start of each experiment, all treatments were submerged in a bucket of water up to the growing media level. Plant canopies were kept dry. After 20 hours of submersion, the pots were then drained for 2 hours on a metal grid to allow free flow of excess water until the growing media reached field capacity (Figure 5.1; *Left*). The treatments were weighed on a balance scale at their field capacity state. The treatments were then randomly placed on the load cell platforms at 10:30 am to continuously monitor weight changes, which is inferred as moisture changes / moisture loss over 12 days of monitoring (Figure 5.1; *Right*). Lights were automatically turned on / off everyday to provide daylight source, and no irrigation was applied throughout the experiment. Weight was continuously recorded and logged in a Modular 600 Multi-Channel data logger, located underneath the bench rig (see Figure 2.8 and 2.10(c) in Chapter 2). Weight outputs that were logged via the data logger (in volts) at 1-minute interval, were then transferred into Microsoft Excel and converted into unit weight (kg) using the RDP650 programme software for Windows (RDP Electronics Ltd).

Figure 5. 1: (*Left*) Treatments drained for 2 hours to reach field capacity after being submerged for 20 hours; (*Right*) Treatments placed on load cells for continuous weight change monitoring.

After 12 days of monitoring, the data logger was stopped, and each treatment was weighed on a scale again to see the weight differences before and after monitoring. Weight changes in kg were converted into a volume in liters assuming that the density of water is 1000 kg / m^3. Volumes were converted to depths of moisture changes / ET (in mm) by assuming that the weight loss occurred over the plan area of the plant pot, i.e. 0.15 m x 0.15 m = 0.0225 m^2. Each treatment had four replicates, and four sets of trials were conducted consecutively. The data collection took place between 11/08/17 and 28/10/17, a total of 8 weeks. After each experiment was complete, photos were taken of each plant canopy to identify any signs of stress. Finally, each plant's leaves were harvested to measure the plant's total leaf area, fresh weight, number of leaves and leaf biomass. However, due to the difficulty of measuring leaf area of *F. glauca* because of small leaf size and large number of leaves, a different method was used to estimate the total leaf area of this species, which was based on taking the leaf area of 20 sample leaves and multiplying it by the weight of the whole plant. A detailed methodology is presented in Chapter 4 (Section 4.5).

As the treatments were weighed using a balance scale before and after the load cell monitoring, a comparison between balance scale and load cells is possible. Figure 5.2 and Figure 5.3 demonstrates an example of a strong correlation of the weights for all of the treatments (Test 4) using both weighing methods (balance scale and load cell) before and after the 12-day monitoring.

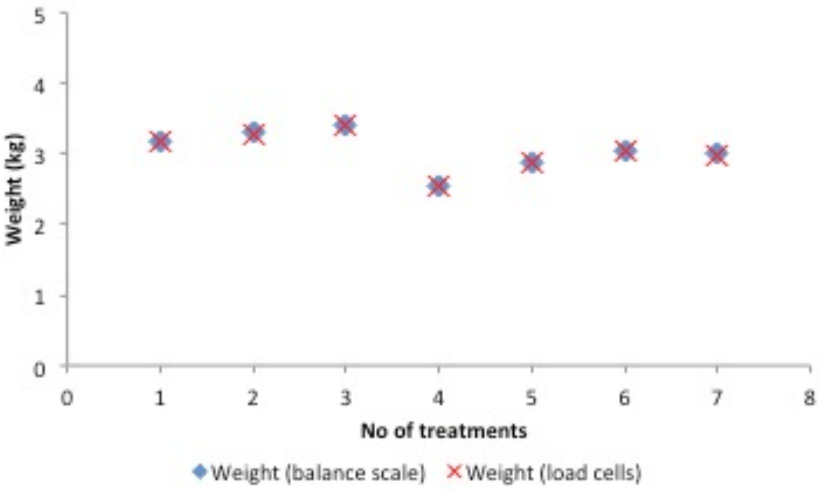


Figure 5. 2: Weight correlation of all treatments using a balance scale and load cells before the monitoring (at field capacity).

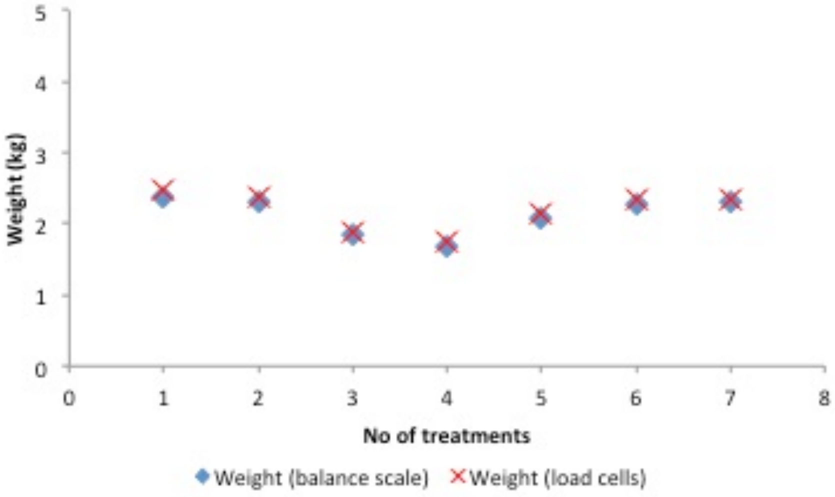


Figure 5. 3: Weight correlation of all treatments using a balance scale and load cells after the monitoring.

5.6 Results

5.6.1 Load cells calibration result

Based on the load cells calibration, a shift between the calibration done prior to Test 1 and the calibration done after Test 2 was detected on some of the load cells, due to some sudden intervention or event, such as equipment being accidentally moved that might have affected the load cell. The shift in the calibration curve for LC1 demonstrated the maximum possible error out of all the load cells (Figure 5.5). The data shows a clear shift and the voltage increased by approximately 1.3V between the calibrations done before Test 1 and after Test 2. However, the gradient / rate of change of the mass with voltage remained constant throughout all of the tests, and the analysis of the experiment was inferred from the rate of change in mass based on the voltage, such that absolute values are not important. Nonetheless, checks were made on data records for any sudden changes within the tests, and of the sample replications for any odd behavior of the treatments in Test 1 and / or Test 2 because the shift occurred at some points between those tests. For all the checks made, there did not appear to be any unexpected behavior (i.e. sudden shifts or jumps) in the recorded data. Therefore, the inference is that the shift happened between the tests, and not during tests, therefore all the results are treated as valid.

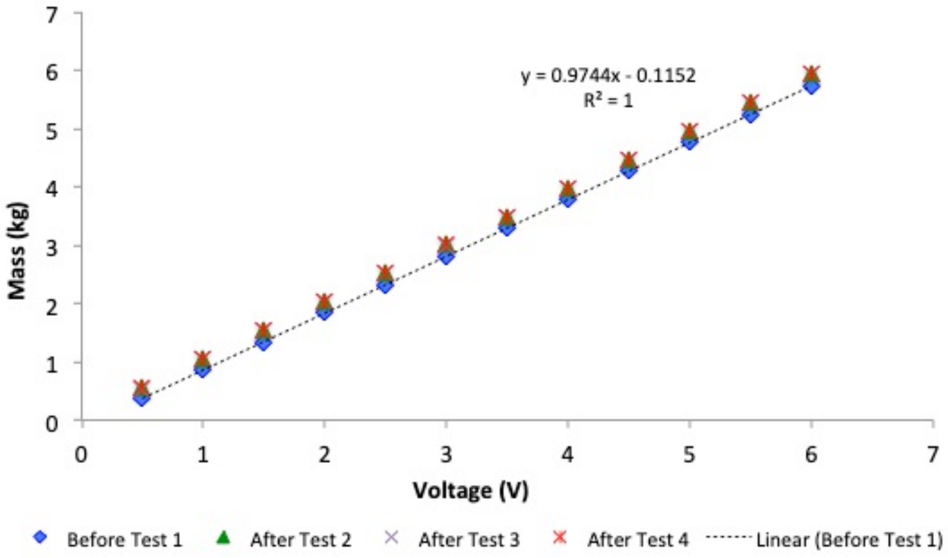


Figure 5. 4: Example of a strong correlation ($R^2 = 1.0$) of the regression equation on one of the load cells (LC 4) before and after the overall monitoring was conducted.

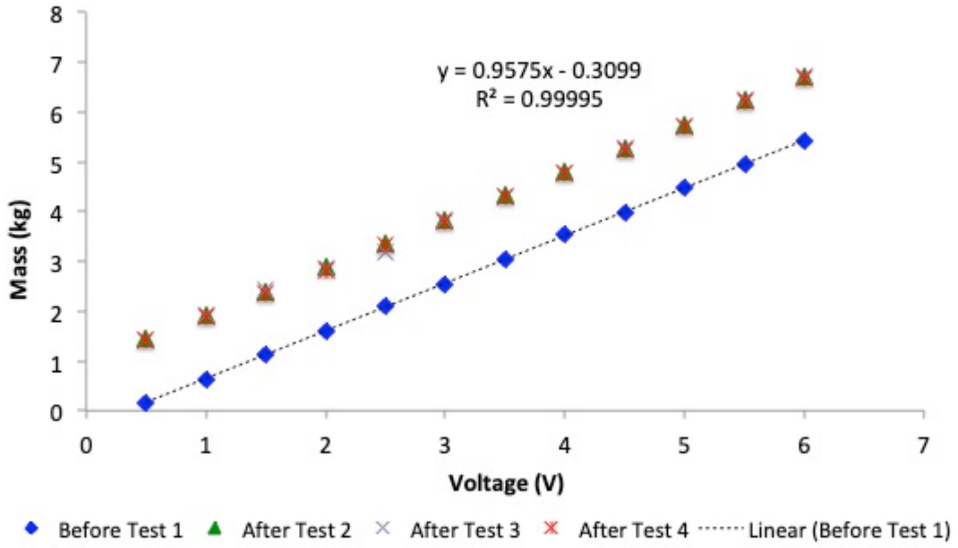


Figure 5. 5: Example of a correlation of the regression equation on one of the load cells (LC 1) that had a shift between Test 1 and Test 2.

5.6.2 Temperature and relative humidity

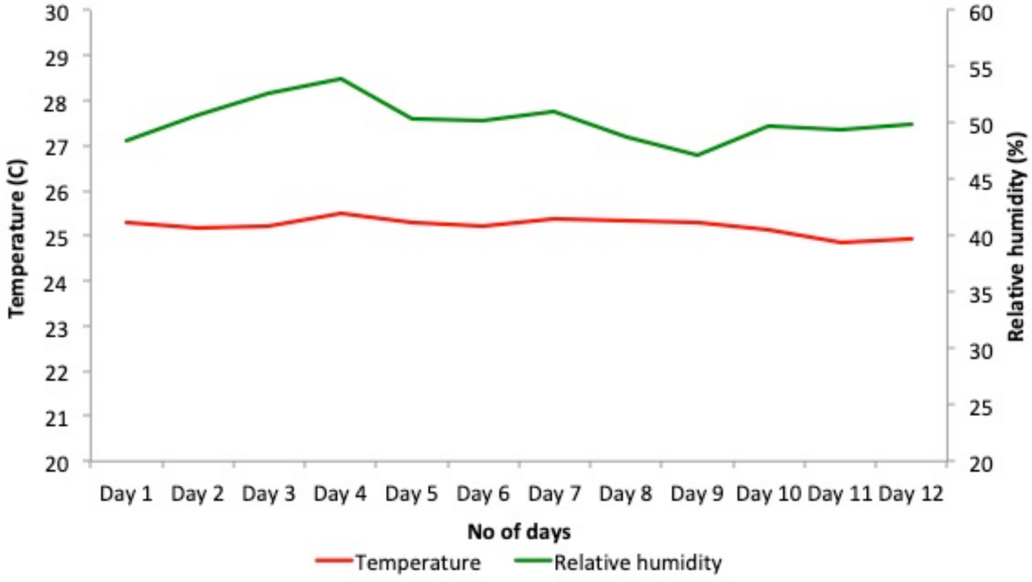


Figure 5. 6: Mean daily air temperature and relative humidity during the experiments in the laboratory environment.

The experiments took place from late summer until early autumn. The diurnal indoor temperature during the observation period ranged between 24.1°C and 26.2°C, with an average of 25.2°C, and mean daily relative humidity (RH) was 50.2% (ranging from 40.8 to 62.4%) (Figure 5.6). Although the replicated temperature value was higher than the mean summer temperature in the UK, which was 15.8°C in 2018 (Met Office, 2018), this research sought to investigate how these plants could survive in drought stress conditions (i.e. due to consistent warm temperatures inducing continuous ET, thus drying out the soils) in which the principles could then be applied in broader climatic regions. Figure 5.6 presents the average daily temperature and RH for the four sets of experiments over the duration of 12 days.

5.6.3 Evapotranspiration performance by treatments

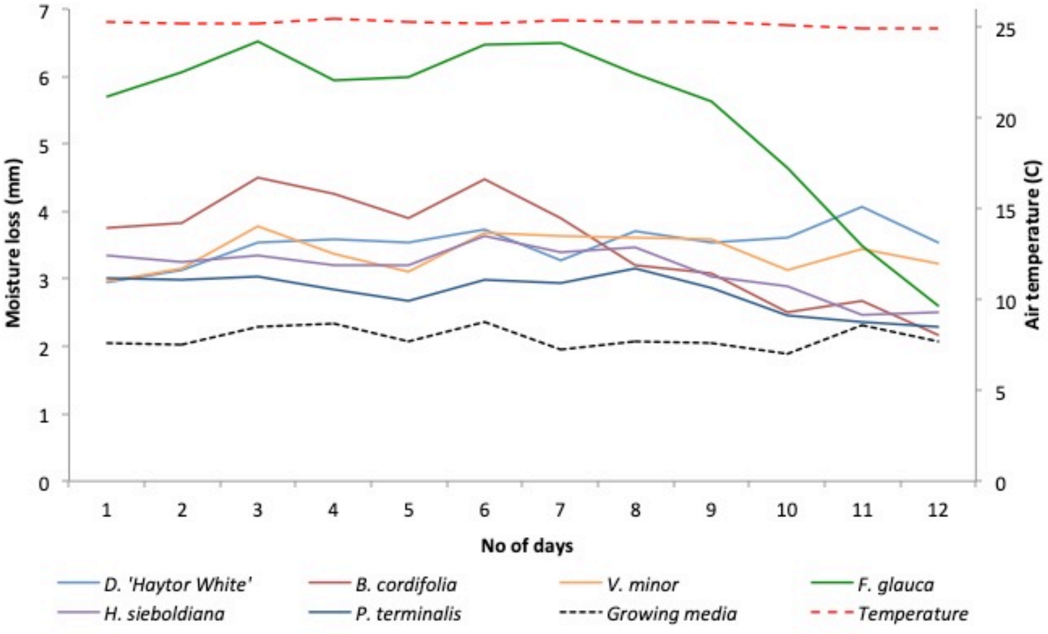


Figure 5. 7: Mean daily ET rates by the six plant taxa over 12 monitoring days.

Over the course of 12 days, the highest cumulative ET was by *F. glauca* (65.57 mm) and lowest (evaporation) by the growing media (25.51 mm); of the vegetated treatments, *P. terminalis* had the lowest ET rates (33.58 mm) (Table 5.2). Of the plant taxa, mean daily ET rates was also associated with *F. glauca* (5.46 mm d^{-1}), and lowest by *P. terminalis* (2.80 mm d^{-1}). Most of the treatments demonstrated an observable decrease in ET rates over time except for *D.* 'Haytor White', which gradually increased over time; and the growing media where evaporation was relatively consistent throughout the 12 days. It was noticeable that the plants lost the highest amount of water on Day 6 except for *B. cordifolia* and *P. terminalis* (highest observed ET rate on Day 3 for *B. cordifolia* and Day 8 for *P. terminalis,* but Day 6 still showed a relatively high ET rate for both species). As the gravimetric data (in kg) was converted into water depth (in mm), the original raw data of mean daily weight loss and cumulative weight loss over the course of the entire experiment are provided in Table 5.1 for comparison purposes.

Table 5. 1: Mean daily and cumulative weight (moisture) loss (kg) by the six plant taxa.

Treatments	Mean daily weight (moisture) loss (kg)	Total cumulative weight loss (ET) (kg)
D. 'Haytor White'	0.079	0.950
B. cordifolia	0.079	0.950
V. minor	0.076	0.915
F. glauca	0.123	1.475
H. sieboldiana	0.071	0.848
P. terminalis	0.063	0.756
Growing media	0.048	0.574

Table 5. 2: Mean daily and cumulative ET rates (mm) by the six plant taxa.

Treatments	Mean daily ET rate (mm d^{-1})	Total cumulative ET (mm)
D. 'Haytor White'	3.52	42.22
B. cordifolia	3.52	42.24
V. minor	3.39	40.66
F. glauca	5.46	65.57
H. sieboldiana	3.14	37.69
P. terminalis	2.80	33.58
Growing media	2.13	25.51

Repeated measures of analysis of variance (ANOVA) were conducted to identify whether there were any statistical differences of the mean ET rates between the treatments, due to the time component within the data series. Overall, there is a significant difference in the cumulative ET between the treatments over the course of the monitoring period. Between the vegetated treatments, *F. glauca* with the overall highest ET rate was significantly different to all the other species ($p < 0.05$), but no statistical difference found between the other species with each other. However, all species (except for *P. terminalis*; $p = 0.71$) showed significant difference compared to the growing media ($p < 0.05$).

5.6.4 Evapotranspiration rates during the first three days

Plant transpiration (and ET, if soil is included) demands are known to be highly influenced by availability of moisture (Poë *et al.*, 2015; Kemp *et al.*, 2019). Here, ET performances of each treatment during different moisture conditions (first and last three days) of monitoring were observed. The purpose was to identify how different plants performed during abundant moisture availability (first three days, when soil was at / near field capacity state), and when water became limited towards the end of monitoring period (last three days). Figure 5.8 and Figure 5.9 demonstrates ET performance by the six plant species during the two moisture conditions.

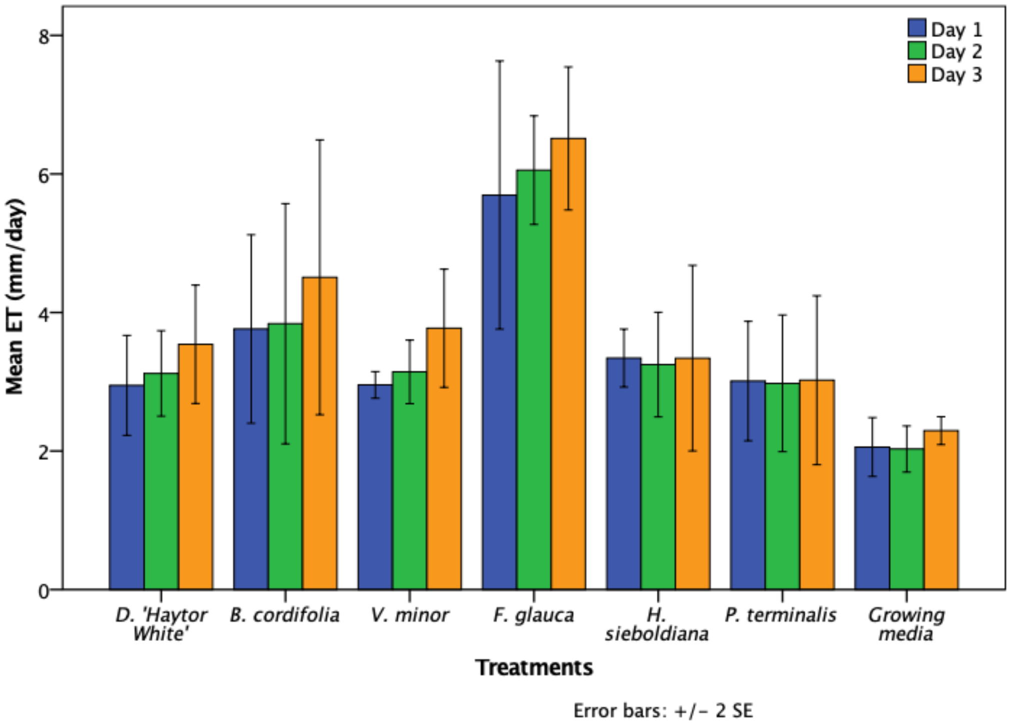


Figure 5. 8: Mean ET rates of all treatments from Day 1 to Day 3.

During the first three days, ET rates within each species were quite consistent as the environmental condition was relatively consistent. *Festuca glauca* had the highest observable ET rates on all three days, which was significantly different from the rest of the species except for *B. cordifolia* (p = 0.46 on Day 1, p = 0.88 on Day 2 and p = 0.40 on Day 3). There was no significant difference over the first three days between the other species. However, all species had significantly higher ET rates than the growing media, except for *B. cordifolia* (p = 0.08, 0.20 and 0.14 on Day 1, 2 and 3 respectively) and *P. terminalis* (p = 0.24, 0.20 and 0.85 on Day 1, 2 and 3 respectively) on all three days, and *H. sieboldiana* on Day 3 (p = 0.61).

5.6.5 Evapotranspiration rates during the last days

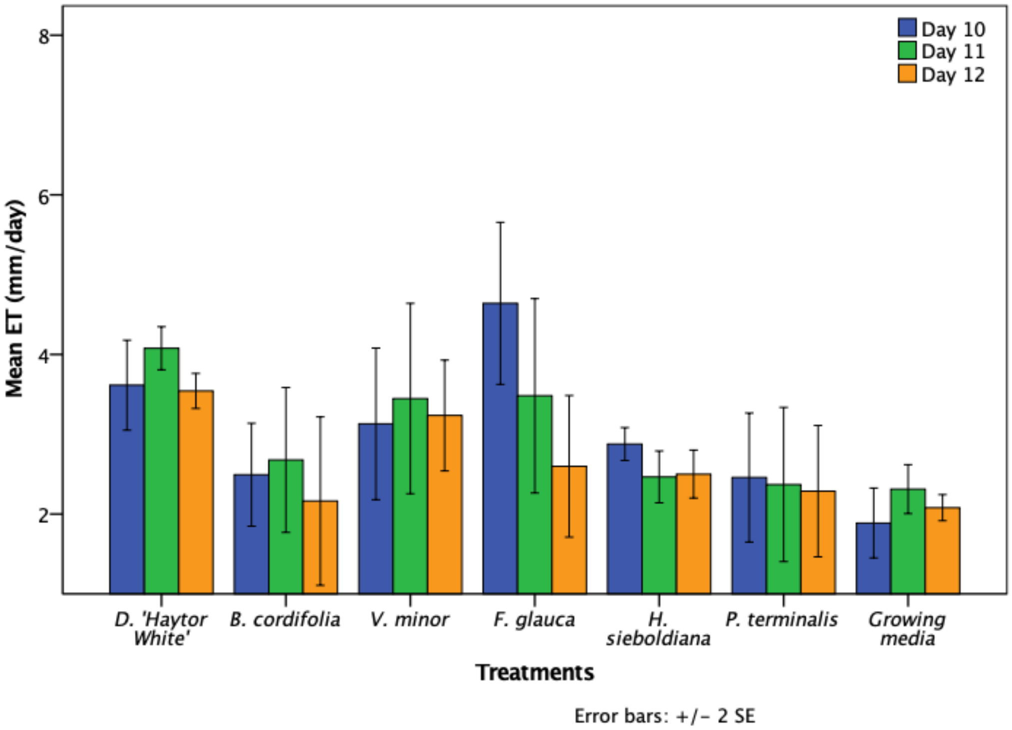


Figure 5. 9: Mean ET rates of all treatments from Day 10 to Day 12.

On Day 10, the highest ET rate was still associated with *F. glauca*, but decreased significantly on Day 11 and Day 12. Interestingly, *D*. 'Haytor White' had higher ET rate than the first three days (Figure 5.8), but instead of decreasing in ET rate, *D*. 'Haytor White' had gradual increase in ET rate throughout the experiment. By Day 12, *D*. 'Haytor White' and *V. minor* had higher ET rates than *F. glauca,* however these were not significant (p = 0.23 and p = 0.90 for *D*. 'Haytor White' and *V. minor* respectively). By the end of the monitoring (on Day 12), all species demonstrated an observable decrease in daily ET rate (except for *D*. 'Haytor White'), and only *D*. 'Haytor White' and *V. minor* were found to be significantly different than the growing media ($p < 0.05$).

5.6.6 Plant stress tolerance

After 12 days of continuous monitoring of ET rates in the laboratory environment, each plant's physical forms were physically observed to identify signs of stress. The stress signs were ranked on a scale from 1 to 6; 1 - severely stressed (dead leaves); 2 - very poor condition (70% dry / dead); 3 – poor condition (50% dry / dead); 4 - unhealthy (20% dry / dead); 5 – moderately healthy; and 6 - very healthy. Statistical analysis showed no statistically significant difference found between the stress signs of the different species based on the mean scores given ($p > 0.05$). However, based on the observation of the physical conditions of the plants after the experiment, various levels of stress signs were observed on different plant species (Figure 5.10).

a) *D.* 'Haytor White' b) *B. cordifolia* c) *V. minor*

d) *F. glauca* e) *H. sieboldiana* f) *P. terminalis*

Figure 5. 10: Examples of stress signs exhibited by each species during the entire four tests.

At the end of each monitoring of all four tests, *F. glauca* showed consistent stress signs. *Festuca glauca,* which lost the highest mean overall moisture over the whole monitoring period, showed signs of stress where a considerable amount of their leaves were very dry. *Bergenia cordifolia* and *D.* 'Haytor White' also lost a relatively high amount, although not as high as *F. glauca*. However, their physical conditions at the end of the monitoring did not show major stress signs on any of the replicates. Minimal dry leaves were observed on *B. cordifolia*, and only some edges of the leaves have started to turn red (especially after Test 3 and Test 4). *Dianthus* 'Haytor White' was among the species that evapotranspired a considerable amount of moisture during the experiment (after *F. glauca* and *B. cordifolia*). *Dianthus* 'Haytor White' exhibited rather consistent stress signs where only the inner leaves of the canopy and some tip of the leaves were dry, while the outer leaves maintained green and healthy. This was consistent on all four tests / replicates.

Similarly, *V. minor* lost a moderate amount of moisture, and it also did not show major stress signs except for a number of leaves and stem turning black / dark brown, indicating signs of pathogen infections due to the stress condition. *Hosta sieboldiana* exhibited major signs through drying of leaves, but not on all replicates. Severe leaf dryness was observed only after Test 2 and Test 3, on Replicate (Rep.) 2 and Rep. 3, but Rep. 1 and Rep. 4 maintained a healthy condition (after Test 1 and Test 4). This may be due to the conditions of the individual plant itself before the start of the monitoring (which may have already been in poor or possibly stress condition before the tests). Finally, *P. terminalis* showed the least stress signs. Several dry leaves and stem were seen on Rep. 1 (after Test 1), however, the rest of the plants (Rep. 2, Rep. 3 and Rep. 4) were observed to be healthy at the end of each test.

5.6.7 Evapotranspiration in relation to leaf area

Evapotranspiration rates during the monitoring period were observed on per unit of leaf area basis. Initially, *F. glauca* had the highest overall ET and was statistically significantly different to the rest of the species, while *P. terminalis* had the lowest cumulative ET rates over the duration of 12 monitoring days. When ET rates by the species were expressed on per unit of leaf area basis (Table 5.3), *H. sieboldiana* had the highest cumulative ET per unit of leaf area (11.03 mm m^{-2}). This was statistically significant than the rest of the species except for *D.* 'Haytor White' ($p = 0.13$) and *F. glauca* ($p = 0.97$), which lost second and third highest amount of total moisture per unit of leaf area respectively (6.85 mm m^{-2} and 6.36 mm m^{-2}). *Pachysandra terminalis* had the lowest total ET per unit of leaf area (1.94 mm m^{-2}), and was statistically significant than the rest of the species ($p < 0.05$).

The highest mean daily ET rate per unit of leaf area was also observed on *H. sieboldiana* (0.92 mm d^{-1} m^{-2}) (Table 5.3), which again, was significantly different from all species except for *D.* 'Haytor White' (p = 0.17) and *F. glauca* (p = 0.28). Both of these species also lost a considerable amount of moisture per day, per unit of leaf area (0.57 mm d^{-1} m^{-2} and 0.53 mm d^{-1} m^{-2} respectively). Daily moisture loss per unit of leaf area was lowest by *P. terminalis* (0.16 mm d^{-1} m^{-2}), which was significantly different from all species except for *F. glauca* (p = 0.17).

Table 5. 3: Mean total leaf area, number of leaves and total ET rates per unit of leaf area of the six plant taxa.

Plant species	**Mean total leaf area (m^2)**	**Mean number of leaves**	**Mean daily ET / unit of leaf area (mm d^{-1} m^{-2})**	**Total ET / unit of leaf area (mm m^{-2})**
D. 'Haytor White'	6.51	655	0.57	6.85
B. cordifolia	9.46	25	0.37	4.48
V. minor	11.55	909	0.29	3.58
F. glauca	7.94	-	0.53	6.36
H. sieboldiana	3.89	7	0.92	11.03
P. terminalis	17.26	402	0.16	1.94

5.6.8 Evapotranspiration per leaf area on Day 1 and Day 12

Evapotranspiration rate per unit of leaf area of the six plant taxa was observed for the first day of the monitoring (Day 1) and the last day of the monitoring (Day 12) (see Figure 5.11), to identify differences between ET rates (per unit of leaf area) during presumably abundant and limited moisture conditions. As leaf area data was taken after each test because these were done destructively, leaf area data at the beginning of the observation (Day 1) is unavailable. However, it is expected that to some extent, the total leaf area is higher at the beginning of the monitoring because some plant leaves showed some stress signs by either drying, browning or damaged at the end of the tests, therefore leaf area was not calculated for these affected leaves (leaf area data calculated on fresh green leaf only).

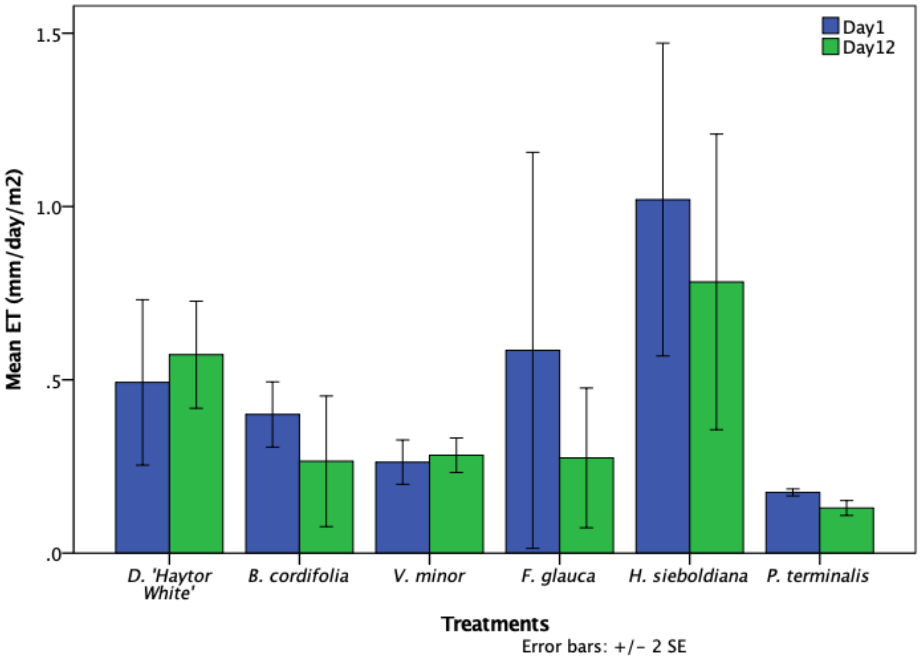


Figure 5. 11: Mean ET rates per unit of leaf area of all treatments on Day 1 and Day 12.

On Day 1 when moisture was ample and at / near field capacity, *H. sieboldiana* had the highest daily ET rate per unit of leaf area (0.89 mm d^{-1} m^{-2}), followed by *F. glauca* (0.71 mm d^{-1} m^{-2}). *Hosta sieboldiana* was statistically different from *B. cordifolia, V. minor* and *P. terminalis* ($p < 0.05$). *Pachysandra terminalis,* which lost the least amount of moisture per unit of leaf area, was significantly different from all species except for *F. glauca* ($p = 0.46$).

On Day 12, *H. sieboldiana* still had the highest daily ET rate per unit of leaf area (0.69 mm d^{-1} m^{-2}), however, this time followed by *D.* 'Haytor White' (0.50 mm d^{-1} m^{-2}). *Hosta sieboldiana* was not statistically significant to the other species except for *P. terminalis* ($p < 0.05$). On this day, *F. glauca* did not lose as much moisture (0.29 mm d^{-1} m^{-2}) compared to Day 1, and was not statistically significant from any of the species. On both days, *P. terminalis* had the lowest ET rate per unit of leaf area (0.15 mm d^{-1} m^{-2} and 0.12 mm d^{-1} m^{-2} on Day 1 and Day 12 respectively).

5.7 Discussion

5.7.1 Evapotranspiration performance by treatments

Overall, *F. glauca* lost the highest total amount of moisture throughout the whole monitoring period (65.57 mm), and *P. terminalis* lost the least, with total ET almost half of that of *F. glauca* (33.58 mm). There were three moisture loss behaviours worthy of note. This generally shows how the plants tend to use their available water when it is abundant (at the beginning of monitoring), and eventually when it became limited (towards the end of monitoring). Firstly, *F. glauca* showed a large moisture loss in the first 7 days, ranging from 5.70 mm to 6.49 mm a day. However, from Day 7 onwards, a slight decrease in moisture loss was seen and a steeper slope from Day 9 to Day 12 (Figure 5.7). This assumes that moisture availability became limited as *F. glauca* lost a significant amount in the beginning, and the plants were then beginning to perceive deficits, which then caused the stomata to close, thereby decreasing the rate of ET / transpiration losses (Schachtman and Goodger, 2008; Bertolino *et al.*, 2019). The rapid reductions between Day 10 and Day 12 (Figure 5.9) however, suggest that moisture was becoming very scarce or indeed some of the leaves were becoming rapidly dysfunctional. It is feasible that some plants / leaves of *F. glauca* reached permanent wilting point 'zone' (PWP) on Days 11 and 12 (although this may be difficult to perceive in a grass, as leaves tend to desiccate rather than droop, and the crown of the plant may itself remain viable). Nevertheless, it was evident that almost 50% of the leaves in this species were dry / dead by the end of the experiment. This may reflect its low ET rate at the end due to less functioning of leaves and less leaf surface area (as some leaves had died).

Bergenia cordifolia, which lost the second highest overall amount of moisture, also exhibited a steep curve after Day 6, in which ET rates decreased from Day 6 to Day 12 (Figure 5.7). Indeed, of all the species, *Bergenia cordifolia* lost the least amount of moisture on Day 12 (2.16 mm d^{-1}), which was almost as low as the growing media (2.08 mm d^{-1}). Similar to *F. glauca*, *B. cordifolia* may have lost a considerable amount of moisture in the beginning, and because it had used so much of its available water, its moisture loss rates decreased over time as moisture may have become limited. On the other hand, *B. cordifolia* maintained a healthy condition at the end of each monitoring period. None of its replicates showed major stress signs, except for leaves turning red / brownish especially on Rep. 3 and Rep. 4, which is suspected to be due to changing atmospheric condition into slightly colder weather, which is a natural phenomenon for *B. cordifolia*. Therefore, it was a good indicator of plants that could survive water stress and also maintained a good healthy condition. *Hosta sieboldiana* followed a similar pattern to *B. cordifolia,* with high ET rates from Day 1 to Day 8, which then decreased gradually from Day 9 to Day 12. This moisture loss pattern is consistent with a study by Poë *et al*., (2015) who found ET rates by *Sedum* and meadow flowers were high during the first 7 days, and reduced to zero or close to zero per day, after 14 days of monitoring

While these species showed a large ET rate in the beginning and lost less moisture towards the end, interestingly, *D*. 'Haytor White' demonstrated the opposite pattern. During the 12 monitoring days, ET rates by *D*. 'Haytor White' increased from 2.95 mm d^{-1} on Day 1, to a maximum of 4.08 mm d^{-1} on Day 11. The precise reason for this 'slow start' is unclear, but may relate to these plants adapting to the laboratory conditions after being moved in from outside; environmental conditions including irradiance levels affecting stomatal aperture (Araújo *et al*., 2011). Certainly, this conservative approach to moisture use early on, meant that *D*. 'Haytor White' could increase its ET as it acclimatized to the new environment, as it still had plenty of moisture reserves in the growing media. This ability to conserve moisture during periods of stress or transition may indicate a drought-tolerant species (Araújo *et al*., 2011) as they tend to close their stomata and open them slowly in order to survive when water is limited.

Lastly, *V. minor* and *P. terminalis* generally maintained their ET rates throughout the monitoring period and lost relatively similar amount each day. Daily ET rates by *V. minor* ranged between 2.96 mm d^{-1} and 3.69 mm d^{-1}, and *P. terminalis* between 2.29 mm d^{-1} and 3.15 mm d^{-1}, which did not show a significant increase or decrease during different moisture availability. Both these species appeared to demonstrate a conservative approach to water use, irrespective of what the availability was, and as such maintained low but regular ET rates throughout; a useful strategy for survival, but not one that leads to rapid soil drying and the ability for the soil to hold more rainwater.

As expected, the growing media lost the least amount of moisture throughout the whole monitoring period, at a relatively consistent rate. This is due to the absence of vegetation, therefore the inability to help lose moisture via transpiration. This observation provides an indication that different species responds differently to moisture availability in their systems, while some tend to be more efficient in water use and survive better in drought condition, others do not.

According to Poë *et al.* (2015), the maximum moisture storage capacity of the plants could be predicted through the known moisture loss via ET under the UK's climatic conditions after their experimental trial of 28 days, when the plants experienced wilting. In this research, wilting was not observed, but rather leaf dryness / dying as a sign of water deficit stress that was clearly observed on some plant species (which could imply a more severe stress sign than wilting). Therefore, if adopting their methods and assuming that maximum moisture storage capacity of the plants was equivalent to the amount of total moisture loss (ET) at the end of the experiment (12 days), *F. glauca* would have the largest moisture storage capacity as it lost the highest moisture cumulatively after 12 days. However, this method may not be appropriate to apply for all species, as it is hypothesized that some plants use their available moisture differently and the various species expressed different levels of stress and adaptations to this stress. Indeed, species such as *P. terminalis* and *B. cordifolia*, did not show major signs of stress (except with individual replicates) and therefore the estimation of their maximum moisture storage capacity was unable to be determined precisely. Furthermore, this method would seem to be inapplicable on those plants that regulate their moisture more efficiently (i.e. ET small amounts per day and did not show major stress signs / increased in ET rates over time such as *D.* 'Haytor White'), or regulate stomata based on other (non-hydrological) factors. As such, these plants may still have available moisture stored in the growing media, despite low ET rates. Differences between the studies may also be due to the shorter period of monitoring of 12 days here, compared to 28 days by Poë *et al.* (2015).

Based on the stress signs exhibited by all six species (Section 5.6.6), it was clear that different plant utilized their available moisture differently, which was reflected by their ET rates pattern. For example, although *F. glauca* lost a great amount of moisture, it did not withstand drought or moisture deficit stress well throughout all four repeated tests, and started to show considerable amount of leaf dryness after the 12 days of monitoring. If the experiment had been conducted for more than 12 days, it is possible that the leaves of *F. glauca* might have dried out completely because it lost a significantly high amount of moisture in the beginning and lost small amounts at the end of the monitoring, which indicates that it did not conserve its moisture even though its water availability had become limited.

5.7.2 Transpiration in relation to leaf area

Pachysandra terminalis had the highest total leaf area, followed by *V. minor* and *B. cordifolia*, while *H. sieboldiana* had the lowest total leaf area (Table 5.3). However, *H. sieboldiana* had the highest total ET per unit of leaf area (11.03 mm m^{-2}), and mean daily ET rate (0.92 mm d^{-1} m^{-2}) per unit of leaf area, followed by *D*. 'Haytor White' and *F. glauca* (Table 5.3). Although *F. glauca* had the highest ET rate (per plant basis) on Day 1, towards the end of the monitoring (Day 12), *F. glauca* did not lose as much moisture (Section 5.6.7). This may have been due to some stress within the plant leaf, resulting in almost half of the plants to dry out / die, which then lost the functioning of a considerable amount of leaf due to less surface area (i.e. stomata failed to function). Furthermore, while overall high ET by *F. glauca* may be associated with higher number of leaves (therefore more stomata present), when calculated on a per leaf area basis, *H. sieboldiana*'s leaf type was observed to be more EWU. It had the highest ET in all circumstances observed on a per leaf area basis; cumulatively (11.03 mm m^{-2}) and daily (0.92 mm d^{-1} m^{-2}), as well as at the start of the monitoring (0.89 mm d^{-1} m^{-2} on Day 1) (presumably abundant moisture availability) and at the end of the monitoring (0.69 mm d^{-1} m^{-2} on Day 12) (reduced moisture availability) (Section 5.6.7). This may be associated with its eco-physiology; as *H. sieboldiana* is known to adapt in shady and moist environmental condition, it may be accustomed to having sufficient moisture, therefore able to evapotranspire moisture efficiently.

5.7.3 Key findings

- Over the course of 12 monitoring days, *F. glauca* lost a significantly high amount of total moisture via ET (65.57 mm) compared to other species, and *P. terminalis* lost the least (33.58 mm).

- Three moisture loss trends were detected within the vegetated treatments; *F. glauca*, *B. cordifolia* and *H. sieboldiana* evapotranspired a high amount of moisture in the beginning (up to Day 6 to Day 8 depending on species), and then gradually decreased in ET rates until the end of the monitoring. *Dianthus* 'Haytor White' lost small amounts in the beginning and then increased in rates throughout the monitoring period (until Day 11), while *V. minor* and *P. terminalis* generally maintained their ET rates pattern throughout the monitoring.
- During the first three days, *F. glauca* lost the highest amount of moisture (5.70, 6.06, 6.51 mm on Day 1, 2 and 3 respectively), but during the last three days, *F. glauca* lost significantly less moisture on Day 11 and 12 (3.48 mm and 2.60 mm on both days respectively). In contrast, in the case of *D.* 'Haytor White', from losing a small amount in the first three days started to exceed all the other species, (including *F. glauca*) at the end of the monitoring, resulting in the highest ET rates on Day 11 and 12 (4.08 mm and 3.54 mm respectively).
- Based on the physical observation of plant stress, *F. glauca* (all replicates) showed consistent stress signs through drying of leaves. All the other species did not show major stress signs, while *H. sieboldiana* only showed extreme leaves dryness after Test 2 and Test 3, which may be due to the condition of the individual plant before the test rather than the species.
- *Hosta sieboldiana* had the highest ET rate per unit of leaf area, cumulatively (11.03 mm m^{-2}) and daily (0.92 mm d^{-1} m^{-2}), although it had among the lowest total ET (37.69 mm) on a per plant basis. In contrast, although *P. terminalis* had the highest total leaf area (Table 5.3), on a per unit of leaf area basis, it lost the smallest amount of total moisture (1.94 mm m^{-2}) and daily ET per unit of leaf area (0.16 d^{-1} m^{-2}).
- Based on the findings of this experiment, the key parameters influencing ET are the plant type, which governs their EUW based on moisture availability. However, some plants were affected by the phenological changes, which influenced the effectiveness in their ET rates.

5.8 Chapter summary

Evapotranspiration (ET) performance under semi-controlled climatic condition confirms that among the key drivers of ET are moisture content and / or moisture availability, and that ET performance varies depending on plant species. Of the six plant taxa observed, *F. glauca* had the highest accumulated ET rate compared to the other species (total 65.57 mm, and up to 6.49 mm per day), but it also exhibited considerable stress signs, which indicates that despite having the best ET performance, *F. glauca* did not withstand drought stress condition well. Evapotranspiration rates generally decreased over time for most species, as moisture became limited, though this pattern depended on the species and their EUW. Some plants conserved their available moisture, which then allowed them to withstand drought stress, while others either maintained a consistent rate or increased in moisture loss rate. This highlights the importance of plants' EUW and gives an indication of the types of plant morphology and the way they utilize their moisture during conditions of drought, which can be recommended as drought-tolerance species. The results and discussion presented here will be brought together with the findings of Chapters 3 and 4, and further discussed with an overall synthesis, along with a final conclusion of the research in Chapter 6.

CHAPTER 6

GENERAL DISCUSSION, CONCLUSIONS AND FUTURE WORK

6.1 Introduction

The roles of the effects of leaf morphology on hydrological performance, namely rainfall interception, retention and evapotranspiration (ET) have been widely studied and documented in a number of previous literatures. However, most of these studies focused on the effectiveness of larger scale vegetation, such as forests and even individual trees (Clark, 1940; Swift *et al.*, 1975; Fahey and Jackson, 1997; Xiao *et al.*, 2000; Givnish, 2002; Calder *et al.*, 2003; Pizarro *et al.*, 2006; Wang *et al.*, 2007; Komatsu *et al.*, 2008; Li *et al.*, 2016; Rahmat *et al.*, 2019). There is still limited information and knowledge on the roles of smaller scale plantings such as shrubs, herbaceous plants and groundcover plantings especially in the context of urban planting (with the exception of some studies on green roof plants; Lundholm *et al.*, 2010; MacIvor and Lundholm, 2011; Nagase and Dunnett, 2012; Wang *et al.*, 2012; Krishnan and Ahmad, 2014; Poë *et al.*, 2015; Kemp *et al.*, 2019). This research investigated the influence of groundcover plants, focusing on different leaf morphological traits (i.e. canopy size and structure, leaf shape, leaf size, leaf area, leaf angle and orientation and general leaf surface texture), and how they can effectively influence hydrological performance. The hydrological performance in this context refers to a few hydrological processes related to a plant hydrological cycle. These include rainfall interception, storage / retention (and detention), evaporation, transpiration and evapotranspiration (ET) (when it is difficult to differentiate how water is lost). The definitions of these terms are provided in the glossary.

The primary aim of this study was to investigate the extent of different types of groundcover vegetation in effectively reducing urban stormwater runoff, in the landscape and plant (physiological) perspective. This is to help guide landscape architects to choose appropriate and suitably functional plants, to counter environmental problems associated with climate change effects. As climate change and unpredictability of rainfall pattern continues to intensify, stormwater runoff that is not mitigated and managed will eventually result in more severe environmental problems such as urban flash floods, which is a major threat to people's health and lives, infrastructure and the built environment (Mirza, 2011; Zscheischler *et al.*, 2018). Plants can help reduce the volume and velocity of runoff by interception of water at its source (i.e. rainfall), and then either retaining and storing the moisture that is eventually lost through ET, or detaining it temporarily, which reduces the rate of the water flow that reaches the drainage systems (Xiao and McPherson, 2016; Berland *et al.*, 2017). Although the hydrological processes are in principle the same with all plants, the effectiveness and efficiencies depends on the plants' physical and physiological features. This is where the importance of different plant dynamics and their EUW comes into context.

The main aims and objectives of the research presented in this thesis were:

1. To observe the hydrological performances by groundcover plant species under different environmental conditions and different planting scales.
2. To identify the effectiveness of different plant leaf traits in capturing water and the subsequent evapotranspiration of moisture.
3. To determine that even within small-scale green infrastructure, plant species choice may be important in influencing water capture (interception), retention and evapotranspiration characteristics.

The main hypotheses that were developed for each of the experiments in this research were:

1. Plants with a higher number of small leaves and denser leaf coverage will intercept and retain more water than plants with fewer, but larger leaves.
2. Species that possess broad leaves will evapotranspire more water than those that possess narrow leaves and small leaves.
3. Plants with smaller or narrower leaves (i.e. generic traits often associated with greater drought tolerance) will have higher chance at surviving low moisture conditions compared with those with larger leaves.

A small range of model plants were used. These were *Dianthus* 'Haytor White', *Bergenia cordifolia*, *Vinca minor*, *Festuca glauca*, *Hosta sieboldiana* and *Pachysandra terminalis* (Table 2.1). In general, the study confirmed two of the main hypotheses (hypotheses 1 and 3) and partly rejected hypothesis 2. The study did reveal that plants with higher number of small leaves intercepted more moisture compared to plants with fewer but larger leaves (though this depends on foliage type). The study also confirmed that needle / narrow leaved species had greater ET, therefore survived well in low-moisture conditions without showing major signs of stress. However, although *B. cordifolia*, a broad-leaved species had relatively high ET rate, *D*. 'Haytor White' and *F. glauca*, which had small and narrow-shaped leaves still evapotranspired higher amounts of water. Furthermore, broad-leaved *H. sieboldiana* had amongst the lowest overall ET rates on a plant basis. Therefore, this rejects the hypothesis that species possessing broad leaves will evapotranspire more water than those with narrower, fine leaves.

6.2 Canopy interception and retention

The undertaking of this research preliminarily started with identifying rainfall interception and retention performances by the plant canopies, which is the first hydrological process related to plant and water relationship (i.e. the first interaction when a raindrop falls onto a plant canopy). Interception and retention performances were investigated through different approaches and scales of experiments, including using artificial rainfall (spraying vs. submerging and using watering can; Chapter 3) and actual rainfall that was measured on site (Chapter 4). Leaf morphology was found to have a significant influence on moisture interception and retention, though responses by the plants varied between methods. However, the main general findings were consistent, in that narrow-leaved / needle-leaved species (e.g. *D*. 'Haytor White' and *F. glauca*) intercepted and retained more water compared to broad-leaved species and species that possessed many small leaves.

This finding is consistent with the general principles in the literature (Clark, 1940; Xiao *et al.*, 2000; Wang *et al.*, 2007; Carlyle-Moses and Gash, 2011; Li *et al.*, 2016). Many of these previous studies compared interception of larger scale vegetation, for example between coniferous (needle-leaved) and deciduous broad-leaved forests. Higher interception by forests and urban trees may be attributed to the denser arrangements of tree stands, thereby providing more canopy cover and enabling higher rainfall capture and less rainwater reaching the ground. However, in urban areas, there is very limited space to plant such number of trees due to building densification and larger areas of impermeable surfaces. Therefore, other vegetation types and various scales of planting may need to be considered. This includes the use of groundcover plants. Nonetheless, even on smaller-scale plantings, this finding is also consistent with the few interception (and retention) studies on green roof plants, where grass or grass-like morphology (graminoids) were found to retain higher moisture compared to other structural function (e.g. forbs and sedum) (Lundholm *et al.*, 2010; MacIvor and Lundholm, 2011; Nagase and Dunnett, 2012).

Through different series of experiments conducted to determine moisture retention by different leaf traits, *F. glauca* retained the highest amount of rainfall that ranged between 3.08 mm and 24.06 mm during two observed rainfall events (Section 4.6.8, Chapter 4). This value is on the higher side of retention by small plants (e.g. shrubs / groundcovers), which was significantly higher than the rest of the species observed in this research. This may reflect the fact that when the differences in daily weights (kg) were converted into depth of water (mm), it was divided by the pot surface area rather than the full area of the canopy. An additional calculation of the plant canopy surface area was done as an indicative estimate for a typical plant species (mean of three samples taken). It was found that the full-canopy *F. glauca* (which retained the highest rainfall amount of 24.06 mm) had the largest canopy surface area compared to the rest of the species (see Section 4.7.4). This may explain the high retention by the full-canopied *F. glauca* - which was due to larger canopy area (thereby acted as a bigger 'umbrella' to capture rainfall), as well as its grass-like leaf morphology with dense and tight canopy that encourages higher interception and retention, as previously discussed.

Dianthus 'Haytor White' also retained considerable amounts of moisture, which ranged between 4.96 mm and 11.76 mm during the two observed rainfall events (Chapter 4). Smaller values were observed with smaller pot size on an individual plant scale (0.60 mm) and community scale (1.96 mm) when rainfall was artificially applied (spraying and watering can), however, it still retained higher than broad-leaved *B. cordifolia* and small-leaved *V. minor* (Chapter 3). Under natural rainfall occurrences in an outdoor environment (Chapter 4), broad-leaved *H. sieboldiana* and small-leaved *P. terminalis* consistently retained lower amounts of moisture, with the highest value of 9.02 mm and 5.08 mm for both species respectively, which was during the largest observed rainfall (Day 23). Factors affecting water interception and retention by the six ’model’ groundcover species with contrasting leaf traits are discussed:

6.2.1 Leaf morphological trait

Rainfall interception is defined as the process of raindrops hitting leaf or stem surfaces. Water is then either i) retained on the leaf surface, ii) drips off the canopy and is caught by another leaf, iii) drips off the canopy and falls to ground, or iv) runs off a leaf and flows down the stem, either being captured elsewhere on the plant or flows to the soil. Interception is highly influenced by the leaf morphological traits, as leaf shape, texture, angle and orientation affect what happens to the droplets. The findings of higher interception by narrow-leaved species (*D*. ‘Haytor White’ and *F. glauca*) may be attributed to the narrow leaf shape, as well as the relatively high number of leaves (discussed in Section 6.2.4). Narrow-leaved plants tend to have more overlapping foliage, therefore creating a ‘multi-layer interception’, which is where the water that has been intercepted by the top layer is re-intercepted by the bottom layer foliage (Li *et al.*, 2016). These types of plants also often have wider varieties of leaf angle, and it is very common to have leaves that are angled facing upward. Therefore, when droplets fall onto upward-facing leaves, it helps direct water flows deeper into the canopy, encouraging higher retention. Moreover, narrow leaves tend to produce more splash effect, therefore creating smaller ‘spray’ droplets that have a greater chance of staying on the leaf than larger sized drops.

In contrast, broad-leaved species *B. cordifolia* and *H. sieboldiana* retained the least amount of water. Although *B. cordifolia* has dense overlapping foliage, its broad leaves have smooth and glossy surfaces, which result in less retention of water as the drops easily slide across the leaf and drop off, a point highlighted by Goldsmith *et al.* (2017) for this leaf type. On the other hand, *H. sieboldiana* has fewer leaves, which results in a relatively open canopy structure. This results in less interception, as more droplets tend to fall in the gaps between the leaves and directly onto the soil.

As for interception *per se*, this only accounts for when water (e.g. rainfall) hits the surface of the leaf; the water that remains on the leaf surface or any water that is stored in the leaf cells is defined as retention (or if it finally runs-off, as detention). The process of interception does not directly determine higher retention or moisture storage capacity. Therefore, a simple method of determining the difference between water being intercepted and *then* retained, and water being directly retained by plants was conducted by comparing the effects of spraying plants with water, to that of submerging them directly into water. While the spraying imitates 'rainfall' by vertical application, submerging ensures the whole plant canopy (all parts of each leaf) is exposed to water. The results found that broad-leaved *B. cordifolia* retained higher moisture levels compared to the needle-leaved *D.* 'Haytor White', when submerged in water. This may be attributed to leaf surface wettability (discussed in Section 6.2.2) and also *B. cordifolia*'s relatively large area of leaves and stems combined (the latter parameter not measured) compared to *D.* 'Haytor White'.

6.2.2 Leaf wettability and leaf roughness

The degree of leaf wetness traits (see Section 1.10.5) of the observed species can be categorized into three groups; *B. cordifolia* has low hydrophobicity (hydrophilic), *V. minor* and *P. terminalis* have medium hydrophobicity, *F. glauca* has medium to high hydrophobicity, and *D.* 'Haytor White' and *H. sieboldiana* have high hydrophobicity. However, these were only categorized based on general and physical observation of droplets on their respective leaf surfaces, actual droplet impact angles were not measured.

In this study *F. glauca* and *D.* 'Haytor White' actually retained the highest amount of water despite being classified as having medium-high and high hydrophobic leaves, respectively. One reason for this is that other factors were also influencing water retention on the entire plant, not just the leaf surface texture. Water droplets that fall on hydrophobic leaves will tend to coalesce and form spherical droplets (the higher the hydrophobicity, the higher the contact angle) (Sikorska *et al.*, 2017). Depending on the shape of the leaves, the droplets will either roll off the leaf surface and fall to the ground, or be retained on the plant itself (Matos and Rosado, 2016). The narrow / linear leaves of *F. glauca* and *D.* 'Haytor White' and their orientations may have caused the coalesced droplets to immediately roll towards the deeper canopy and presumably be held in the acute angles between leaves and stem. Furthermore, hydrophobic leaves are often associated with the presence of trichomes (leaf hairs) and cuticle wax structures (Brewer and Smith, 1997; Wang *et al.*, 2015a) (however these parameters were not measured in this study). Depending on the density of these structures, the trichomes may help retain more water droplets because they can prevent droplet spread and promote higher retention on leaf surfaces (Matos and Rosado, 2016) (refer to Figure 1.8). This was observed in a study by Kemp *et al.* (2019), where plants with leaf hairs (*Stachys byzantina* and *Salvia officinalis*) were correlated with higher retention capacities.

High retention by *B. cordifolia* too, when the canopies were submerged, may be associated with different leaf wetness of the abaxial and adaxial surface on this species, as leaf hydrophobicity between the abaxial and adaxial leaf surfaces of some plants may vary significantly (Wang *et al.*, 2014; Holder and Gibbes, 2017). When submerged, all plant surfaces (both abaxial and adaxial, and also stem surfaces) are in contact with water. High retention value by *B. cordifolia* may be associated with perhaps higher hydrophilicity of its abaxial surface. In contrast, due to the high hydrophobicity of *D.* 'Haytor White' and its leaf angles encouraging fast water movements, when the canopies were lifted from the water, most of the droplets may have immediately rolled and dripped off the canopy, which resulted in lower retention.

This finding implies that plants with highly hydrophobic leaves do not always have low retention capabilities, which contradicts the general knowledge that high hydrophobic leaves retain less moisture (Herwitz, 1987; Wang *et al.*, 2014). Other factors such as leaf shape, angle and orientation, number of leaves and canopy architecture also influence moisture capture and retention. This is consistent with some previous studies that allude to storage capacity not simply relating to leaf hydrophobicity (Monson *et al.*, 1992; Brewer and Smith, 1997; Wang *et al.*, 2014; Matos and Rosado, 2016). Furthermore, Wang *et al.* (2014) indicated that leaf roughness and retention are only physical interactions, whereas chemical attractive and repulsive forces of water droplet and leaf surfaces also govern droplet adhesion and moisture retention.

6.2.3 Leaf surface area

In general, experiments here found that narrow-leaved species (i.e. *F. glauca* and *D.* 'Haytor White') retained greater amounts of water compared to other species. However, contrasting results were found when retention was divided by the plant's total leaf area to give a value per unit leaf area. Interestingly, broad-leaved species *B. cordifolia* and *H. sieboldiana* retained higher moisture than the rest of the species, per unit of leaf area, despite *H. sieboldiana* having amongst the lowest overall retention. This may be because these leaves, due to their larger intact surfaces can trap and pool water more effectively than small leaves. As such, on a per unit leaf area basis they may be more efficient. This situation was found during the visual observation of raindrop impact in Section 3.8.3 (Chapter 3).

Nonetheless, the study did not find a significant relationship between retention and leaf area. High leaf area does not necessarily contribute to higher retention. For example, although high overall retention by *F. glauca* may be attributed to its high leaf area, *P. terminalis* and *V, minor* were also among the species that had high leaf area but retained intermediate to lowest amounts of moisture, while *D.* 'Haytor White' with an intermediate leaf area retained relatively high amount of water. It is hypothesized that leaf area reflects the number and density of the foliage, which in some situation may contribute to high retention, however, leaf morphology (shape, angle, orientation, texture) may play a bigger role in influencing retention.

The result of the study pertaining to leaf area disagrees with many previous studies that implied needle-leaved species are capable of intercepting larger amounts of moisture due to having larger LAI as a result of higher number of leaves and denser canopy structure (Aston, 1979; Xiao *et al.*, 2002; Xiao and McPherson, 2016; Li *et al.*, 2016), and Wohlfahrt *et al.* (2006) who indicated the significance in correlations between higher LAI values with larger moisture storage capacities. To some extent, this may be true, as needle-leaved plants do tend to have higher number of leaves and denser canopy structure. However, this can only be relevant when compared to large, broad-leaved species and not necessarily plants with small, but higher number of leaves such as *P. terminalis* and *V. minor*, as these two species had among the highest leaf areas studied here, but still retained intermediate to low amounts of moisture. Obviously, scale and many other factors differ between trees and groundcover plants, and further study is required to elucidate similarities and contrasts.

6.2.4 Number of leaves

Similar concept to the leaf area can be applied to the roles of number of leaves on retention capabilities. High numbers of leaves often result in higher leaf area and denser canopy coverage. This tends to result in higher interception and retention, which was the case with needle-leaved plants compared to broad-leaved plants. However, in this study, the role of number of leaves still also depends on the leaf shape and orientation.

Number of leaves of each species (except for *F. glauca*) was obtained by counting individual leaves. The leaf counting took place when fresh weights were being assessed, and this was not possible with *F. glauca,* as the large number of leaves present meant that they would start to dry out before the fresh weigh could be determined. However, the physical observations (particularly based on foliage density) suggests that *F. glauca* had the highest number of leaves, though this was not verified by actual counts in this species. *Vinca minor*, *D.* 'Haytor White' and *P. terminalis* were associated with having the highest number of leaves (of those species counted); whilst *B. cordifolia* and *H. sieboldiana* had the least, respectively. As mentioned, *F. glauca* intercepted and retained greater amounts of water than the rest of the species, which was likely to be due to its leaf shape characteristics and dense foliage coverage as well as having large numbers of leaves. *Dianthus* 'Haytor White' also intercepted considerable amounts of rainfall and it also possessed considerably higher numbers of leaves (see Table 4.7 in Chapter 4). However, both *V. minor* and *P. terminalis* also had relatively high numbers of small leaves, but did not retain as much moisture. Therefore, there appears to be a relatively poor overall relationship between leaf number and water retention *per se*. As such, it can be concluded that while number of leaves can play an important role in intercepting and storing water, there is an indication that leaf shape, angle, orientation and surface properties tend to have stronger influences on water interception and retention than simply the numbers of leaves present. Thus, the hypothesis that more leaves increase retention is only partially true.

6.2.5 Moisture storage capacity

Much of this research is ultimately aimed at understanding better the capacity for the landscape to store and dissipate water, so as to avoid surface flooding from heavy and frequent rainfall events. But where can water be stored, and what affects the volume of water that can be stored before flooding occurs? Plants can aid the storage capacity of the landscape in two distinct areas; i) by holding water on their surfaces and possibly even within their tissues and; ii) by influencing how much water moves in and moves out of the soil. In scenarios based on groundcover plants, the volume of water held on / within the tissues is likely to be considerably less than that held within the soil matrix. Rainwater held on the plant will be affected by factors such as leaf surface area, hydrophobicity / hydrophilicity of leaves and other plant parts, and the complexity of the canopy and angles between leaves and stems (as already discussed). It will also be affected by the amount of moisture already on the plant surface, so an already saturated plant is unlikely to hold much more water once a further rainfall event occurs.

Nonetheless, moisture loss from the leaf and stem surfaces that restores moisture storage capacity are highly determined by climatic factors such as, temperature, relative humidity and wind movement and speed (Gerosa *et al.*, 2012; Duffková, 2013; Poë *et al.*, 2015). Thus, the capacity for the surfaces of the plant to hold moisture will be increased when these factors combine to enhance evaporation, i.e. warmer, drier and windier atmospheric conditions. In practical terms, a plants capacity to hold more water is improved after a period of dry weather (Voyde *et al.*, 2010b). This was evident in some of the data in Chapter 4, which is consistent with a study by Li *et al.* (2016), who found higher interception storage (rapid increase in rate) in the beginning of a rainfall occurrence mainly because of the relatively dry foliage.

According to Gómez *et al.* (2001), moisture storage capacity of a plant increases with higher projected leaf area index. However, this research did not find significant relationship between leaf area and moisture storage capacity. When sprayed with water, *D.* 'Haytor White', which had the highest leaf area value intercepted and retained the highest amount of moisture, while *B. cordifolia,* which had the second highest leaf area value intercepted and retained the least (Chapter 3). This is because spraying only allows water to be intercepted and retained on the top of leaf surfaces as water was vertically sprayed to mimic rainfall. Some lower layers of the leaves (and abaxial leaf surfaces) may not even encounter the sprayed water; therefore moisture storage of the plant is not fully utilized. In contrast, when the plants were fully submerged in water, all of its leaf surfaces were exposed to water. *Bergenia cordifolia* retained the highest amount when submerged and *D.* 'Haytor White' retained the least despite having the highest leaf surface area (see Section 3.5, Chapter 3). This suggests that *B. cordifolia* utilized its maximum moisture storage capacity when both its adaxial and abaxial surfaces were in contact with water, which implies that it may have larger moisture storage capacity, at least in theory (however, the actual occurrence of both surfaces being completely covered in water is likely to be relatively rare in nature). Overall, this finding does not support the notion by Gómez *et al.* (2001) and that other factors over and above total surface leaf area are influencing water retention.

Nonetheless, if estimating moisture storage capacity by the amount of water retention (when artificial rainfall was vertically applied, as well as actual rainfall) by plants after a dry period, *D.* 'Haytor White' consistently retained the highest amount of moisture under all rainfall interception and retention observations. The same result was also found on rainfall occurrence on Day 18, after the longest observed continuous dry period of 11 days (see Section 4.6.8, Chapter 4). Thus, this suggests that to some extent, *D.* 'Haytor White' may have larger moisture storage capacity due to large number of small needle leaves. This finding is consistent with a study by Xiao and McPherson (2016).

6.2.6 Raindrops and rainfall characteristics

Rainfall characteristics including rainfall duration, frequency and intensity, as well as raindrop sizes were not thoroughly observed and measured in this study. One of the aspirations of this study though, was to observe in very broad terms how contrasting different raindrop sizes might affect moisture adhesion and retention. Two types of artificial rainfall methods / water application characteristics were applied onto the plants; fine spray, representing very small droplet size; and using a watering can, which represented relatively larger droplets. However, the relationship between raindrop size and water interception in this study was not quantified because for the larger droplet size (using watering can) the plant pot size was also larger (3.5 litre) compared to when the plants were sprayed using fine houseplant sprayer (~0.3 litre pot), although the same plant species were used. It would be erroneous to make direct comparisons when both factors changed in size. However, through this limitation, a number of important issues were raised which are highlighted in Section 6.8 of this chapter.

Rainfall interception and retention by the six plant taxa were observed under two rainfall events of varying depths; 2.7 mm (Day 18) and 11.3 mm (Day 23). It was found that most of the species retained greater amount of water with larger rainfall depth compared to the relatively smaller rainfall depth (Table 4.4, Chapter 4). This result contradicts with a number of previous studies that found interceptions / retentions were generally higher with smaller rainfall (intensity and depth) than larger rainfall characteristics (Clark, 1940; Gómez *et al.*, 2001; Xiao and McPherson, 2011). This may be explained by the high available moisture storage capacity and antecedent dry period. Prior to rainfall on Day 18, the treatments experienced the longest continuous dry period of 11 days (from Day 7 to Day 17). During this time, moisture storage capacity within the plant and soil was recharged through the processes of transpiration, evaporation, and even both; evapotranspiration (ET). When the first rainfall occurred after this dry period (on Day 18), although the plants may have intercepted and retained a large portion of the rainfall, on a pot surface area unit, due to the long antecedent dry days, this amount of rainfall may not have be enough to actually saturate the plant and fill the moisture storage. Therefore, when the next large rainfall occured (on Day 23), the plants were able to retain more moisture because the depth of rainfall was larger.

In general, the process of interception helps plants capture rainwater as raindrops hits the canopy and leaf surfaces. This water may both be retained (or detained) on the external leaf surface, and then lost through evaporation, or drip off onto the ground. Water that hits the ground recharges the soil moisture storage capacity, percolates deeper to replenish groundwater aquifers (Freeze and Cherry, 1979), or runs off as surface runoff. The retained water may be used by the plant (for photosynthesis) or may be temporarily detained, in which the plants delay the process of water becoming runoff (Stovin *et al.*, 2017; Yuan *et al.*, 2017). Both of these processes highlight the roles of plants in mitigating stormwater runoff, but what happens to the retained water is also equally as important. Water that is retained on the leaf surface will be lost through evaporation, and water stored in the internal organ of the plant may be lost through transpiration. The combination of these moisture loss processes is called evapotranspiration (ET).

6.3 Moisture loss / evapotranspiration (ET) by plants and soil

In this research, highest ET rates were associated with narrow-leaved *F. glauca* for both the indoor and outdoor experiment. Evapotranspiration rate by *F. glauca* ranged between 2.28 mm d^{-1} and 3.23 mm d^{-1} for the outdoor experiment and mean daily ET for the indoor experiment was 5.46 mm d^{-1}. *Bergenia cordifolia* was also among the species with higher ET rates, ranging from 1.83 mm d^{-1} to 1.96 mm d^{-1} under natural climate (outdoor) and 3.52 mm d^{-1} under semi-controlled climatic conditions (indoor). Under both climatic conditions, *P. terminalis* consistently had the lowest ET rates (up to 0.99 mm d^{-1}, outdoor and 2.80 mm d^{-1}, indoor). Based on the findings of these experiments, several factors were found to have significant influence on the moisture loss performance.

Evapotranspiration (ET) by different plant taxa was determined using two methods; through observing daily moisture changes of the plants (by weighing) under natural weather conditions (outdoor environment; Chapter 4); and by continuous monitoring of weight loss (effectively moisture loss) of the plants over a 12-day period in an indoor laboratory environment (Chapter 5). There were some variations on ET based on days within the experiments and canopy size (Chapter 4), but overall plant water use (ET rates) were often high for *F. glauca* and *B. cordifolia*, sometimes high for *D.* 'Haytor White' and *V. minor*, and often low for *H. sieboldiana* and *P. terminalis*, when taken on a whole plant basis. Within the more consistent environment of the laboratory semi-controlled environment (Chapter 5), *F. glauca* was clearly a higher user of water compared to other species (e.g. Figure 5.7).

6.3.1 Leaf type

One of the objectives of this research was to identify if plants with particular leaf types were better at removing moisture from the growing media (soil) than others, and if so, could such plants be promoted due to their ability to dry the soil quickly, thus recharging the soil's capacity to hold more moisture in a future rainfall event. On many occasions, species with narrow, strap or needle-shaped leaves (i.e. *F. glauca* and *D.* 'Haytor White') evapotranspired more moisture than species associated with broader leaf types. This is consistent with Calder *et al.* (2003), Komatsu *et al.* (2008), and Hisada *et al.* (2011), who indicated that conifer type / needle-leaved trees are capable of evapotranspiring more water than broad-leaf trees; but contradicts other previous findings on leaf types, which concluded that broadleaf forests are capable of higher ET rates than conifer forests (Fahey and Jackson, 1997; Pizarro *et al.*, 2006).

Other factors, however, may explain, at least partially, some of the variations in the citation results here. Do such studies from the literature make like for like comparisons, for example, is moisture loss being calculated over a whole year, a season, or just a day? A conifer may transpire more water, but this may be due to a greater number of leaves per tree, or a greater total area of canopy, or simply because the leaves are present all year round and some transpiration still occurs in late autumn / early spring (Swift *et al.*, 1975; Givnish, 2002; Komatsu *et al.*, 2008). In some aspects, it is also counter-intuitive that narrow, needle or strap-like leaves would correlate with greater water use, as conifers and other narrow leaved plants are often associated with environments where they need to resist excess desiccation (e.g. from drying cold winds – boreal conifers (Givnish, 2002), or high winds and warm summer temperatures – savannah grasses (Osborne and Sack, 2012), or soil moisture deficits and high temperatures – Mediterranean sub-shrubs and ornamental plants (Toscano *et al.*, 2019)). Thus, further investigations are required as to understand why the two potentially most drought-adapted species in this study i.e. *F. glauca* and *D*. 'Haytor White' were also those plants associated with the greatest ET rates.

6.3.2 Leaf number and leaf surface area

In theory, plants that have higher number of leaves and / or a total greater leaf area may tend to transpire at a greater rate (Givnish, 2002) than those with few leaves or a limited total surface leaf area. Theoretically, this is due to a larger surface area supporting a greater number of stomatal pores that are used for gas exchange, but also enhance the potential for moisture vapor loss to take place. A high leaf number and a high total leaf surface area may partially explain the high moisture loss associated with *F. glauca* – but this was difficult to verify as this species proved to be challenging in terms of measuring its total leaf number and area – and estimates were employed rather than using empirical data. These estimates, however, suggest a relatively high total leaf area (Table 4.7) and this may explain the high water use traits by this species. Similarly, *V. minor* also had considerably high water use (ET rates) under both climatic conditions (outdoor and indoor), which proved to be due to relatively high number of leaves and total leaf area. Although leaf numbers and leaf area are probably important in determining water use for a given plant, they may not explain differences in water use between species.

Interestingly, comparisons between other species in the study tended to suggest that both the total leaf area and number of leaves were not the key determinants for moisture loss. High ET rates were also noted with *B. cordifolia* and *D.* 'Haytor White' in both outdoor (Chapter 4) and indoor (Chapter 5) experiments, yet these were species with only intermediate total leaf areas. Moreover, the species with the greatest total leaf area and moderate-high number of leaves (Chapter 5), *P. terminalis*, actually had the lowest cumulative ET, and as well as the lowest ET per unit of leaf area (Chapter 4 and 5). Even when comparing ET rates within a species, halving the canopy size did not always half the amount of water used (comparisons of ET rates for full and half canopy specimens in Table 4.6). Leaf number (on its own) was a poor correlator of water use, with *D.* 'Haytor White' having a significantly greater number of leaves than *B. cordifolia*, yet having similar overall water use.

6.3.3 Water use per unit of leaf area

When water use was calculated on a per unit leaf area basis (water lost for a given leaf surface area), the ranking of species was illuminating. High transpiration per unit of leaf area was observed with the broad-leaved *B. cordifolia* (Chapter 4) and *H. sieboldiana* (Chapter 5) (although the half-canopied *F. glauca* was associated with high transpiration rate per unit of leaf area in some cases (e.g. Chapter 4)). In terms of water use, narrow-leaved *F. glauca* and *D.* 'Haytor White' was generally at the intermediate range, whereas the small, rounded leaved *V. minor* was a relatively low water user per unit area. Lowest transpiration rates per unit of leaf area though, were associated with *P. terminalis,* with small-medium sized number of leaves. So it can be concluded that even given the same leaf area, some species transpired more water than others.

6.3.4 Evapotranspiration in terms of water availability

Evapotranspiration rates, in practice, were often influenced by moisture availability of the growing media (Poë *et al*., 2015; Kemp *et al*., 2019) (though the pattern of moisture loss depends on species); with high ET rates being associated with relatively high soil moisture content (e.g. Figure 5.6, Days 1 - 3), and decreased as moisture become limited (Figure 5.7, Days 10 - 12). However, not all species demonstrated the highest ET rates during the highest moisture content at or near field capacity, which contradicts with the findings by Poë *et al*. (2015). Moisture loss rate gradually increased from Day 1, and was found to be highest on Day 6 for most species, except for *B. cordifolia* and *P. terminalis* (highest observed ET rate on Day 3 for *B. cordifolia* and Day 8 for *P. terminalis*, but Day 6 still showed a relatively high ET rates for both species), with no significant differences in the changes during the first 6 days. This may be explained as the plants' water use and stomatal behavior took a few days to stabilize under the new conditions, or even potentially the growing media was over-wetted at the start; a factor than can impair stomatal behavior (or causes stomatal closure, under water-logged condition) (Bradford and Theodore, 1982; Herrera, 2013; Bashar *et al.*, 2019). In general, most species demonstrated an observable decrease in ET rate over the 12 days of monitoring (Figure 5.5), as soil conditions became progressively drier, such results being consistent with previous studies (Berghage *et al.*, 2007; Voyde *et al.*, 2010a; Poë *et al.*, 2015).

Variations in results and trends between the species under tests here, may relate to the fact that different plant species can have distinctive morphological functions that affect moisture use. Some species utilize the available moisture to maximize transpiration during dry periods until soil reserves are depleted and they reach wilting point, while others conserve moisture and use water slowly, thereby actually prolonging the period before the wilting point is reached (Cameron *et al.*, 2006). For the indoor experiment, three different moisture loss patterns were observed over time, suggesting how different plants respond to their available moisture. *Festuca glauca, B. cordifolia* and *H. sieboldiana* had higher ET rates at the beginning of the monitoring when moisture was abundant (at field capacity) and then gradually decreased in rate over time, presumably as moisture became limited. *Festuca glauca* was associated with high moisture use characteristics and dried out the growing medium effectively. However, this species exhibited major stress with almost 50% of leaves drying / showing signs of necrosis by the end of the experiment, which in itself may partially explain lower transpiration rates at the end. In contrast, *B. cordifolia* with similar moisture loss pattern did not demonstrate major stress signs at the end of the experiment. This suggests that although *B. cordifolia* lost a relatively large amount of moisture in the beginning and water availability may have decreased towards the end, the physical condition of the canopy and leaves remained healthy, indicating that this species may have adapted to the progressively drying conditions by reducing its transpiration rate through effective stomatal control (Farooq *et al.*, 2009; Gao *et al.*, 2016). Although stomata closure is being associated with reduced water availability, and thus the water use of the plant can vary between different species (Cameron *et al.,* 2006). Increases in efficiencies in use of water as soils became progressively drier has been noted in species such as *Trifolium* (Lazaridou and Koutroubas, 2004) and *Pinus* and *Artemisia* (DeLucia and Heckathorn, 1989). Both hydraulic (Giorio *et al.*, 1999) and chemical (Christmann *et al.*, 2007; Schachtman and Goodger, 2008; Sharp and Davies, 2009) root-to-shoot signals are implicated in the control of stomatal opening / closing, and these as well as other factors can determine water use rates.

In contrast to the previously mentioned species, *D*. 'Haytor White' lost a relatively small amount of water in the beginning of the monitoring in the semi-controlled environment, but increased its ET over time. This can be explained by relatively low water use at the start, being induced by the change of the conditions from outdoor to indoor, which may have affected this species more than others (stomatal behavior can alter due to changes in irradiance, temperature, humidity and wind) (Schulze *et al.*, 1974; Gerosa *et al.*, 2012). It is possible that *D*. 'Haytor White' took longer to adapt than other species and only after a few days were stomata fully functional. It may also be that increments in leaf number (growth) over the experimental period increased water use marginally. For this genotype, ET generally rose for 11 days, before decreasing again – possibly as a consequence of moisture deficits beginning to affect the plants (Figure 5.5). *Dianthus* 'Haytor White' is considered an alpine species; therefore, potentially quite adaptive to a range of extreme conditions. Alpine species can tolerate drought due to the predominately free-draining nature of the soils (with little moisture retention capacity) and exposure to strong desiccating winds (and in summer, potentially high temperatures and irradiance levels) (Körner and Diemer, 1987). As a 'stress-tolerator' rather than a 'competitive' community plant, it might not be expected to use water excessively nor grow fast, and so will not necessarily deplete its moisture reserves quickly.

Finally, *V. minor* and *P. terminalis* had consistent ET trends throughout the monitoring period (Chapter 5), with *P. terminalis* having a relatively low moisture loss rate. Both of these species usually grow in moist and well-shaded area (e.g.

woodland, low mountain areas). In such conditions, growth may be impaired more by a lack of light rather than a lack of moisture, and in such 'dark-adapted' 'woodland-floor' species, high stomatal conductance and high ET rates may not be required / the norm (Leuschner, 2002). Consistent 'natural' low ET rates though, could also be an adaptation to dry periods encountered in woodlands – as although these environments are not associated with high irradiance and temperatures, soil moisture deficit may still result from time to time due to high moisture extraction rates caused by the surrounding trees. Certainly, in these experiments, *P. terminalis* particularly, was associated with low ET with leaves remaining relatively physically healthy during times of stress. As such, this plant sounds like a good candidate for tolerating stress, but sadly without the desired capacity to dry out the soil rapidly.

Hosta sieboldiana along with *P. terminalis,* tended to have low mean ET, but this species showed major stress signs through leaves drying on two of four replicates (Rep. 2 and Rep. 3), while the other two was very healthy. The inconsistency of conditions for *H. sieboldiana* at the end of each replicated run (indoor semi-controlled conditions) may be attributed to the conditions of the individual plant prior to the experiment, where some plants may have already experienced some degree of stress whilst placed outside (leaves of this species can also senesce naturally in late summer). *Hosta sieboldiana* used for the outdoor experiment during mid-summer (Chapter 4), showed fairly consistent signs of severe stress signs - 70% of leaves being dry and necrotic by the end (matched by lower chlorophyll fluorescence data). This indicates *H. sieboldiana* was not well adapted to the drying cycles it experienced outdoors (Section 4.6.12, Chapter 4). Again, this is consistent with a species adapted to damp and well-shaded conditions.

6.3.5 Microclimate and stomatal behavior

As outlined above, the ET performances by six plant species were investigated under two different climatic conditions; natural climatic condition during late summer / early autumn season; and in a semi-controlled (constant) laboratory environment. The temperature and relative humidity (RH) for laboratory test was relatively consistent for all tests (temperature ranged between 24.1°C and 26.2°C; and lower range of RH that ranged between 40.8 and 62.4%), as the purpose was intended to eliminate confounding factors (i.e. microclimate) that affect ET, which would be difficult to measure. The indoor test demonstrated ET to be more affected by time and moisture availability. On the contrary, for the outdoor experiment, ET was observed on Day 9, which had the second highest temperature during the observation with temperature of 18.3°C. Relative humidity (RH) was relatively high on this day, which as 86.2%. Stomatal conductance was not measured; however, plants naturally lost their moisture via transpiration by opening their stomata, which is directly affected by the surrounding conditions.

Mean diurnal ET patterns were observed across all species for a 24-hour period of Day 11 to Day 16. Diurnal ET showed strong regular variations, where ET started to increase from 9:00, and typically peaked between 11:00 to 15:00 for most species, which is consistent with a study by Voyde *et al.* (2010a). For some species (i.e. *F. glauca, D.* 'Haytor White' and *B. cordifolia*), a second peak was observed between 14:00 to 17:00. This 'two-peaked' phenomenon was also found in studies by Schulze *et al.* (1974) and Gao *et al.* (2016). The decrease in ET rate usually around midday (highest radiation and temperatures of the day) may be associated with low stomatal conductance that is controlled by the ambient temperature and RH, to prevent more moisture loss by these species (Schulze *et al.*, 1974; Blanken and Rouse, 1996). According to Gerosa *et al.* (2012), this may happen during very high temperatures, when the evaporative and transpiration demand is simply larger than the xylem's capability to replenish moisture to the leaves. This temporary 'midday' stomatal depressions are often associated with drought-tolerant species (Blanken and Rouse, 1996), and can also be observed in the newly expanding shoots and leaves of plants during warm periods, even when soil moisture capacity is at an optimum for plant growth.

Essentially, plants that have the ability to i) regulate their stomata closely in line with the prevailing conditions, ii) transpire rapidly and effectively when moisture is readily available, and iii) close their stomata to reduce moisture losses when soil moisture deficits start to become severe, are ideal for the scenarios discussed in this thesis. In essence, species that can tolerate drought and survive periods of water shortage, while at the same time re-initiate transpiration at short notice after a rain event, would seem ideal. In shrubs, Cameron *et al.* (2006, 2008) identified that *Cotinus coggygria* possessed such traits. In this study, the selection is less obvious; although *F. glauca* had high ET rates, it could also instil damage to its foliar tissues.

Perhaps *D.* 'Haytor White' proved the most promising, in that although it took some time in the semi-controlled environment (Chapter 5) to gradually increase its ET rates, while also managing to sustain the rates close to the end of the experiment (and lost a relatively high total amount of moisture), it only showed minor indications of plant injury. Similarly, *B. cordifolia* is worthy of further consideration, as this species exhibited quite high ET rates, whilst showing some surprising tolerance of dry conditions despite being such a large-leaved subject.

6.3.6 Comparison between ET rates under natural and semi-controlled conditions

Evapotranspiration rates were compared between mean daily ET rates by the plants for the outdoor experiment (Chapter 4) and for the indoor laboratory experiment (Chapter 5). Overall, ET rates by the plants under different environmental conditions showed consistent trends between water usages of plant species. *Festuca glauca*, which had the highest mean daily ET rate under both conditions, (up to 3.25 mm d^{-1} and 5.46 mm d^{-1} for the outdoor, and indoor conditions respectively). *Bergenia cordifolia*, which had the second highest under both conditions had higher mean daily ET rates during the laboratory experiment (3.52 mm d^{-1}) compared to outdoor (up to 1.96 mm d^{-1}). *Dianthus* 'Haytor White' performed relatively similar to *B. cordifolia* (indoor) but had lower ET rates (outdoor) (up to 1.72 mm d^{-1}). *Pachysandra terminalis* had the lowest ET rates under both conditions; the indoor condition having higher daily ET rate (2.80 mm d^{-1}) than outdoor (up to 0.99 mm d^{-1}).

In general, ET rates were higher for the indoor experiment, with the exception of a few plants (e.g. *D.* 'Haytor White' and full-canopied *V. minor*). This may be due to the higher (and constant) temperature in the laboratory environment with lower RH compared to the outdoor condition on both days (as stated above). Higher temperature induce higher and faster ET rates due to increased levels of heat energy (Poë *et al.*, 2015). While ET rates for the outdoor experiment was governed by the availability of moisture as well as climatic factors (i.e. air temperature, relative humidity, wind speed), daily ET rates for the indoor condition was highly influenced by the moisture availability as the climatic condition was constant (and of course EUW by different plant species). Nonetheless, *F. glauca*, *D.* 'Haytor White' and *B. cordifolia* were the three species that consistently had higher ET rates under both conditions.

Overall, the lack of consistency between leaf size / type and water use across species strongly suggests that more subtle eco-physiological factors are influencing water use than simply the shape and type of leaf. Thus, it is important that leaf size and type, nor indeed total leaf number, should be used as simple guidance to determine which plants can dry out the soil quickly and thus recharge the storage capacity. More nuanced understanding of plant water use is required.

6.4 Overall research findings

In general, hydrologic responses were different by species. Leaf morphological traits were found to play an important role, which confirms the research's main hypothesis (as outlined in Section 1.2, Chapter 1). The overall findings of this study suggest that groundcover plant species could help reduce runoff by intercepting and thus retaining rainfall up to a significant number of 24.06 mm, and evapotranspiring up to 5.46 mm d^{-1} (*F. glauca*), though this depends on species and foliage types. The lowest retention was associated with small-leaved type plant (*P. terminalis*), which retained a maximum of 4.88 mm during the largest rainfall event (11.3 mm of rainfall depth), and generally evapotranspired less than 3 mm d^{-1}, although this species had high number of small leaves.

Consistent with previous research, needle-leaved / narrow-leaved species (i.e. *F. glauca* and *D*. 'Haytor White') intercepted and retained more rainwater than broad-leaved species. This was most likely due to the various angles and orientation of leaves, as well as relatively larger number of leaves compared to broad-leaved species; which on a per unit leaf area basis could retain and transpire more moisture (e.g. *B. cordifolia* and *H. sieboldiana*). There are many factors that control the amount of interception and retention and it cannot be concluded that these are affected by morphological traits alone. Plant leaf surface texture and wettability, leaf surface area and number of leaves, rainfall, microclimatic and environmental conditions all influence rainfall interception and retention by the canopy, though some are more significant than others. The relationships between these variables are complex and their significance and importance can vary depending on different situations.

Although many of the previous studies that compared interception between coniferous forests and deciduous broad-leaved forests saw similar findings pertaining to leaf morphology as in this research, the same principle and reference cannot be readily applied with smaller plantings in urban areas. Interception by forests and trees are attributed to the arrangements of tree stands in forests that are close together (Gómez *et al.*, 2001; Carlyle-Moses and Gash, 2011), which provides dense canopy cover enabling more rainfall capture and preventing more rainwater reaching the ground. In urban areas, there are very limited spaces to plant large numbers of trees, due to the dominance of built structures, impermeable sealed surfaces and the increasing densification of cities, therefore the importance of different plant dynamics (e.g. perhaps the use of non-tree species) and various scales of planting may be the more suitable choice.

Plant canopies are often associated with having relatively small moisture storage capacity compared to soil, and therefore are not a significant variable in mitigating urban stormwater runoff (MacIvor and Lundholm, 2011; Stovin *et al.*, 2015; Kemp *et al.*, 2019). While to some extent, this may be true, what tends to be forgotten is the importance of plants in continuing the circulation of the hydrological process by facilitating the movement of water back into the atmosphere from the soil matrix, and acting as a moisture release mechanism. Furthermore, the presence of plant canopies is particularly important when rainfall events occur close together and soil moisture storage is not restored, therefore, plant canopies may be the sole retention mechanism (Kemp *et al.*, 2019). Within the context of urban flooding, plants are providing an ecosystem service by intercepting and retaining rainwater on their leaves and canopies, and evaporating this back into the atmosphere, which according to Lundholm *et al.* (2010) is a plant's main contribution to retention. Evapotranspiration is especially important in urban areas as it could be enhanced; where temperatures are usually relatively higher than in rural / 'green' surroundings (urban heat island effect), due to 'oasis' effect (Yuan *et al.*, 2017). Moreover, through the action of their roots, plants draw in soil moisture and transpire this back into the atmosphere too; thus, increasing the proportion of soil pores that are air filled rather than water filled, and leaving capacity to drain / store more rainwater in the future.

The capabilities of different plant species to evapotranspire water were observed in this research. Moisture loss from the soil back to the atmosphere through plants, i.e. evapotranspiration is determined by a number of factors. Air temperature and humidity affect evaporation and transpiration, with higher temperatures and lower atmospheric humidity encouraging moisture loss (Sterling, 2004; Poë *et al.*, 2015). Greater number of leaves and greater total leaf area per plant also tend to increase moisture loss, in general terms. Water also needs to be readily available at the root / soil interface for transpiration to occur and ET rates can increase as soil moisture availability decreases. Other factors may regulate the behaviour of the stomata, thus affecting ET rates; these include aspects such as irradiance levels, wind, soil osmotic potential, oxygen levels in the rhizosphere as well as leaf age and history (Schulze *et al.*, 1974; Sojka, 1992; Araújo *et al.*, 2011; Gerosa *et al.*, 2012; Zhou *et al.*, 2015). As such, just counting the number of leaves or calculating the surface area of all the leaves a plant has will not necessarily help predict water use or overall ET. Similarly, just knowing how many stomata are present on a given leaf area, or when those stomata tend to open and close, will also not entirely allow a full understanding of a species' water use characteristics in the landscape. Therefore, the value of this research is that it compares different plant genotypes under the same / similar conditions to determine how they affect water transport through the soil-plant-atmosphere continuum, and helps provide recommendations for landscape architects on the appropriateness of different plant species. Evaluation of the data also alludes to why certain species may be better under some circumstances than others.

Overall, highest ET rates were associated with narrow-leaved species *F. glauca* and *D.* 'Haytor White', and broad-leaved *B. cordifolia*, although the patterns of moisture loss could differ between these species. Maximum water use was linked to *F. glauca,* however, this species did not withstand drought stress well as it showed some major drying and dead leaves after the experiments were complete. This suggests that even though narrow-leaved species such as *F. glauca* were found to have higher retention and ET performance, it does not necessarily imply that this species is the best at tolerating drought stress, and therefore might require additional maintenance (e.g. irrigation) if it was to be implemented in an urban green infrastructure setting. Conversely, grasses are adept at regenerating foliar growth quickly, and it may well be that *F. glauca* can tolerate a degree of die-back and still be functional within the landscape; further long-term research is required here.

Dianthus 'Haytor White' provided a good compromise plant in that although its ET rate was generally not as high as *F. glauca*, it was a steady performer and maintained ET rates even under quite dry regimes. There were some leaf damages under stress, but overall, this genotype performed well, and combined with its capacity to hold rainwater is worthy of further consideration. Evapotranspiration rates were favourable for *B. cordifolia* and *H. sieboldiana* when assessed on a per unit of leaf area basis, but overall lacked enough leaves to maximize soil drying. *Bergenia cordifolia* though, may warrant further study as it seemed relatively resilient (despite its large leaves), and may help with enhancing ET within urban landscape settings. In contrast, *H. sieboldiana* was prone to leaf damage. Interestingly, plants with large numbers of smaller leaves and a high total leaf area value (i.e. *P. terminalis*), evapotranspired the least amount. However, even though it had the lowest ET rates, it also showed the least stress signs at the end of the experiment, which may indicate that it was conserving its moisture, and thereby only lost small amount of daily moisture during times of drought – a useful landscape plant in general, but not one that could be advocated for helping recharge the soil moisture storage capacity. *Vinca minor* could be classified as a 'sound generalist' and although not necessarily promoting high ET rates at any given period, it maintained steady levels of moisture loss under a number of situations, and again showed some stress tolerance.

Although this research only evaluated six taxa, and evaluations over a greater species range is required, a number of principle points have come to light. These include; i) the desire to have plants that can both capture and 're-use' rainwater effectively, especially over short-time intervals; ii) the need to identify plants that are resilient – some tolerance to drought was apparent in this study, but under some circumstances the capacity to tolerate water-logging will also be important; and iii) functional plants should not be identified based on morphological aspects alone. The value of this research is that it has provided some level of 'surprises' and as such, plant selection should not rely solely on what species look like or even where they come from originally (i.e. their eco-physiology); taking such approaches alone may be misleading in terms of selecting the most appropriate plant species. Although the data strongly advocates the use of fine-leaved species for rainwater capture, the 'story' is more complex when trying to identify plants that maximize ET.

6.5 Summary of key findings

- Leaf morphology significantly affects the hydrological performance (i.e. interception, retention and to some extent of ET), but more on rainwater interception and retention than ET.
- Leaf morphological traits such as shape, angle, orientation and surface texture play a bigger role in intercepting and retaining moisture than leaf area and number of leaves.
- Narrow-leaved species (i.e. *D*. 'Haytor White' and *F. glauca*) had the highest retention (11.76 mm to 24.06 mm for the two species respectively), but broad-leaved species (i.e. *H. sieboldiana* and *B. cordifolia*) had higher retention per unit of leaf area (up to 3.64 mm and 5.45 mm respectively).
- *Pachysandra terminalis* had consistent low overall rainwater retention (up to 5.08 mm), and *V. minor* had the lowest retention per unit of leaf area (up to 2.72 mm).
- The highest observed retention was by *F. glauca,* which was 24.06 mm, during the largest rainfall occurrence on Day 23, which may be associated with large canopy surface area compared to the rest of the species (as well as the discussed leaf morphology).
- Evapotranspiration under constant climatic condition is highly dependent on moisture availability, which is driven by plants' efficiencies in use of water (EUW).
- Grass species / narrow-leaved *F. glauca* had the highest mean daily ET rate, which was 5.46 mm d^{-1} under artificial laboratory (indoor) environment, and 5.24 mm d^{-1} under natural climatic condition (outdoor).
- Small-leaved species *P. terminalis* had the lowest overall ET rates and also per unit of leaf area (up to 1.71 mm d^{-1}), despite having high total leaf area.
- Although *B. cordifolia* did not retain as much moisture, it was among the species that evapotranspired a relatively high amount of moisture, while also keeping good health – highest chlorophyll fluorescence found on *B. cordifolia.*
- Canopy size played a role in influencing the rate of moisture capture and moisture loss. However, not all species showed significant differences between

different canopy sizes. *Vinca minor* demonstrated the largest differences between the full and half canopy during both dry period and peak rainfall period.

- Interception was generally higher with full-canopied plants than half canopied plants (except for *B. cordifolia* on Day 18, and *D.* 'Haytor White' on Day 23). Evapotranspiration was also higher by full-canopied plants than half canopied plants.
- However, interception and ET rates by all species per unit of leaf area was higher by half-canopied plants than the full-canopied plants, which may be attributed to the trimmed canopies activating more resources to grow faster to compensate for the original leaf loss (i.e. in effect, these plants are 'working' harder than the full-canopied plants).
- No significant relationship between leaf area and number of leaves were found with overall ET rates. There was also no obvious pattern found on leaf morphology on ET rates. Evapotranspiration rate was highly influenced by moisture availability, species-specific factors and EUW by different species.
- Based on drought-tolerance test (by monitoring stress signs at the end of the experiment), needle-leaved species *D.* 'Haytor White' was found to be most efficient at sustaining and using moisture more effectively to reduce stormwater runoff. This is because it was among the species that intercepted the most moisture, while also efficiently conserved its moisture during dry periods, and it did not show major stress signs at the end of the tests.
- *Bergenia cordifolia* was also found to perform efficiently. It had the highest interception rate per unit of leaf area, and also relatively high ET rates under some situations, but showed the least signs of stress.
- *Pachysandra terminalis* had the lowest ET rates cumulatively and per unit of leaf area. Despite being a woodland under-storey species, *P. terminalis* was able to conserve moisture by evapotranspiring low rates and did not show major stress signs at the end of the drought period.
- Evapotranspiration rates under semi-controlled environment and natural climatic condition showed consistent trends. *Festuca glauca*, *B. cordifolia* and *D.* 'Haytor White' had the highest mean ET rates while *H. sieboldiana* and *P. terminalis* was often associated with lower ET rates.

6.6 Conclusions

Most urban spaces today are in desperate need of green infrastructure as it offers benefits socially, economically and environmentally. This is especially so, due to the effects of climate change becoming more intense, paralleled by city densification resulting in greater areas of impermeable surfaces and greater risks of flooding. The importance of groundcover planting as a component of SuDS or small-scale green infrastructures to reduce the impact of stormwater runoffs are highlighted through observation of rainfall interception and retention under different environmental scenarios, and also the moisture storage recharging capacity via transpiration and evapotranspiration (ET). With increased implementation of SuDS and their numerous benefits in urban areas, it is important to identify different plants' functional traits and thus carefully select suitable plants to be planted in urban areas in order to optimize the hydrologic performance.

In conclusion, understanding different plants' physiological behaviour (as well as the physical attributes associated with it) is key to evaluating the importance of plants' functional traits in relation to the hydrological performance. Groundcover vegetation are especially crucial in urban areas, where smaller plantings (e.g. ornamental and herbaceous plants) are more suitable in the application of SuDS designs such as raingardens, green roofs, stormwater planters, roadside planting and in pocket parks or small spaces in between buildings. Urban greening has not only become a trend in the landscape architecture field, but has become an awareness, in which even the public has taken part. Therefore, planting implementation in the public urban spaces has increased in demand, not only for aesthetic purposes, but to actually serve and benefit the environment through the provision of various ecosystem services. Hence, there is a requirement for further knowledge on which plants optimize ecosystem service delivery (Cameron and Blanuša, 2016), and in this case flood avoidance.

This research highlights the two 'hydrological' services that landscape plants can perform in our towns and cities. Firstly, they can help 'hold back' stormwater runoff either permanently or temporarily, by capturing and storing a proportion of the rain that falls. Secondly, and perhaps more importantly, they can evapotranspire moisture back to the atmosphere, thus helping to recharge the capacity of the soil to hold water in any subsequent rainfall event. It is this 'de-saturation' of the soil water that may be the most important factor in helping urban areas cope with increasing rainfall. This research highlights the significance of different leaf traits influencing ET, as different plants regulate their stomatal behavior differently, which affects their ET performance and moisture use efficiencies. Although the findings of this research suggest that narrow-leaved species are more effective in hydrologic response in order to help mitigate urban stormwater runoff, the roles of other leaf traits (i.e. broad-leaved and small-leaved) can also be beneficial with different significance levels. For example, *B. cordifolia* was among the species that evapotranspired a considerable amount, whilst also surviving any ensuing drought stress. In reality, varying the types of plant species present in SuDS schemes or similar infrastructures is important, not only to provide resilience in the system *per se*, but also to allow other ecosystem services to be provided and enhanced (e.g. for biodiversity, aesthetics, air quality). Sustainable drainage system (SuDS) designs should not only incorporate diverse plant mixtures that optimize hydrological performance, but also meet other desirable criteria. Thus, further work is required to provide a wider palette of plants that can be used by landscape architects and other professionals with respect to urban stormwater and flood management as well as deliver wider ecosystem services.

6.7 Research implications

It is hoped that this research will raise awareness and increase interest of the importance of herbaceous and shrub plantings in reducing urban surface runoff, and not to overlook the role of groundcover plants. Narrow or needle-leaved species (i.e. *D.* 'Haytor White') as a component of SuDS are recommended to optimize water usage and effectively capture rainwater and reduce runoff. These types of plants not only use their moisture most effectively, but are also better at surviving drought stress without showing major stress signs. In choosing plant species for SuDS implementation, using diverse mix of high performance plants is more advantageous to increase aesthetic value, as well as benefit from multi-functionality and complementary of the hydrological functions, and survivability of different plant species. The knowledge obtained from this research can hopefully assist landscape architects to carefully select plant species with suitable characteristic and traits to increase opportunities for effective hydrological performance.

6.8 Research limitations and future work

Many questions regarding the roles and influence of small plants in reducing the impact of runoff in urban areas were answered in this study; however, there were several limitations of the research that were not within the main focus of the objectives. This has raised several new questions that could potentially be undertaken by future research.

- The study found different plant leaf traits to influence rainfall interception and retention performance. However, it was not clear whether the intercepted droplets were retained on leaf surfaces (and then lost through ET), or absorbed by the plant, and if so, by what route / manner. Questions remain as to what happens to all the water held temporarily on the plant surfaces.
- It was found that leaf wettability and surface texture played a significant role in determining water interception and retention. Components such as trichomes and cuticle wax are known to influence the impact of raindrop on leaf surfaces; however, the study did not directly measure and comprehensively observe the drop impact angle of moisture droplets on different leaf surfaces. This could characterize the impact of different droplet size (and potentially rainfall intensity) on different leaf surfaces.
- Little is still known about the stomatal behavior of many ornamental plants, and this work highlights that there could be quite different strategies employed by plants as to when to open / close their stomata. Further elucidation of this will help better understand the value of plants in terms of recharging the potential of the soil to hold water, and also in terms of survival during drought periods.
- Three moisture loss patterns were found on six plant species. However, the longest dry period monitoring only lasted for 12 days. Longer duration observation could potentially demonstrate greater difference in moisture loss patterns with regards to ET rates and stress signs during drought periods.
- Little attention was paid to which plants survived water-logging and how quickly ET can be restored after the plants themselves are flooded. This is an important component that demands future research attention.

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