University of Reading

Impact of plant choice and water management on the provision of ecosystem services by green roofs

A thesis submitted for the degree of Doctor of Philosophy

Sarah Kemp

School of Agriculture, Policy and Development

September 2017

Declaration of original authorship

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

Sarah Kemp

Acknowledgements

This research was financially supported by an EIT Climate-KIC PhD studentship.

First and foremost, I want to thank my supervisors Prof Paul Hadley and particularly Dr Tijana Blanuša for all of the time, guidance, support and encouragement they have given me over the past four years. I am glad to have had the opportunity to learn from them. I am also grateful to Prof Čedo Maksimović and the rest of the Blue Green Dream team at Imperial College, London for all of their constructive input and advice.

I would also like to thank all glasshouse staff in the School of Agriculture, Policy and Development at the University of Reading, especially Val Jasper and James Hadley for their help and advice setting up and maintaining my experiments, as well as Matthew Richardson for contributing his time and expertise helping me with the controlled environment cabinets. Thanks also to Dr Madalena Vaz Monteiro and the statistical advisory service for guidance and advice in various elements of this study, and to Paul Mealey and Dr Gracie Barrett from the RHS for constructing rainfall simulators for use in my experiments and advice on substrates, respectively.

Finally, I want to thank my family and friends for their support and encouragement, and for always being willing to lend a hand and help me with my experiments. Thank you especially to David, for his unwavering support throughout this journey, for encouraging and motivating me, and mostly for believing in me and being by my side every step of the way.

Abstract

Green roofs (GRs) can provide multiple ecosystem services (ESs) such as air quality improvement, biodiversity support and climate regulation. The hypothesis was tested that plants with different structural and functional characteristics (canopy size and density, evapotranspiration (ET) rates) differ in the provision of stormwater management and runoff quality improvement. Experiments were conducted comparing the potential of industrial standard GR cover (*Sedum*) to alternative species with higher ET rates (*Heuchera micrantha* 'Obsidian', *Salvia officinalis* and *Stachys byzantina*). High ET was strongly linked to rainfall retention, with *Salvia* and *Stachys* providing the greatest overall retention (32% of the total rainfall), although large, dense canopies were also advantageous when antecedent substrate moisture was high, with *Sedum* retaining 17% compared to 13% with *Stachys*.

Species with high ET rates will require irrigation to maintain plant health and provision of ESs, but strategies for sustainable irrigation of GRs are needed. In this study, crop coefficients of 1.47, 2.98, 2.94 and 1.66 for *Heuchera*, *Salvia*, *Stachys* and *Sedum* respectively were calculated and used in a simple ET-based model (using the FAO-56 Penman-Monteith equation) that was proposed for scheduling GR irrigation based on plant water use. Greywater as an alternative water source for irrigation was also investigated. Plant health and functioning (and thus provision of ESs) for most species were not affected by greywater irrigation with no negative effects in *Stachys* and *Sedum*, but ET rates of *Heuchera* and *Salvia* were reduced by 14% and 9% respectively after 6 weeks of greywater irrigation. Species differences were also apparent in improvement of runoff quality after both freshwater and greywater irrigation, with the highest quality runoff from *Stachys*.

Results highlight the importance of appropriate species choice for improving the provision of ESs on GRs, and suggest that the irrigation requirements of these species could be met by using greywater.

List of symbols and abbreviations

Abbreviations

B	Boron
CAM	Crassulacean Acid Metabolism
CE	Controlled environment
EC	Electrical conductivity (µS cm^{-1})
ESs	Ecosystem services
ET	Evapotranspiration (mm)
FAO-56 PM	Penman-Monteith equation for calculating ET_o developed by the FAO
GR	Green roof
g_s	Leaf stomatal conductance to water vapour (mmol m^{-2} s^{-1})
GW	Greywater
ICP-OES	Inductively coupled plasma – optical emission spectroscopy
IRGA	Infrared gas analyser
K_c	Crop coefficient for use in FAO-56 PM equation
K_s	Stress coefficient for use in FAO-56 PM equation
LAI	Leaf area index
MRM	Meadow Roof Medium ‘industry standard’ substrate
Na	Sodium
P	Phosphorus
PAR	Photosynthetically active radiation (µmol m^{-2} s^{-1})
RH	Relative humidity (%)
SAR	Sodium adsorption ratio
SMC	Substrate moisture content (m^3 m^{-3})
T	Air temperature (°C)
TW	Tap water

UoR AO	University of Reading atmospheric observatory
VC mix	Vermiculite: peat-based compost 50:50 mixed ‘model’ substrate
VPD	Vapour pressure deficit (kPa)

Mathematical symbols

c_p	Specific heat of dry air (J kg^{-1} K^{-1})
d	Zero plane displacement height (m)
d_r	Inverse relative distance between the Earth and the sun
e_a	Actual vapour pressure of the air (kPa)
e_s	Saturation vapour pressure of the air (kPa)
$e^o(T)$	Saturation vapour pressure at temperature T (kPa)
ET_a	Actual evapotranspiration (mm day^{-1})
ET_c	Calculated crop evapotranspiration (mm day^{-1})
ET_o	Reference evapotranspiration (mm day^{-1})
G	Soil heat flux (MJ m^{-2} day^{-1})
G_{sc}	Solar constant (0.0820 MJ m^{-2} day^{-1})
h	Crop height (m)
J	Julian day
k	Von Karman’s constant (0.41)
LAI_{active}	Active (sunlit) leaf area index
P	Atmospheric pressure (kPa)
R_a	Extraterrestrial radiation (MJ m^{-2} day^{-1})
r_a	Aerodynamic resistance to turbulent heat and/or vapour transfer from the surface to some height above the surface (s m^{-1})
RH_{max}	Maximum daily relative humidity (%)
RH_{min}	Minimum daily relative humidity (%)
r_l	Bulk stomatal resistance of the well-illuminated leaf (s m^{-1})

R_n	Net radiation flux at the surface (MJ m^{-2} day^{-1})
R_{nl}	Net longwave radiation at the surface (MJ m^{-2} day^{-1})
R_{ns}	Net shortwave radiation at the surface (MJ m^{-2} day^{-1})
R_s	Incoming shortwave radiation (MJ m^{-2} day^{-1})
r_s	Bulk surface resistance to flow of water vapour from inside the leaf, vegetation canopy of soil to outside the surface (s m^{-1})
R_{so}	Clear-sky radiation (MJ m^{-2} day^{-1})
T_{max}	Maximum daily air temperature (°C)
T_{min}	Minimum daily air temperature (°C)
u_2	Wind speed at 2 m height (m s^{-1})
z	Elevation above sea level (m)
z_h	Height at which air humidity is measured (m)
z_m	Height at which wind speed is measured (m)
z_{oh}	Roughness length governing the transfer of heat and vapour (m)
z_{om}	Roughness length governing momentum transfer (m)

Greek symbols

α	Albedo
δ	Solar declination (rad)
Δ	Slope of the saturation vapour pressure temperature curve (kPa °C^{-1})
λ	Latent heat of vaporisation (MJ kg^{-1})
ρ_a	Air density (kg m^{-3})
ρ_w	Density of liquid water (kg m^{-3})
σ	Stefan-Boltzmann constant (4.903 x 10^{-9} MJ K^{-4} m^{-2} day^{-1})
τ	Coefficient of transmissivity to solar radiation (for glasshouse)
φ	Latitude (rad)
ω_s	Sunset hour angle (rad)
Υ	Psychrometric constant (kPa °C^{-1})

Statistical terms

ANOVA	Analysis of variance
d.f.	Degrees of freedom
LSD	Least significant difference between means
R^2	Coefficient of determination
SEM	Standard error of the means

Contents

List of Figures

List of Tables

Chapter 1

Introduction and literature review

1.1 Introduction

Urbanisation results in the modification of natural systems and processes, altering the climate of urban areas (Alexandri and Jones, 2008). Land use change (i.e. the replacement of vegetation with hard, impervious surfaces) has detrimental impacts on several aspects of the urban environment, and may contribute to increased surface flooding (Section 1.2.1), elevated urban temperatures (Section 1.2.2), increased noise, air and water pollution, and reduced biodiversity and habitat changes (Gaston, 2010). In addition, human health and comfort may be adversely affected by the higher summer temperatures and increased air and noise pollution (Jenerette *et al.*, 2011).

Water demand in urban areas is also increasing as populations continue to grow and the standard of living rises (Bedbabis *et al.*, 2014), with global water demand doubling approximately every 21 years (Li *et al.*, 2010b). This may lead to competition for limited water resources and restrictions for its usage, thus reducing the availability of water for landscape irrigation (Jones and Hunt, 2010).

In the UK and northern Europe, climate change has led to an increase in the frequency of hot summer days, heat waves and heavy precipitation events, and an increase in the area affected by droughts (since 1950; IPCC, 2013). Climate warming, with associated changes in precipitation patterns, is projected to continue for many decades (Wigley, 2005). In the UK, this is projected to result in (IPCC, 2013):

- drier summers with an increased likelihood of drought and water shortages affecting larger areas for longer periods of time;
- an increase in heavy precipitation events and a greater chance of flooding, especially in urban areas;
- an increase in the frequency and duration of heat waves, with associated health risks;
- higher urban temperatures and consequent air quality deterioration, leading to higher usage of air conditioning and thus carbon dioxide (CO_2) emissions (Crutzen, 2004).

As global population continues to rise, the extent of urbanisation increases, as does the proportion of the population living in urban areas. In 2014, 54% of the world's population was estimated to live in urban areas, which is expected to increase to over 66% by 2050; in the UK, this figure was 82% in 2014, projected to increase close to 90% by 2050 (United Nations, 2015). Furthermore, urban areas are expected to be the most greatly impacted by climate change (Gill *et al.*, 2007).

1.1.1 Provision of ecosystem services by urban vegetation

Ecosystem services (ESs) are defined as "the benefits people obtain from ecosystems" (Millennium Ecosystem Assessment, 2005, p.40), and have been classified into four categories: provisioning, regulating, cultural and supporting services (Table 1.1). Provisioning, regulating and cultural services provide direct benefits to people, whereas supporting services are essential for maintaining the provision of all other ESs but do not benefit people directly.

Table 1.1: Summary and examples of ecosystem services classified as provisioning, regulating, cultural and supporting services by the Millennium Ecosystem Assessment (2005).

Provisioning Products obtained from ecosystems • Food • Materials • Fuel • Medicines	**Regulating** Benefits obtained from regulation of ecosystem processes • Climate regulation • Air quality regulation • Water regulation (including runoff quantity and timing and water quality) • Pest and disease regulation
Cultural Non-material benefits obtained from ecosystems • Recreation • Spiritual fulfilment • Education • Aesthetic value	**Supporting** Services which are necessary to sustain all other ecosystem services • Water cycling • Nutrient cycling • Photosynthesis

Reintroducing vegetation into urban areas has been shown to benefit the urban environment through provision of a number of ESs, some of which have been widely studied, including stormwater management (i.e. reduced surface flooding), surface and aerial cooling (i.e. reduced urban heat island effect), and air quality improvement (Dimoudi and Nikolopoulou, 2003; Gill *et al.*, 2007; Jim and Chen, 2009). Additional ESs provided by urban vegetation include noise reduction, energy savings, carbon sequestration, biodiversity support, production of food and medicines, nutrient cycling, and a broad range of cultural services including health benefits, increased property values, and historical significance (Sailor *et al.*, 2008; Cameron *et al.*, 2012; Netusil *et al.*, 2014; Davies *et al.*, 2017).

Vegetation can be incorporated into urban areas as street trees, parks, public and private gardens, green roofs and walls, allotments, and green corridors (Cameron *et al.*, 2012). Characteristics of the vegetation within green infrastructure (including composition, structure, location, and species) may influence the ESs provided (Sadler *et al.*, 2010); some types of vegetation are therefore more efficient at providing certain services, allowing maximisation of desired services through selection of appropriate vegetation. For example trees are generally recognised as being better at capturing air pollution than shorter vegetation due to their large leaf surface area and greater surface roughness causing more wind turbulence (Fowler, 2002; Davies *et al.*, 2017). Similarly, vegetation type, cover, and longevity greatly affect the amount of carbon that may be sequestered (Nowak and Crane, 2002).

Green walls and roofs are useful when the available space for greening is low, for example in densely urbanised cities such as Hong Kong (Cheng *et al.*, 2010), and are still able to provide a wide variety of ESs including the provisioning of food, regulation of climate, air quality and water, and urban habitat provision, as well as supporting services such as photosynthesis and water and nutrient cycling (Oberndorfer *et al.*, 2007; Whittinghill *et al.*, 2015). The focus of the present research is the provision of regulating services on green roofs, particularly stormwater management, water quality improvement and temperature regulation. Previous research has established that green roofs have good potential to provide these ESs (e.g. Vijayaraghavan *et al.*, 2012; Sims *et al.*, 2016; Heim *et al.*, 2017), and they were therefore chosen to be studied in more detail by examining the potential of plants with various characteristics to maximise provision of these services (Section 1.6).

1.1.1.1 Green roofs

Green roofs, or vegetated roofs, are made up of a series of layers including the vegetation, substrate, and various membranes for waterproofing, support and protection (Getter and Rowe, 2006; Oberndorfer *et al.*, 2007; Ouldboukhitine *et al.*, 2011). They are classified as extensive, semi-extensive or intensive, mainly depending on the depth of the substrate used, which can also determine the type of vegetation grown. Extensive green roofs have shallow substrate, typically considered to be less than 150 mm (MacIvor *et al.*, 2016), and generally require very little maintenance or irrigation. The shallow substrate and typical lack of irrigation restrict the types of vegetation that can be planted on extensive green roofs, and they therefore tend to have lower aesthetic value and a more functional purpose (Oberndorfer *et al*., 2007). Conversely, intensive green roofs have a deeper substrate layer (> 200 mm; Nagase and Dunnett, 2010), allowing a much greater variety of plants to be incorporated, and are often used as recreation spaces in urban areas. However, due to the deeper substrate, larger plants and intended use as a roof-top garden, intensive green roofs usually require some structural support, regular maintenance and irrigation. Semi-extensive green roofs lie in between extensive and intensive roofs, combining the growing techniques of extensive roofs with a slightly deeper substrate, thus allowing a wider range of plants to be grown (Dunnett and Nolan, 2004; Bianchini and Hewage, 2012), particularly when supplementary irrigation is available. Since the focus of this research is to investigate how ESs provision can be maximised by species selection, the semi-extensive green roof model has been selected as the most appropriate for the purposes of this study, and forms the basis for experimental design (see Section 1.6.2).

Environmental conditions on green roofs may be harsh, and plants can be exposed to both high and low temperature extremes and high wind speeds. Green roofs are also prone to soil moisture deficiencies and drought, especially the thin substrate layer of extensive green roofs, which restricts root growth and thus species selection (Oberndorfer *et al.*, 2007; Nagase and Dunnett, 2010). The traditional criterion for selecting green roof plants has therefore been their ability to tolerate stress and drought, and thus succulent (especially *Sedum* spp.) or grass species have been a frequent choice (Butler and Orians, 2011; MacIvor and Lundholm, 2011). However, recent studies have suggested that it may be possible to select plants based on their ability to provide ecosystem services as well as their ability to survive (Blanuša *et al.*, 2013), particularly when supplementary irrigation is available. Indeed, results indicate that alternative species may in fact be much better at providing several ecosystem services than the traditional *Sedum*, including stormwater management, cooling and air pollutant removal (Nagase and Dunnett, 2012; Speak *et al.*, 2012; Blanuša *et al.*, 2013). However, it is also evident that irrigation would be vital for non-succulent species on green roofs to prevent plant death (Butler and Orians, 2011), or a reduction in the provision of ESs, particularly those dependent on high evapotranspiration (ET) rates, such as cooling (Blanuša *et al.*, 2013; Vaz Monteiro *et al.*, 2017) and stormwater management.

Green roofs are advantageous in cities with competition for land area as they do not require additional land space and also have the benefit of using space that is currently wasted (Gill *et al.*, 2007). Indeed, Stovin *et al.* (2012) estimate that 40 – 50% of impermeable surfaces in most cities are rooftops, some of which could be used for retrofit of green roofs. The presence of substrate and vegetation on the roof also provides insulation to the building, helping to regulate the temperature inside; the need for air conditioning in the summer and heating in the winter is thus decreased, reducing energy usage and associated CO_2 emissions (Akbari *et al.*, 2001). Furthermore, there is evidence that the quality of runoff from green roofs is better than that from a conventional roof, since the substrate and vegetation may act as a sink for some nutrients such as zinc and copper (Seidl *et al.*, 2013). However, green roofs may also act as a source for other nutrients such as phosphorus that may leach from the green roof and increase the pollutant load of the runoff (Berndtsson *et al.*, 2009; Speak *et al.*, 2014).

1.2 Provision of ecosystem services by green roofs

1.2.1 Stormwater management

The removal of vegetation from urban areas and the consequent decline in interception and infiltration of rainfall results in more rapid and larger volumes of surface runoff (Gill *et al.*, 2007); this is enhanced by the impermeable nature of most urban surfaces. Pataki *et al.* (2011) estimate that urban areas with 50 – 90% impervious surfaces may lose 40 – 83% of precipitation as surface runoff compared to just 13% in a forested catchment. This increased surface runoff puts pressure on the existing drainage and sewerage systems as they are often forced to cope with greater volumes of water than they are designed for. The combination of inadequate drainage, increased volumes of runoff and the rapidity of its occurrence may result in flooding of urban areas (Stovin *et al.*, 2013). Surface runoff from urban areas is also likely to transport a range of urban pollutants to receiving water bodies, which may result in a deterioration of water quality and adverse effects on aquatic ecosystems (Carter and Rasmussen, 2006). Climate change models indicate that there is likely to be an increase in the frequency of high intensity precipitation events in the UK (IPCC, 2013), further increasing the risk of flooding in urban areas and negative impacts on receiving water bodies and aquatic ecosystems.

1.2.1.1 The role of green roofs in stormwater management provision

The layers of a green roof along with its vegetation enable interception, infiltration, and storage of the rain water resulting in delayed, prolonged and reduced peak runoffs compared to a standard roof. Water is stored primarily in the substrate, with some additional storage provided by the vegetation canopy (MacIvor and Lundholm, 2011; Sims *et al.*, 2016). This water is subsequently lost from the green roof through evaporation from the substrate and vegetation surfaces and by uptake and transpiration by the vegetation (Dunnett and Kingsbury, 2004). Through these mechanisms, green roofs have been shown to delay the start of runoff and peak runoff (Carter and Rasmussen, 2006), as well as prolonging the duration of runoff compared to a conventional non-vegetated roof (e.g. for up to 9 hours; Teemusk and Mander, 2007), thus helping to mitigate the risk of flash flooding and combined sewer overflow. Additionally, studies have shown that green roofs can retain between 0 and 100% of the total rainfall in individual storms (e.g. Stovin *et al.*, 2012), depending on storm size and other factors, discussed in Section 1.2.1.2.

Rainfall will infiltrate into and be stored in the substrate, until the substrate reaches field capacity and can retain no additional water, after which runoff occurs (Sims *et al.*, 2016). The finite volume of water that can be stored in the substrate in this way is defined by the substrate retention capacity of the green roof. This can result in a delay in runoff production compared to a standard roof, where runoff from a green roof is initially negligible until the substrate reaches saturation, after which runoff characteristics are more similar to those of a conventional roof (Carter and Rasmussen, 2006). Following a rainfall event, the retention capacity of the green roof is restored through ET (Sims *et al.*, 2016), thus allowing a greater volume of water to be retained by the roof in subsequent storms.

1.2.1.2 Factors affecting rainfall retention on green roofs

A number of variables affect the ability of a green roof to reduce and delay runoff, such as the type and depth of the substrate, and the roof slope and geometry (VanWoert *et al.*, 2005; Getter *et al.*, 2007) as well as hydrological factors such as rainfall characteristics and antecedent soil moisture (Stovin *et al.*, 2012; Whittinghill *et al.*, 2015; Sims *et al.*, 2016).

The age of the green roof may also influence retention performance as the substrate undergoes chemical and physical alterations over time, for example a decrease in mean particle and pore sizes due to settling of the substrate components and root growth (Berndtsson, 2010; De-Ville *et al.*, 2017). Indeed, Getter *et al.* (2007) found that at the end of their 17-month study the substrate had higher porosity, more macropores and organic matter, and almost four times greater water-holding capacity compared to at the start of the study. These changes may alter the drainage properties of a substrate, including hydraulic conductivity or macropore flow, thus altering runoff patterns from green roofs, for example resulting in quicker initiation of runoff (Getter *et al.*, 2007). Nonetheless, old green roofs (e.g. 43 years old; Speak *et al.*, 2013) have still been shown to be able to provide significant rainfall retention, and Mentens *et al.* (2006) found no correlation between green roof age and annual runoff.

The volume of water that may be retained in the substrate corresponds to the field capacity of that particular substrate (Sims *et al.*, 2016) and, as such, the type and depth of substrate, as well as the antecedent moisture conditions, can affect the amount of water storage available. Deep substrates (e.g. > 150 mm) have been shown to retain a greater volume of water than shallower substrates, with a significant correlation between substrate depth and annual runoff identified by Mentens *et al.* (2006). Substrate properties also influence the drainage and retention characteristics of a green roof, with substrates of high porosity, low field capacity and low organic matter typically having lower retention and thus higher runoff (Dunnett *et al.*, 2008; Stovin *et al.*, 2015). Antecedent soil moisture content (SMC) also has a strong influence on the ability of a green roof to retain water, as a substrate near its field capacity will not be able to retain much water compared to a substrate that is initially relatively dry (Volder and Dvorak, 2014). Indeed, in a study of three identical green roofs located in different climatic regions of Canada, Sims *et al.* (2016) attributed differences in retention between the roofs during similar storms to differences in antecedent SMC, resulting from varying ET rates in different climates.

The characteristics of the dry weather period preceding a rainfall event are therefore also an important factor determining the retention of a green roof, since they dictate the antecedent SMC and the substrate's water retention availability at any given time (Sims *et al.*, 2016). However, although some studies have identified a significant link between the length of the antecedent dry period and runoff (Carpenter *et al.*, 2016; Heim *et al.*, 2017) others have found no clear relationship (e.g. Speak *et al.*, 2013; Sims *et al.*, 2016), and Stovin *et al.* (2012) found that although a short dry weather period equated to low retention, long dry weather periods did not always equate to high retention, as a green roof has a finite capacity for water retention. The effects of weather, climate or season on restoration of substrate retention capacity, and thus retention performance of green roofs, have also been noted in several other studies (e.g. Voyde *et al.*, 2010a; Speak *et al.*, 2013; Nawaz *et al.*, 2015). In addition to seasonal variations in precipitation, high temperatures during the summer increase ET rates, resulting in faster restoration of the substrate retention capacity and thus higher retention in subsequent rainfall events (Carter and Rasmussen, 2006). Conversely, when the weather is cooler and wetter with high relative humidity, ET and hence restoration of the substrate's retention capacity is restricted, resulting in lower retention; this has been observed during the winter (e.g. Dunnett *et al.*, 2008) and also when summer conditions are particularly wet (e.g.Voyde *et al.*, 2010a; Speak *et al.*, 2013).

Characteristics of individual rainfall events, such as depth, intensity and duration, influence the retention performance of green roofs, with an inverse relationship frequently identified between rainfall depth and the proportion of rainfall retained by a green roof (Whittinghill *et al.*, 2015). Carter and Rasmussen (2006), for example, reported that nearly 88% of total rainfall was retained by a green roof during small storms (< 2.54 mm) whilst only 48% was retained in large storms (> 7.62 mm). This decline in retention with increasing storm size occurs because the substrate can only retain water until it reaches field capacity, after which excess rainfall is released as runoff (Volder and Dvorak, 2014; Sims *et al.*, 2016). Rainfall retention by a green roof also shows an inverse relationship with the intensity of the rainfall (Villarreal and Bengtsson, 2005), possibly because the substrate is unable to absorb the rainfall fast enough during intense storms (Stovin *et al.*, 2012), thus potentially resulting in the generation of runoff before the substrate has reached its retention capacity.

1.2.1.3 The effect of vegetation type and physiology on green roof retention performance

The majority of studies have focussed on the effects of substrate and rainfall characteristics on the retention performance of green roofs, with few studies accounting for the effect of the vegetation itself (MacIvor and Lundholm, 2011; Nagase and Dunnett, 2012; Stovin *et al.*, 2015). Although the substrate (along with green roof retention layers) is recognised as the major store for rain water (VanWoert *et al.*, 2005), vegetation has been frequently acknowledged as a small but significant component, influencing retention and runoff patterns (Voyde *et al.*, 2010a). For example, MacIvor and Lundholm (2011) found that vegetation was able to retain up to an additional 4% of rainfall on top of that retained by the substrate alone, depending on species. Furthermore, significant differences in retention have been identified with different species (Nagase and Dunnett, 2012; Whittinghill *et al.*, 2015; Aloisio *et al.*, 2016), suggesting that vegetation choice can influence the stormwater management capabilities of green roofs.

Vegetation influences green roof rainfall retention through direct interception of rainfall on the canopy, and uptake of water from the substrate through ET, which restores the substrate's retention capacity for subsequent rainfall events. As such, physical characteristics of the vegetation (e.g. canopy structure, leaf traits, root system structure, ET rate etc.) are important in determining how much water is intercepted and lost through ET. Larger plants with horizontally aligned leaves, dense canopies, and hairy leaves are thought to increase the interception and retention of rainfall, thus reducing runoff (Lundholm *et al.*, 2010; Nagase and Dunnett, 2012; Aloisio *et al.*, 2016). High root mass may also result in better soil structure, increased water-holding capacity and thus greater retention (Teemusk and Mander, 2007; Nagase and Dunnett, 2012), although conversely, MacIvor and Lundholm (2011) observed that high root density resulted in the lowest retention, and suggest that this may be due to decreased substrate porosity and water-holding capacity. Additionally, it has been suggested that green roofs with a variety of species may intercept and retain a greater proportion of water than monocultures due to the more complex structure of the canopy and the roots, although studies have reported contrasting results (Dunnett *et al.*, 2008; Lundholm *et al.*, 2010; Whittinghill *et al.*, 2015). Moreover, species mixes may increase the total ET, thus resulting in lower antecedent SMC and greater storage capacity for rainfall in subsequent storms (Brandão *et al.*, 2017).

Species with higher evapotranspiration (e.g. high leaf area or plants that have C_3 or C_4 photosynthesis, e.g. grasses and many crop plants including corn and rice, rather than Crassulacean Acid Metabolism (CAM), e.g. *Sedum*) are able to restore the substrate's retention capacity quicker, thus allowing more water to be retained by the green roof in subsequent rainfall events (Berghage *et al.*, 2007; Stovin *et al.*, 2013). However, the majority of retention studies to date have only tested species with low ET rates, such as *Sedum* or other succulents, and so the ability of green roofs planted with species with substantially higher ET rates to provide stormwater management needs further investigation. As the substrate is recognised as the primary store of water, the contribution of interception to green roof retention is generally viewed as minimal compared to the role of the vegetation in restoring substrate retention capacity (Stovin *et al.*, 2015). As such, species with low ET rates, such as *Sedum*, have typically shown lower retention rates than other species tested (Nagase and Dunnett, 2012; Whittinghill *et al.*, 2015).

1.2.2 Surface and aerial cooling

Urban areas are typically warmer than surrounding rural areas as a result of an alteration in the radiation budget of urban areas by removal of vegetation and the introduction of darker materials. This lowers the albedo of urban areas to an average of 0.15 compared to 0.18 – 0.25 for vegetation (Oke, 1987), meaning that less solar radiation is reflected and more is absorbed and re-released as long-wave radiation (i.e. heat) giving rise to the urban heat island effect (UHI). The UHI effect is enhanced by the release of anthropogenic heat, as well as the nature of urban building materials, which tend to have a high heat capacity thus allowing more heat to be stored during the daytime and released at night (Ng *et al.*, 2012). Removal of vegetation also results in reduced ET in urban areas, and consequently, the proportion of energy partitioned as latent heat of evaporation (i.e. the heat absorbed per unit mass as water changes phase to water vapour; Oke, 1987) decreases and a greater proportion of energy is used as sensible heat (i.e. addition of energy that is sensed as a rise in temperature; Oke, 1987), further increasing urban temperatures (Bowler *et al.*, 2010). Heat islands are usually greater in large cities with a high percentage of impervious surfaces. They reach their maximum expression on clear, still days (i.e. low cloud cover and wind speed) in the summer, and at night (Gaston *et al.*, 2010), when UHI intensity (i.e. the temperature difference between urban areas and surrounding rural areas) has been found to reach over 10°C in London (Doick *et al.*, 2014). UHIs are expected to get larger and more intense as the climate continues to warm (IPCC, 2013).

The elevated temperature in urban areas in the summer also results in greater use of air conditioning, thereby increasing greenhouse gas emissions and further enhancing the greenhouse effect. Indeed, Akbari *et al.* (2001) found a 2 – 4% increase in urban peak electricity usage with every 1°C rise in daily maximum temperature (above 15 – 20°C).

1.2.2.1 The role of vegetation in cooling provision

Vegetation in urban areas can provide surface cooling and, if established at a large enough scale throughout a city, has the potential to cool the air too through modification of the urban energy budget (Oke, 1987; Taha, 1997; Yu and Hien, 2006). The main mechanisms by which plants provide cooling is through increased reflection of solar radiation, shading, and greater partitioning of energy as latent heat for evapotranspiration (e.g. Cameron *et al.*, 2014; Blanusa *et al.*, 2016). Vegetation has a higher albedo than most urban surfaces, so more solar radiation is reflected (Li *et al.*, 2010a) and less is absorbed and used to heat the air and surfaces. Some solar radiation is also harnessed by the vegetation for use in photosynthesis and other biological processes, further reducing the energy available for heating (Eumorfopoulou and Kontoleon, 2009). Plant canopies (and the substrate in which they are planted) shade the area below the vegetation and thus prevent solar radiation from reaching the ground or building surface; this in turn reduces the absorption of radiation and its re-emission as heat, resulting in cooler surfaces and potentially reducing the heating of the air (Dimoudi and Nikolopoulou, 2003). The transpiration of vegetation also has an evaporative cooling effect, as a greater proportion of the available energy is partitioned as latent heat for evapotranspiration (Bowler *et al.*, 2010) and thus less energy is used as sensible energy to heat the air.

Several studies have found that green roofs can reduce roof surface temperatures in the summer compared to conventional rooftops (Jim and Peng, 2012; Dvorak and Volder, 2013; Heim *et al.*, 2017) and compared to rooftops with bare, unvegetated substrate (e.g. by up to 3 °C; Lundholm *et al.*, 2010), whilst air temperatures in urban parks can be up to 1.3°C lower than in the surrounding built environment, with smaller diurnal temperature fluctuations (Yu and Hien, 2006). Furthermore, greater aerial cooling can be achieved with larger vegetated areas (Dimoudi and Nikolopoulou, 2003; Vaz Monteiro *et al.*, 2016b) and the extent of cooling may also extend beyond the immediate vegetative cover, for example between 20 and 440 m from the greenspace, depending on weather conditions (e.g. temperature and wind speed and direction) at night in London (Doick *et al.*, 2014). The cooling provided by urban vegetation may also indirectly improve air quality as the lower temperatures slow photochemical reactions and hence the production of pollutants such as ozone (Pataki *et al.*, 2011).

Vegetation (and substrate) around a building envelope can also modify the temperature inside the building by providing insulation, blocking the entry of solar radiation into the building, reducing heat fluxes through the walls or roof, and by reducing air flow around the building and regulating relative humidity (Eumorfopoulou and Kontoleon, 2009; Pérez *et al.*, 2011). Vegetation may therefore provide a form of passive cooling, decreasing the need for temperature control devices such as air conditioning units and leading to energy savings; this may indirectly help to improve air quality as fewer pollutants are emitted from power plants (Yang *et al.*, 2008). Winter energy savings may also be achieved, as the vegetation reduces wind speed around the building envelope, thus reducing cold drafts into the building and decreasing the heating demand inside (Cameron *et al.*, 2012). The use of deciduous plants has the additional benefit of allowing solar radiation to reach the building surfaces when the leaves are shed in the winter, thus enabling some heat flux into the building (Ip *et al.*, 2010).

1.2.2.2 Factors affecting cooling provision by vegetation

In addition to the vegetation type and physiology (Section 1.2.2.3), there are several factors that may affect the cooling performance of vegetation including the substrate moisture availability, and local weather and climate conditions. For a plant to provide evaporative cooling it must have an adequate supply of water for transpiration to continue; if there is insufficient moisture in the substrate, plants may close their stomata to prevent water loss by transpiration, thus increasing leaf temperature and reducing evaporative cooling (Jones *et al.*, 2002). Since climate change projections suggest an increased likelihood of more frequent and prolonged periods of drought in the UK (IPCC, 2013), the extent of the cooling provided by evapotranspiration may therefore be restricted (Cameron *et al.*, 2012) unless supplementary irrigation is available, potentially increasing the relative importance of shading and reflectance for cooling.

Climate has been shown to affect the cooling potential of vegetation, with greater cooling achieved in hot, dry climates than cool or humid climates (Alexandri and Jones, 2008). This is likely to be due to restricted ET rates in cool/humid climates, thus reducing evaporative cooling, whilst in hot/dry (or windy) climates ET may increase (Pérez *et al.*, 2011). Similarly, local weather conditions may also affect the amount of cooling provided by vegetation, with the greatest cooling usually reported on the hottest days (Cheng *et al.*, 2010; Blanuša *et al.*, 2013) and less cooling generally observed on overcast days (Eumorfopoulou and Kontoleon, 2009; Jim and Peng, 2012), when ET is inhibited by the higher relative humidity (Cantuaria, 2000). Additionally, low solar radiation on overcast days may suppress photosynthesis, restricting stomatal opening and resulting in less transpiration (Jim and Tsang, 2011).

1.2.2.3 The effect of vegetation type and physiology on cooling

The structure and function of the vegetation itself, including leaf colour, thickness and size, the presence of leaf hairs, canopy density and height, and ET rate (Vaz Monteiro *et al.*, 2016a; 2017; Charoenkit and Yiemwattana, 2017), also influences the amount of cooling achieved (Wong *et al.*, 2003; Cameron *et al.*, 2012; Blanuša *et al.*, 2013) and the aerial extent of cooling (Vaz Monteiro *et al.*, 2016b). Several studies have employed models to estimate the cooling that may be provided by different forms of green infrastructure (Dimoudi and Nikolopoulou, 2003; Ouldboukhitine *et al.*, 2011; Ng *et al.*, 2012), but typically use only average values for plant characteristics such as albedo, ET rate and leaf temperature. The differences between plant types and physiology are generally not taken into account when estimating the impact of vegetation on temperature modification, yet they have been shown to affect the magnitude of cooling provided in plant-level experiments (Wong *et al.*, 2010; Liu *et al.*, 2012; Blanuša *et al.*, 2013).

Vegetation with higher leaf area index (LAI) (i.e. a greater canopy density) is able to provide more cooling and produce a lower ambient air temperature (e.g. Wong *et al.*, 2003; Yu and Hien, 2006; Vaz Monteiro *et al.*, 2017) as larger leaves, greater vegetative coverage, and more dense vegetation (e.g. greater number of leaf layers) provide greater shading, thus resulting in lower surface temperatures below the vegetation (Ip *et al.*, 2010; Wong *et al.*, 2010; Ouldboukhitine *et* *al.*, 2011; Sternberg *et al.*, 2011). This means that the amount of shading provided may vary as the vegetation grows and, in the case of deciduous plants, will vary seasonally. It has also been suggested that green roofs consisting of a mixture of vegetation types (rather than monocultures) may be able to reduce rooftop temperatures more due to the greater height and complexity of the vegetation layers trapping more air (Dunnett *et al.*, 2008; Lundholm *et al.*, 2010; Heim *et al.*, 2017). Additionally, the extent of evaporative cooling provided varies depending on the transpiration rate of particular species (Blanuša *et al.*, 2013; Vaz Monteiro *et al.*, 2017). Succulent species such as *Sedum*, commonly chosen for green roofs, typically have low ET rates, whereas broadleaf species have higher ET rates and thus have been shown to provide greater cooling (Blanuša *et al.*, 2013; Vaz Monteiro *et al.*, 2017); indeed, ET has been identified as the primary mechanism for this cooling provision with some species (Vaz Monteiro *et al.*, 2016a; 2017).

1.3 The process of evapotranspiration

Provision of some ESs, such as stormwater management and cooling (Section 1.2), is highly dependent on ET; it is therefore necessary to understand the physical process and the plant and environmental factors that may influence the rate at which ET could take place on a green roof.

1.3.1 Evaporation

Evaporation is the physical process of converting liquid water to water vapour, which is then transferred from the evaporating surface to the atmosphere. The energy required to break the bonds between the molecules of liquid water, known as the latent heat of vaporisation, is primarily supplied by solar radiation (Verhoef and Egea, 2013). The water vapour must then diffuse through the boundary layer, a thin layer of still air above the evaporating leaf or soil surface, before being transported higher into the atmosphere by turbulent transfer. The thickness of the boundary layer depends mainly on wind speed and the size of the surface (Kramer and Boyer, 1995), with high wind speeds disrupting and lowering the resistance of the boundary layer and thus increasing evaporation rates (Kent, 2000). Turbulent mixing of the air ensures that water vapour is continually transported away from the evaporating surface and a water vapour pressure gradient between the evaporating surface and the atmosphere is maintained, thus enabling continued evaporation. Evaporation can occur from any surface, including open water bodies, the soil surface, and leaf or canopy surfaces.

1.3.2 Transpiration

Transpiration is the process through which water is lost from the plant, consisting of evaporation of water from cell surfaces into intercellular air spaces and subsequent diffusion of the water vapour out of the leaf (Kramer and Boyer, 1995). This occurs when stomata open to allow uptake of CO_2 for photosynthesis and is driven by a water vapour pressure gradient between the leaf and the atmosphere (Taiz and Zeiger, 2006). The air spaces inside the leaf are connected to the air of the atmosphere by the open stomata, causing water vapour to diffuse from inside the leaf air spaces, where concentrations are high, to the atmosphere, which has relatively lower concentrations (Kent, 2000; Smith *et al.*, 2010). Consequently, the water vapour concentration in the air spaces inside the leaf decreases, and so water evaporates from the surfaces of the mesophyll cells until the water vapour concentration and the water in the cells are in equilibrium again (Smith *et al.*, 2010).

Evaporation of water from the mesophyll cells lowers their water potential, causing water to flow into these cells from adjacent cells by osmosis, consequently lowering the water potential of the adjacent cells: this sets up a water potential gradient across the leaf, which results in water being drawn into the leaf from the xylem and flowing across cells until it reaches the furthest mesophyll cell, from which the water evaporates into the leaf's internal air spaces (Kent, 2000). Water is subsequently pulled up the xylem by cohesion-tension, and thus also pulled into the roots from the soil, due to the negative pressure created in the leaf by the evaporation of water from the mesophyll cells (Taiz and Zeiger, 2006).

The rate of transpiration depends on the vapour pressure gradient between the internal leaf spaces and the atmosphere, the water potential gradient within the plant, the resistances associated with the diffusion pathway from the leaf to the air, the supply of water to the evaporating surfaces and the amount of energy available for evaporation (Kramer and Boyer, 1995). Since there is a large surface area of mesophyll cells from which water is evaporating compared to the volume of the internal leaf air spaces, the air inside the leaf is assumed to be close to saturation (Taiz and Zeiger, 2006). As such, the absolute humidity difference between the leaf air spaces and the atmosphere varies with temperature: an increase in leaf temperature lowers the internal relative humidity and causes more water to evaporate from mesophyll cell surfaces, thus increasing the concentration of water vapour in leaf air spaces, whilst an increase in ambient air temperature lowers the relative humidity of the outside air, thus increasing the water vapour concentration gradient between leaf and atmosphere and increasing the rate of transpiration (Kent, 2000; Taiz and Zeiger, 2006).

Since water vapour must pass through the leaf as well as the boundary layer before entering the turbulent atmosphere, there are two main resistances associated with the diffusional pathway of water vapour from the leaf: stomatal resistance and boundary layer resistance. The resistance to water vapour diffusing through the stomata is relatively low, and hence approximately 90% of water lost through transpiration is through the stomata (Kent, 2000). Stomatal resistance, and therefore transpirational water losses, are regulated by controlling stomatal aperture (Taiz and Zeiger, 2006). Stomata are generally open during the daytime to allow entry of CO_2 for photosynthesis, but closed at night to prevent water loss (Oxlade, 2007). Opening and closing of the stomata is controlled by the guard cells, which respond to environmental factors such as light intensity and quality, the water vapour concentration gradient between leaf and air, plant water status, leaf CO_2 concentrations and temperature (Kaufmann, 1990; Collatz *et al.*, 1991; Oxlade, 2007; Smith *et al.*, 2010). The water status of the roots or soil has been recognised as having a direct effect on stomata (feed-forward response), meaning that stomatal conductance may decrease as the soil dries (Davies *et al.*, 1994; Giorio *et al.*, 1999). Control of stomatal aperture also allows plants to regulate their canopy temperature (Jones, 1998a), since transpiration results in evaporative cooling of the leaf and thus a consequence of stomatal closure and reduced transpiration may be higher leaf temperatures (Costa *et al.*, 2013).

Boundary layer resistance arises due to the layer of still air next to the leaf or soil surface, which the water vapour must diffuse through before it can be transported higher in the atmosphere through turbulent mixing (Verhoef and Egea, 2013). The thickness of the boundary layer is a function of wind speed, the shape and size of individual leaves, and the surface roughness of the canopy (Kramer and Boyer, 1995). When wind speeds are high, and hence boundary resistance is low, stomatal resistance/aperture plays the largest role in controlling water vapour loss from the leaf (Kaufmann, 1990). Conversely, when wind speeds are low and the boundary layer is thick, stomatal aperture has little effect on transpiration rate as boundary layer resistance dominates (Jones, 1998a; Taiz and Zeiger, 2006). Additionally, in large planted areas, stomatal aperture and the shape and size of individual leaves are less important controls on ET than the surface roughness, and hence the boundary layer resistance of the whole crop canopy (Kramer and Boyer, 1995).

Transpiration rates also vary between plant types, for example due to differences in the size and number of stomata, and the total leaf area available for transpiration in different species (Azam-Ali, 2013). Additionally, leaf morphological characteristics such as size and shape, presence of leaf hairs and sunken stomata may affect the movement of air around the leaf, thus affecting the boundary layer resistance and influencing transpiration rate (Taiz and Zeiger, 2006), and leaves with an impermeable, waxy coating may also limit water loss (Nagase and Dunnett, 2012).

1.3.3 Evapotranspiration

Evapotranspiration (ET) is the combination of simultaneous evaporation from the soil and plant surfaces and transpiration from plants. Both evaporation and transpiration are the same physical process, in which liquid water at a surface is converted to water vapour and subsequently replaced by more liquid water at that surface (Azam-Ali, 2013). Although it is difficult to distinguish between the two processes, the portion of crop ET accounted for by evaporation or transpiration depends partly on the exposure of the soil surface, with soil evaporation dominating when crops are small or sparse and ground cover is low. Crop growth stage and time of year are therefore important factors. When ground coverage is high, transpiration is the dominant process accounting for the bulk of the total crop ET (Nouri *et al.*, 2013). Additionally, transpiration may slow or even stop when the soil water supply is limited, so that all ET is accounted for by evaporation (Castiglia Feitosa and Wilkinson, 2016) until the soil surface becomes dry and evaporation also stops (Allen *et al.*, 1998).

1.3.4 Factors affecting evapotranspiration

In addition to crop type and management, ET is influenced by atmospheric factors including the energy available to convert liquid water to water vapour, the capacity of the atmosphere to hold water vapour at a particular air temperature (i.e. the relative humidity), and the turbulence of the atmosphere (Azam-Ali, 2013). The main meteorological parameters influencing the rate of ET are solar radiation, air temperature, air humidity, and wind speed. Solar radiation represents the primary supply of energy for the conversion of liquid water to water vapour; the amount of solar radiation reaching the surface depends on location (i.e. latitude) and time of year, as well as the cloud cover at any specific time (Allen *et al.*, 1998). Air temperature influences ET by providing some additional energy to the evaporating surface in the form of sensible heat, as well as reducing the energy required for the evaporation process (Tan *et al.*, 2015). The removal of water vapour from the evaporating surface is driven by the humidity gradient between the air and the leaf (Allen *et al.*, 1998), which is described by the vapour pressure deficit (VPD) and is a function of air temperature and humidity. In humid environments, the air is often close to saturation and can hold little more water vapour, thus resulting in low VPD and low ET rates, whereas in arid environments the VPD between the evaporating surface and the atmosphere is high, resulting in higher ET rates. Wind affects the thickness of the boundary layer and hence the boundary layer resistance, with higher wind speeds resulting in lower resistance and thus higher ET. Additionally, high wind speeds promote turbulent mixing of the atmosphere, resulting in greater replacement of the saturated air above the evaporating surface with drier air, and thus allowing ET to take place at a faster rate (Tan *et al.*, 2015).

Together, these meteorological factors determine the maximum possible ET rate of a crop, known as the potential evaporation, ET_p (encompassing both evaporation and transpiration). For ET to proceed at its maximum potential there must be a continual supply of water to the evaporating surface (either through the leaf or the soil). If the water supply is limited, ET will be restricted and actual ET (ET_a) will be lower than ET_p (Verhoef and Egea, 2013). The water content of the soil and the frequency of surface wetting through either rainfall or irrigation therefore also play important roles in regulating ET rate, since decreasing SMC over time following wetting may restrict the supply of water to the evaporating soil and leaf surfaces resulting in reduced ET (Stovin *et al.*, 2013). Indeed, several studies found that the ET rate of various green roof species declined exponentially over time as soil water availability was reduced (Berghage *et al.*, 2007; Voyde *et al.*, 2010b). Furthermore, some succulent species, including *Sedum*, may utilise Crassulacean Acid Metabolism (CAM) when soil moisture is restricted, whereby carbon dioxide is fixed at night and stomata are closed during the daytime, thus reducing ET and conserving water (Farrell *et al.*, 2013). In contrast, other species may continue to photosynthesise, and therefore transpire, at a high rate even when substrate moisture becomes low (Cameron *et al.*, 2006; Voyde *et al.*, 2010b), and plant response to drying substrate will therefore depend on the particular species and any drought adaptation strategies that may be employed.

1.3.5 Estimating evapotranspiration

There are several methods of estimating crop ET, either through direct measurement or modelling. Methods of direct measurement include the use of weighing lysimeters, which estimate ET based on weight changes over a specified time period after accounting for any gains or losses from precipitation, irrigation or drainage (Verhoef and Campbell, 2005). This can give continuous, accurate values of ET for a range of spatial scales over very short time periods (e.g. half-hourly). For example, ET can be calculated from lysimeter weight changes with Equation 1.1 (Tan *et al.*, 2015) using time steps as small as 10 minutes:

$$ET(time) = \frac{W_a - W_b}{time} \times \frac{1}{A_{plot}} \qquad \text{(Eq. 1.1)}$$

where ET(time) is the ET in a specified time (mm per unit time), W_a is the initial weight of the load cell (kg), W_b is the weight after the specified time interval (kg) and A_{plot} is the area of the plot (m^2). Vegetation in the lysimeter is isolated from the surrounding crop but must be identical in physical characteristics such as height and leaf area index to ensure accuracy and applicability of the measured ET to the whole crop (Allen *et al.*, 1998). However, depending on their size, lysimeters may be relatively expensive and difficult to install and maintain, and measurements may be labour-intensive (Verhoef and Egea, 2013), thus potentially limiting their use, particularly for short timescale measurements.

An alternative method of estimating ET in a specified area is by measuring all other components of the soil water balance in order to determine ET (Verhoef and Egea, 2013):

$$\Delta\Theta = P_r + I + C - ET - D \pm R \qquad \text{(Eq. 1.2)}$$

where ΔΘ is the change in substrate moisture content over a particular time period, P_r is the precipitation received in the specified area over that time period, I is the irrigation received, C is the capillary rise into the root zone, D is the deep percolation and R is runoff, either into or out of the measurement area. All parameters are typically measured in units of mm day^{-1}. Some moisture fluxes are often assumed to be negligible (e.g. C and, on a flat surface, R) or may be difficult and labour-intensive to measure, particularly on short time scales such as hours or days. The soil water balance method is therefore generally only suitable for estimating ET on time scales of a week or longer (Allen *et al.*, 1998).

Since evaporation is limited by the amount of energy available at the surface for converting liquid water to water vapour, ET can also be estimated using a modelling approach of energy flux measurements and the principle of energy conservation (Allen *et al.*, 1998):

$$R_n - G - \lambda ET - H = 0 \qquad \text{(Eq. 1.3)}$$

where R_n is the net radiation reaching the surface, G is the soil heat flux, λET is the latent heat flux (i.e. the ET), and H is the sensible heat flux. All fluxes are in MJ m^{-2} day^{-1} and can be either positive or negative. In this approach, only vertical fluxes are included (i.e. horizontal advection is ignored), which means that it is only suitable for estimating the ET of large, homogenously vegetated areas. Additionally, although values for R_n and G can be easily obtained through measurement or from climate data, H is difficult to measure, which can make it difficult to estimate ET using this method. More complicated micrometeorological methods of estimating ET include the Eddy Covariance method and the Bowen ratio energy balance, both of which also call for extensive, homogenously vegetated areas and may require specialist equipment to accurately measure meteorological and atmospheric parameters with high frequency (Verhoef and Campbell, 2005).

There are also a number of widely utilised models that can be used to calculate ET using equations based on meteorological parameters, including Thornthwaite, Hargreaves, Priestley-Taylor and Penman-Monteith models (Poë *et al.*, 2015). These equations place importance on various easily-measured meteorological parameters such as solar radiation (e.g. Hargreaves) or air temperature (e.g. Thornthwaite) to provide estimates of ET which must then be calibrated for the climate of a particular location to give more accurate estimates (Schneider, 2011). Due to the disparity in ET estimates obtained with each of these models, a standardised model based on the Penman-Monteith equation was developed in FAO Drainage and Irrigation Paper No. 56 (Allen *et al.*, 1998) and subsequently recommended for all ET calculations and provides methods for obtaining or estimating all of the necessary meteorological parameters (see Section 5.1.1).

1.4 Sustainable irrigation of green roofs

Depending on plant type, irrigation of green roof vegetation may be necessary for maintaining plant health and functioning, particularly the maintenance of ET, which are vital for the continued provisioning of ESs, such as cooling (Blanuša *et al.*, 2013; Vaz Monteiro *et al.*, 2017) and stormwater management. Moreover, supplemental irrigation has been shown to significantly increase the surface and aerial cooling that can be achieved by some species, including *Sedum*, as a greater water supply allows more ET to take place (MacIvor *et al.*, 2016), and irrigation has been suggested as a potential strategy for providing additional cooling during heat waves (Broadbent *et al.*, 2017). In addition, since climate change projections for the UK indicate an increased likelihood of summertime droughts (IPCC, 2013), supplementary irrigation of all green roofs is more likely to be required to maintain plant health (Van Mechelen *et al.*, 2015).

Increasingly limited water resources available for landscape irrigation (Section 1.1), along with the cost of installing irrigation systems on green roofs, highlights the need for sustainable irrigation management practices. The use of potable water for irrigation of green roofs is considered to be unsustainable where water shortages occur (Moritani *et al*., 2013), and may be restricted in places where competition for limited resources is high (Silva *et al*,. 2014). Consequently, Van Mechelen *et al*. (2015) suggest three categories of sustainable irrigation management strategies, which can be implemented individually or in combination:

1. Adaptations of irrigation requirements – including selection of plants with low irrigation requirements to minimise water use and optimisation of green roof materials to increase water holding capacity and thus water available to plants;
2. Alternative irrigation sources – rainwater harvesting or reusing household wastewater can reduce potable water use and decrease pressures on sewerage systems. However, the long-term sustainability of alternative water sources should also be considered in terms of potential impact on ESs provision – for example, irrigation with saline waters may result in salt accumulation in the substrate (Al-Hamaiedeh and Bino, 2010), consequently resulting in plant stress and reduced ET, which may compromise the provision of certain ESs (see Section 1.5).
3. Control and monitoring of irrigation regimes – increasing water use efficiency by scheduling irrigation based on plant water needs, for example through monitoring of meteorological parameters and ET.

As the rationale behind the research presented here is to use species selection to maximise ESs provision on green roofs (see Section 1.6), this study focuses on the strategies of using alternative water sources for irrigation, specifically greywater (Sections 1.4.2 and 1.5), and control of irrigation regimes through monitoring plant water use (Section 1.4.1).

1.4.1 Scheduling irrigation based on evapotranspiration

Irrigation management and scheduling has traditionally been practiced in the agricultural context in order to achieve maximum yields of high quality crops whilst also minimising water use and costs associated with irrigation. Water use for agricultural irrigation in England and Wales tripled between 1970 and 2000 (Hess and Knox, 2002), putting water resources under pressure, particularly during periods of drought, and highlighting the need for careful irrigation management. Irrigation scheduling provides farmers with information about their specific crop water requirements, enabling determination of the timing and quantity of irrigation required (Bean and Pitt, 2012). Similarly, scheduling supplementary irrigation based on plant water requirements (i.e. ET of the particular species used) has the potential to reduce water consumption for irrigation of green roofs whilst also maintaining plant health, functioning and provision of ESs, particularly those dependent on high ET rates such as cooling and stormwater management.

Methods of irrigation scheduling commonly employed in agriculture typically fall into two categories: direct measurement of soil water content and water balance methods (Jones, 2004).

Measurement of soil water may involve expensive equipment which can be difficult to install, use or interpret and may require the assistance of specialist consultants; irrigation is scheduled when a pre-determined target soil moisture deficit is reached (Verhoef and Egea, 2013). Water balance methods involve daily recording of the volumes of water received by the crop through rainfall and irrigation and estimation of daily crop ET in order to continually estimate the water balance (Withers and Vipond, 1974); as with direct soil moisture methods, irrigation is scheduled when a pre-determined soil water deficit is reached.

ET can be measured directly with an open-pan or weighing lysimeters, estimated from meteorological measurements, calculated from evaporation equations (Section 1.3.5), or obtained from advisory services at a cost (Hess and Knox, 2002; Verhoef and Egea, 2013). Disadvantages associated with soil moisture-based methods include cumulative errors in the estimated water balance that may eventually become large and require recalibration by direct soil moisture measurement, and the fact that plants may respond to changes in plant water status rather than soil water content (Jones, 2004). Thus, an alternative to soil moisture-based methods for scheduling irrigation is the use of plant indicators to directly assess plant water stress; this could be through direct measurement of plant water content or measurement of plant processes that respond sensitively to water stress, such as stomatal conductance (Withers and Vipond, 1974; Verhoef and Egea, 2013).

1.4.2 Sustainable alternative water sources for irrigation of green roofs

In the UK, landscape irrigation accounts for approximately 7% of domestic water consumption (Environment Agency, 2011), whilst in Australian cities, 30% of potable water is used for domestic irrigation (Pinto and Maheshwari, 2010), presenting a huge potential for water savings if alternatives such as recycled wastewater are used for irrigation instead. In arid and semi-arid regions where water availability is limited due to low rainfall and high evaporation rates, wastewater (either treated sewage effluent or grey wastewater from houses) is already commonly used for irrigating crops – for example more than 70% of Israel's wastewater is used for crop irrigation (Travis *et al.*, 2010). Another common use of recycled water in urban areas is for flushing toilets, which may reduce potable water use by up to 30% (Al-Hamaiedeh and Bino, 2010). Even temperate regions that currently have high rainfall levels and no shortage of freshwater are expected to experience water scarcity in the near future, especially in urban areas (Li *et al.*, 2010b), and therefore using harvested rainwater and recycled domestic wastewater may provide an alternative sustainable water source for irrigation of green roofs.

The varying sources and compositions of these alternative water supplies may have environmental impacts, affecting the growth and functioning of the vegetation and soil chemistry and structure (Misra *et al.*, 2010); this must be clearly understood before large-scale wastewater irrigation systems can be implemented.

1.4.2.1 Rainwater harvesting

Rainwater harvesting involves the collection and storage of rainwater from rooftops, land and road surfaces, and rock catchments, and offers a renewable and sustainable source of water for individual households and communities which may supplement regular water supplies (Abdulla and Al-Shareef, 2009). It is already commonly practiced in many parts of the world – for example, in Australia 26% of households collect rainwater for reuse (Gurung and Sharma, 2014) – and in some countries, such as Spain, regulations dictate that rainwater harvesting systems must be included in new developments with large gardens and roof areas (Domènech *et al.*, 2015). Collection of rainwater has the immediate benefit of reducing surface runoff and helping to prevent flooding, thus reducing the pressure on drainage systems and reducing the pollutant load delivered to water bodies (Ahmed *et al.*, 2014). Using harvested rainwater for tasks such as irrigation also reduces the demand for potable water, leading to financial savings and offering a more sustainable alternative irrigation method (Li *et al.*, 2010b); indeed, modelling of extensive rainwater harvesting systems suggests that freshwater consumption may be reduced by up to 87.6% in residential areas (Bocanegra-Martínez *et al.*, 2014). In arid and semi-arid regions, the use of harvested rainwater for irrigation may also improve the agricultural productivity of rain fed crops (Helmreich and Horn, 2009).

1.5 Greywater for sustainable irrigation of green roofs

Greywater is defined as the portion of household wastewater arising from the kitchen, laundry, bathroom and washbasins, but does not include black water from the toilet (Eriksson *et al.*, 2002). As such, the quality of greywater is lower than potable water but better than municipal wastewater, i.e. wastewater from communities treated in sewage treatment plants (Pinto *et al.*, 2010). Greywater can account for up to 75% of total household wastewater (Ghaitidak and Yadav, 2013), suggesting that there is great potential for its reuse for irrigation purposes, especially in arid and semi-arid regions where freshwater availability is low (Rodríguez-Liébana *et al.*, 2014). Indeed, it has been estimated that greywater reuse for agricultural and domestic irrigation may reduce potable water use by up to 50% (Al-Hamaiedeh and Bino, 2010), resulting in financial savings as well as the preservation of high quality potable water. Recycling domestic wastewater also benefits the environment by reducing the cost and energy consumption of wastewater treatment plants and reducing the pollutant load to the environment (Al-Jayyousi, 2003). Greywater provides greater volumes and is a more reliable supplementary water source than other methods of water conservation that is available all year, regardless of rainfall (Mohamed *et al.*, 2013; Domènech *et al.*, 2015).

The chemical and physical properties of greywater vary greatly between regions and over time, and also depend on its source within the house: for example, greywater originating from the kitchen is often recognised as being more polluted than that from showers and washbasins (Al-Jayyousi, 2003; Environment Agency, 2011), and is in fact sometimes excluded from the definition of greywater due to its high organic load (Criswell and Roesner, 2007). The composition of greywater varies between households and geographical regions depending on the quality of the mains water supply, the products used, and the lifestyles and customs followed by individual households (Pinto *et al.*, 2010). Variations in water consumption and product use over time (e.g. differences between week days and weekends) and degradation of chemicals during transport and storage also affect the composition of greywater produced (Eriksson *et al.*, 2002; Abed and Scholz, 2016).

Despite its variability in chemical composition, greywater generally contains elevated levels of salts, surfactants, oil and grease, microbial contaminants such as pathogens, suspended solids, and organic matter (Misra and Sivongxay, 2009; Travis *et al.*, 2010). It also has higher concentrations of nutrients such as sodium (Na), nitrogen (N), phosphorus (P) and boron (B) than potable water (Rodda *et al.*, 2011b). The physical properties of greywater may also differ from potable water in terms of pH, electrical conductivity (EC), chemical and biological oxygen demands (COD and BOD), temperature, colour, and turbidity (Eriksson *et al.*, 2002; Pinto *et al.*, 2010). The high variability of chemical and physical properties of greywater makes it difficult to obtain average values, and differences in greywater composition may affect its impact on soils and vegetation when used for irrigation; thus, for consistency and repeatability, synthetic greywater is often used in laboratory experiments (Diaper *et al.*, 2008; Travis *et al.*, 2010).

The chemical and physical properties of greywater must be taken into account when selecting sources and systems for irrigation of green roofs, as, in addition to potential health risks, irrigation with greywater may have negative impacts on the environment, such as increased nutrient leaching and groundwater contamination, deterioration of soil structure and chemistry, and plant damage (Wiel-Shafran *et al.*, 2006; Pinto and Maheshwari, 2010; Sawadogo *et al.*, 2014). A summary of the potential impacts of greywater on soils and plants (discussed fully in Sections

1.5.1 - 1.5.3) is presented in Table 1.2. Health risks associated with using greywater for irrigation mainly arise from the spread of pathogens from greywater to people, and through accumulation of potentially toxic chemicals such as metals in plant parts which are then eaten (Jiménez, 2006). Microbial growth in greywater may be promoted by high temperature (due to the use of warm water for personal hygiene) and by storage (Eriksson *et al.*, 2002); health risks due to pathogens may thus be reduced by not storing the greywater and by avoiding direct contact with it. This has implications for the irrigation method used, as surface spraying may spread pathogens through inhalation of aerosols or contact with the water, whereas sub-surface irrigation, without generating any runoff, minimises human contact and health risks (Jeppesen, 1996).

Table 1.2: Characteristics of greywater and their potential impacts on soils and plants.

Greywater characteristic	Impacts on soils	Impacts on plants	Other
High pH	Increases soil pH which can increase the likelihood of micronutrient deficiencies.	Micronutrient deficiencies can limit plant growth.	Reduced plant growth decreases the canopy area available for capture of rainfall or air pollutants and may decrease overall ET.
High concentrations of salts / high EC and SAR	Increased salinity of the soil (increased EC and SAR), leading to deterioration of soil structure and reduced hydraulic conductivity.	High uptake of salts can reduce metabolic processes and limit plant growth.	
High concentrations of surfactants, oils and grease, and organic matter	Reduces the soil's hydraulic conductivity and may cause the soil to become water repellent, thus reducing infiltration rates.	Reduced hydraulic conductivity makes it difficult for plants to take up water and may restrict transpiration.	Reduced transpiration reduces provision of ESs such as cooling and restoration of substrate retention capacity.
High concentrations of nutrients	May accumulate in the soil or leach into groundwater and freshwater bodies.	May act as a fertiliser, especially in nutrient-poor soils, and increase growth and yield. However, nutrients may accumulate to toxic levels and restrict plant growth or health.	Potential human health risk if some nutrients or metals accumulate to toxic quantities in edible plant tissues.

The health implications of using greywater for irrigating edible crop plants have received a lot of attention with many studies investigating the uptake and accumulation of potentially toxic metals such as cadmium (Cd) and B in edible plant tissues (Finley *et al.*, 2009; Misra *et al.*, 2010; Rodda *et al.*, 2011b). Treatment of greywater prior to use may reduce health risks by reducing pathogen and nutrient content, as well as removing surfactants, suspended solids and organic matter and thus also improving greywater quality (Winward *et al.*, 2008; Li *et al.*, 2009; Martín *et al.*, 2013). Treatment systems may be biological (e.g. constructed wetland), chemical (e.g. coagulation) or physical (e.g. filtration) (Li *et al.*, 2009; Dalahmeh *et al.*, 2014). However, since green roof ornamental plants are not grown for consumption, it is generally considered acceptable to irrigate them directly with wastewater, without the need for treatment first (Niemczynowicz, 1999). Indeed, recent research suggests that green walls could themselves be used as treatment systems for greywater (Fowdar *et al.*, 2017; Prodanovic *et al.*, 2017), thus providing a sustainable irrigation source for a range of species to be grown whilst also producing runoff of higher quality than the original greywater that could then be used for other purposes such as toilet flushing.

1.5.1 Effect of greywater irrigation on soils

In addition to the human health risks discussed previously, greywater irrigation can also have negative impacts on the soil and its ability to support plant growth, mainly due to salinity, increased pH and EC, and the presence of surfactants and oils in the greywater compared to potable water (Gross *et al.*, 2005; Finley *et al.*, 2009; Albalawneh *et al.*, 2016). Impacts on the soil will therefore differ due to the great variability in greywater composition, as well as due to variation in soil structure and chemistry between different soil types (Travis *et al.*, 2010). The pH of greywater has consistently been found to be higher than that of tap water (often as high as 9 or 10), which consequently raises the pH of the soil (Pinto *et al.*, 2010; Ali *et al.*, 2013) and may therefore increase the likelihood of micronutrient deficiencies, potentially limiting plant growth (Christova-Boal *et al.*, 1996; Siggins *et al.*, 2016).

Soils continuously irrigated with greywater may accumulate nutrients and metals, including Na, B, N, P, calcium (Ca), potassium (K), magnesium (Mg), zinc (Zn), manganese (Mn), and copper (Cu) (Gross *et al.*, 2005; Rodda *et al.*, 2011b). Accumulation of salts, especially sodium, has a detrimental effect on the soil; Sodium Adsorption Ratio (SAR) describes the concentration of Na^+ relative to the concentrations of Ca^{2+} and Mg^+, both of which counteract the negative effects of Na^+. High SAR (generally regarded as > 6; Al-Hamaiedeh and Bino, 2010) reduces the soil's ability to support plant growth by deterioration of soil structure (e.g. collapse of soil aggregates) and by reducing the hydraulic conductivity, thus making it difficult for plants to take up water (Al-Hamaiedeh and Bino, 2010; Rodda *et al.*, 2011b; Deinlein *et al.*, 2014). Indeed, Misra and Sivongxay (2009) found that the hydraulic conductivities of soils irrigated with greywater were only 5 – 16% of what they were when the same soils were irrigated with tap water. Addition of surfactants, oils and organic matter can also reduce soil hydraulic conductivity, and may cause the soil to become water-repellent, particularly at the surface (Travis *et al.*, 2010), which can also lead to reduced infiltration rates (Travis *et al.*, 2008; Kaboosi, 2016) and thus reduced capacity of a green roof to retain rainfall and provide stormwater management service.

Regular rainfall may prevent the accumulation of salts and metals in the soil by washing them out (Criswell and Roesner, 2007) whilst also preventing soil pH and EC increasing due to greywater irrigation; regional climate may therefore influence the impact of greywater on soils. In arid areas where rainfall is low, alternating greywater irrigation with freshwater leaching may have the same effect and prevent accumulation (Al-Hamaiedeh and Bino, 2010; Pinto *et al.*, 2010). Substantial freshwater leaching during the wet season has also been shown to eliminate soil hydrophobicity that was originally caused by irrigation with wastewater (Nadav *et al.*, 2013). However, if nutrients such as Na have already accumulated through long-term use of greywater, freshwater leaching may result in contamination of the groundwater supply (Misra and Sivongxay, 2009).

1.5.2 Effect of greywater irrigation on plants

Irrigation with greywater may also impact plant health, growth and functioning, either positively or negatively. Nutrients in wastewaters have been recognised as a possible source of nutrition for crops and vegetation that may provide a cheaper alternative to fertilisers and improve yield, whilst also providing a sustainable resource for irrigation in water-scarce areas (Pescod, 1992; Travis *et al.*, 2010; Ali *et al.*, 2013). Indeed, several studies have found higher uptake and concentrations of both macro- and micro-nutrients including N, P, K, Na Ca, Mg, Zn, B, sulphur (S), and iron (Fe) in the tissues of plants irrigated with greywater (Misra *et al.*, 2010; Rodda *et al.*, 2011b). However, continued use of greywater may lead to accumulation and increased uptake of nutrients in the soil and plant tissues, some of which may prove toxic (e.g. Na, B, Zn and aluminium (Al)) even at relatively low concentrations, and thus adversely affect plant health and growth (Christova-Boal *et al.*, 1996; Wiel-Shafran *et al.*, 2006). For example, high uptake of both Na^+ and Cl^- can reduce metabolic processes and photosynthetic activity, thereby limiting plant growth (Deinlein *et al.*, 2014).

Plant tolerance to nutrient concentrations varies between species and is therefore likely to influence any impacts of greywater irrigation (Pinto *et al.*, 2010); for example, citrus trees are considered to be sensitive to boron and should not be exposed to concentrations greater than 0.5 mg L^{-1}, whereas bell peppers are considered semi-tolerant and can be irrigated with concentrations up to 2 mg L^{-1} (Wiel-Shafran *et al.*, 2006). Indeed, Sharvelle *et al.* (2012) found that common garden plants, including small trees, shrubs and grasses, varied in their sensitivity to long-term greywater irrigation, ranging from an improvement or no difference to a significant decline in plant health, and Ouldboukhitine *et al.* (2014) reported deterioration in the visual health of periwinkle irrigated with greywater for 6 months, whilst there was no apparent impact on ryegrass. Indeed,

The vast majority of studies to date, however, have investigated the impact of greywater on vegetable crop species, particularly lettuce, which is considered to be sensitive to water quality and is therefore frequently used as a model plant (Wiel-Shafran *et* al., 2006). Nevertheless, the impacts of greywater irrigation on plant growth and yield (e.g. shoot and root biomass) have still been shown to vary: whilst some studies found increased plant growth and yield compared to freshwater irrigated plants (Misra *et al.*, 2010; Ali *et al.*, 2013) other studies found no difference between tap water and greywater irrigation (Finley *et al.*, 2009; Pinto *et al.*, 2010), and some reported a reduction in plant growth and biomass when irrigated with greywater compared to tap water (Travis *et al.*, 2010). Effects of greywater on plant health have also been variable, as although the majority of studies indicate no detrimental effects to plant health (Finley *et al.*, 2009; Al-Hamaiedeh and Bino, 2010; Pinto *et al.*, 2010), others have observed negative effects such as symptoms of toxicity or chlorosis on the leaves (Bubenheim *et al.*, 1997; Wiel-Shafran *et al.*, 2006), or even plant death (Sawadogo *et al.*, 2014). In their study, Sawadogo *et al.* (2014) reported that irrigation with highly concentrated laundry greywater resulted in the death of all lettuce and okra plants after 12 days and 20 days respectively, again highlighting the difference in tolerance between plant species,

The differences in the impacts on plant health and growth may be partly due to regional differences and variations in soil types and the compositions of greywater used; for example, Finley *et al.* (2009) note the low nutrient content of their greywater whilst Rodda *et al.* (2011b) suggest that low nutrient levels in their soil limited the growth of tap water-irrigated plants. Furthermore, Siggins *et al.* (2016) hypothesise that soil EC, pH and SAR were low in their study, even with greywater irrigation, as a result of high annual rainfall flushing greywater constituents out of the sandy soil. Additionally, the irrigation method may influence the effect of greywater on plant health, as Misra *et al.* (2010) suggest that the leaf chlorosis identified by Wiel-Shafran *et al.* (2006) may have been due to greywater directly contacting the leaves during irrigation, compared to their application of greywater directly to the soil.

1.5.2.1 Impact of phosphorus, boron and sodium on plants

The highest concentrations of P are typically found in laundry greywater (Eriksson *et al.*, 2002) due to their prevalence in laundry detergents. In recent years, however, many countries have moved to limit the concentration of phosphates in laundry detergents to reduce the nutrient load reaching water bodies and protect against eutrophication; EU legislation limiting the concentration of P in laundry detergents to 0.5 g per recommended dosage came into effect in the UK in 2013 (European Commission, 2015). Phosphorus is classed as an essential plant macronutrient, and as such some of the P applied through irrigation is taken up and utilised by plants. However, the majority of P adsorbs to soil particles; thus, when soil becomes saturated with P, and application by greywater irrigation continues, excess P may leach into groundwater or water bodies leading to eutrophication (Christova-Boal *et al.*, 1996; Turner *et al.*, 2013). Indeed, P leaching from green roofs is well-documented even under freshwater irrigation regimes, with the substrate and fertilisers thought to be the major sources (Berndtsson *et al.*, 2009). Enhanced application of P with greywater irrigation is therefore likely to increase leaching and further reduce the quality of the runoff, and it has been suggested that, without careful management, P leaching could limit the environmental sustainability of greywater for irrigation (Turner *et al.*, 2013). Since species differ in their uptake of nutrients, P quantities in the runoff may vary with plant type used (Sharvelle *et al.*, 2012). Excess P is not directly toxic to plants, but may result in deficiencies of other nutrients such as Zn, Fe, Mn and Ca; visual symptoms of these deficiencies typically include interveinal chlorosis, browning of leaf edges, stunted growth and small, distorted leaves (Jones, 1998b).

Boron is a common constituent of many household products including laundry detergents, soaps and cleaning products. Although it is considered an essential micronutrient for plants, B is known to be directly toxic to many species at low concentrations and may consequently limit plant growth (Wiel-Shafran *et al.*, 2006). Different plant types have differing B requirements for growth, leading to variation in B uptake and tolerance levels between species (Marschner, 1995): for sensitive plants, B concentrations above 0.5 mg L^{-1} are considered toxic (Almuktar *et al.*, 2015). Boron is taken up in solution by the roots and transported to stems and leaves where it may accumulate, resulting in toxicity symptoms of necrosis and chlorosis of leaf tips and margins, particularly in older leaves (Türker *et al.*, 2014). The rate of B uptake increases with higher transpiration rates (since it moves with the transpiration stream), higher temperatures and lower soil pH (Türker *et al.*, 2014). Boron also has a high affinity for the soil and in the short-term may be primarily adsorbed onto soil particles, thus keeping B concentrations low in the soil solution, meaning that there may be a lag between irrigation with B-rich waters and a visible effect on plant growth (Grattan *et al.*, 2015). Boron readily leaches from soils, and concentrations in leachate have been observed to increase over time (Sharvelle *et al.*, 2012).

Sodium is commonly found in laundry detergents, and concentrations are typically higher in greywater from the laundry and kitchen compared to bathroom greywater (Travis *et al.*, 2010). Although not classed as an essential nutrient for most species, sodium is generally considered to be beneficial for plants; however, plant responses to sodium differ between species, and high uptake of Na^+ (as well as Cl^-) into plant tissues from saline soils can prove toxic to species with low tolerances (Marschner, 1995; Deinlein *et al.*, 2014). Moreover, sodium accumulation in soils can result in deterioration of soil structure, reduced infiltration, and reduced ability of the soil to support plant growth, for example by decreasing the soil's ability to transmit water thus making it harder for plants to take up water (Misra and Sivongxay, 2009; Travis *et al.*, 2010; Rodda *et al.*, 2011b). As discussed in Section 1.5.1, SAR is an indicator of soil salinity (describing the content of Na^+ ions relative to Ca^{2+} and Mg^+); soil structure and permeability are likely to decline when SAR is 6 or higher, consequently impacting plant growth (Wiel-Shafran *et al.*, 2006). Where Na accumulates in the soil, leaching is also a concern as the Na may be flushed out (e.g. by rainfall or irrigation with freshwater) leading to contamination of groundwater supplies (Misra and Sivongxay, 2009).

1.5.3 Effect of greywater on the provision of ecosystem services

Irrigation with greywater can also impact plant functioning and provision of ESs, although this has rarely been studied. Reduced plant growth and poor plant health that may result from greywater irrigation could mean that there is a smaller canopy area available for capturing rainfall and air pollutants, thus reducing the vegetation's capacity for stormwater management and improvement of air quality. Deterioration of soil quality due to greywater irrigation may also compromise a green roof's capacity for stormwater management by reducing the infiltration rate and the soil's water retention capacity (Misra and Sivongxay, 2009; Kaboosi, 2016).

Reduced soil hydraulic conductivity caused by accumulation of salts and surfactants can make it more difficult for plants to take up water, thus potentially limiting transpiration and reducing water uptake from the soil. Consequently, the health of the plants and their ability to provide ESs may be compromised, since reduced water uptake from the soil will slow the restoration of substrate water retention capacity between rainfall events (Ouldboukhitine *et al.*, 2014), and cooling will be reduced when transpiration is suppressed (Blanuša *et al.*, 2013; Vaz Monteiro *et al.*, 2017). Indeed, Ouldboukhitine *et al.* (2014) hypothesised that reduced plant transpiration with long-term (6 months) greywater irrigation was a major factor affecting the thermal performance of green roof modules compared to those irrigated with freshwater. Some studies, however, report no reduction in plant water use over 60 days with greywater compared to tap water irrigation (Misra *et al.*, 2010; Pinto *et al.*, 2010). Conversely, Sharvelle *et al.* (2012) found that greywater-irrigated plants took up significantly more water than those irrigated with tap water (42.8% of the total irrigation water compared to 19.8%), although this was partly attributed to the significantly higher above-ground biomass of the greywater irrigated plants, rather than higher transpiration, resulting in greater water uptake. The source and quality of the greywater used for irrigation has also been shown to influence plant transpiration (Eriksson *et al.*, 2006), where irrigation with four out of seven greywater samples resulted in higher transpiration in willow than with the control treatment, whilst two greywater samples with high EC and pH > 9.0 proved toxic to willow and substantially decreased transpiration.

1.5.4 Impacts of greywater irrigation on runoff quality improvement

Green roofs may also be able to filter the greywater used for irrigation, by removing and storing (within substrate and plant tissues) some of the chemical constituents and improving the overall quality of the drainage water from the roof. Soils are well-known to be able to perform this function – for example, Misra and Sivongxay (2009) observed lower pH, EC and SAR and a 40 – 60% reduction in the concentrations of Na and K in runoff from soil cores compared to initial untreated laundry greywater. Plant presence may enhance this service and further improve the quality of the runoff, particularly once the vegetation becomes mature and well established (Köhler, 2002). Indeed, studies have found that concentrations of some nutrients are frequently lower in runoff from vegetated roofs than in runoff from roofs with just bare substrate (e.g. Emilsson *et al.*, 2007; Vijayaraghavan *et al.*, 2012). This is thought to be due to a combination of additional uptake and storage of some elements in plant tissues as well as enhanced biological activities (such as degradation of organic matter) in the rhizosphere when plants are present, compared to bare soil (Gagnon *et al.*, 2012). As such, environmental factors such as season and temperature, which affect the rate of some biological processes, are also thought to influence the quality of runoff from green roofs (Buffam *et al.*, 2016). Plant species differ in their capacity to take up nutrients, and so runoff quality also varies with species used (Fowdar *et al.*, 2017); indeed, studies have identified significant differences in the quality of runoff from different species (Sharvelle *et al.*, 2012; Aloisio *et al.*, 2016), although this has received little attention to date and warrants further investigation.

In addition to the type, age and maintenance practices of a green roof, the inherent nutrient content and physical properties of the substrate used also influence the quality of the runoff (Berndtsson *et al.*, 2006; Mendez *et al.*, 2011; Whittinghill *et al.*, 2016). Green roofs may act as a source of some nutrients rather than a sink, particularly when they are newly established or following application of fertilisers (Berndtsson *et al.*, 2006; Emilsson *et al.*, 2007), resulting in higher concentrations in the runoff than in the irrigation water or rainfall and thus potentially delivering a higher pollutant load to downstream water bodies (Buffam *et al.*, 2016). In particular, phosphorus leaching from green roofs is frequently reported (Dietz and Clausen, 2005; Van Seters *et al.*, 2009), and the source of P is thought to be fertilisers added to the green roof or the substrate itself, especially if it contains compost (Berndtsson *et al.*, 2009). Additionally, studies have found that nutrient concentrations in runoff from green roofs tend to be greater following heavier rainfall (Teemusk and Mander, 2007) and at the onset of rainfall due to the 'first flush' effect (Berndtsson *et al.*, 2006; Razzaghmanesh *et al.*, 2014), with concentrations decreasing as rainfall events proceed as well as over longer periods of time as nutrients are continuously leached from the green roof (Razzaghmanesh *et al.*, 2014). Leaching of accumulated salts from the soil may also result in the runoff having higher EC than the irrigation water (Alfiya *et al.*, 2012). Potential soil amendments for green roofs, such as addition of biochar, may enable the soil to retain more nutrients (as well as greater volumes of water), thus resulting in even lower concentrations of nutrients in the runoff (Beck *et al.*, 2011).

As well as the characteristics of the substrate used on a green roof, the chemical and physical properties of the water used for irrigation obviously play a large role in determining the quality improvement of the runoff. Since greywater is generally of lower quality than tap water or rainwater, it is likely that the runoff from a greywater irrigated green roof will be lower quality than runoff from a tap water irrigated green roof, although this has received little attention in the literature. When runoff quality studies have been conducted, results typically show that dissolved solids and concentrations of nutrients such as B and N are higher in runoff from treatments irrigated with greywater compared to tap water, as are physical parameters such as EC and SAR, presumably due to higher concentrations of salts in the irrigation greywater (Alfiya *et al.*, 2012; Sharvelle *et al.*, 2012).

1.6 Research scope and aims

It is clear from results of previous studies that green roofs have good potential to provide ESs such as stormwater management, with many studies reporting significant reductions in runoff with green roofs, and vegetation playing a vital role in addition to substrate alone (Section 1.2.1). However, although some studies have broadly identified some differences in the provision of stormwater management with different vegetation types (Lundholm *et al.*, 2010; Nagase and Dunnett, 2012; Soulis *et al.*, 2017), the majority of studies continue to focus on *Sedum*, and there have been few attempts to identify the characteristics of vegetation that could maximise rainfall retention and the consequent reduction in runoff. As discussed in Section 1.2.1.3, the magnitude of the rainfall retention service provided by vegetation may vary with differing leaf and canopy attributes and, in particular, with varying ET rates since restoration of the substrate's water retention capacity through ET between storms has been identified as the key role played by vegetation on a green roof (Stovin *et al.*, 2015).

One of the aims of the present research is therefore to investigate the potential of possible green roof plants to provide stormwater management and the key mechanisms for provision. The retention performance of three broadleaf species with large, complex canopies and varying leaf traits (e.g. pubescence) will therefore be compared to a typical green roof succulent species, *Sedum*, in terms of their ability to intercept rainfall. Furthermore, the impact of the inherently higher ET rates of the broadleaf species compared to *Sedum* on restoration of substrate water retention capacity, and thus overall stormwater management provision, will also be investigated.

Additionally, this study aims to investigate the effect of varying climatic conditions and water deficit on the ET of each species, thus influencing their ability to provide stormwater management on green roofs in different climates and locations, as discussed in Section 1.3.4. ET rates are known to decrease when substrate moisture becomes restricted, which may be common on extensive green roofs when irrigation is not available, due to the thin substrate layer. Meteorological variables, including air temperature and humidity, also influence the rate at which ET can take place, indicating that the rate of ET between storms, and thus the extent to which the substrate's retention capacity is restored, will vary with local weather conditions and between green roofs located in areas with different climates (Berretta *et al.*, 2014; Sims *et al.*, 2016).

Additionally, plant responses to these conditions may vary, for example through water conservation strategies as discussed in Section 1.3.4, but few studies have attempted to characterise restoration of substrate retention capacity through ET for different species under different environmental conditions (e.g. Poë *et al.*, 2015), particularly for species with inherently high ET rates. This research therefore aims to identify the optimum climatic conditions for each of the species with good potential for stormwater management, under which ET takes place at an optimal rate, thus maximising the provision of stormwater management in particular climates or locations. As such, the ET of the three broadleaf species and *Sedum* during week-long drying down periods will be quantified in controlled environment conditions simulating various potential UK summertime weather scenarios.

As discussed in Section 1.4, irrigation of all green roofs is likely to become necessary in the summertime in order to maintain plant health and provision of ESs, and especially when species with high ET rates are used. Additionally, provision of ESs dependent on high ET rates, such as cooling, may be significantly increased when supplemental irrigation is available (MacIvor *et al.*, 2016). Since water resources available for green roof irrigation are also likely to be limited, however, there is a need to identify strategies for sustainable irrigation. ET-based irrigation scheduling has proven to be a successful method of irrigating agricultural crops to maximise yield while also minimising water use (Section 1.4.1) and one of the aims of this research is therefore to investigate the potential of a similar irrigation scheduling model for green roofs, based on the daily ET of each of the four species, estimated using a standardised version of the Penman-Monteith equation (see Chapter 5 for details), in various hypothetical UK summertime weather conditions. Few studies have quantified the ET of green roof vegetation (Voyde *et al.*, 2010b; Poë *et al.*, 2015), but none of these have attempted to use this information for the purpose of scheduling irrigation.

Similarly, this study aims to explore the potential of greywater as a sustainable alternative source of water for supplementary irrigation of green roofs, thus also contributing towards the conservation of high quality potable water in urban areas whilst maintaining plant health and provision of ESs, and enabling inclusion of species with high ET rates on green roofs. Although several previous studies have investigated greywater as an option for irrigation, any impacts of greywater on substrates and plants are still unclear, as discussed in Sections 1.5.1 - 1.5.2. Moreover, most studies have primarily focussed on vegetable crops or wetland species (e.g. Eriksson *et al.*, 2006; Finley *et al.*, 2009; Al-Hamaiedeh and Bino, 2010), with very few testing green roof species, particularly those with high ET rates, although different species have been shown to respond differently to greywater (Sharvelle *et al.*, 2012). Additionally, very little research has been conducted to investigate whether irrigation with greywater impacts the provision of ESs, particularly those dependent on ET such as stormwater management and cooling

(Eriksson *et al.*, 2006; Ouldboukhitine *et al.*, 2014), and results of these studies are also not conclusive.

The responses of *Sedum* and the three broadleaf species to short-term irrigation with greywater will therefore be tested, and their health, growth and ability to provide ESs compared to plants irrigated with tap water over the same time period. Since impacts of greywater on plants and substrates have been shown to vary depending on the quality of the greywater used for irrigation, an industry standard synthetic greywater will be used throughout the study to ensure that all species are always exposed to greywater of the same quality (see Sections 2.7.1 and 6.1.2 for full details).

Previous studies have frequently reported an improvement in the quality of runoff from green roofs compared to runoff from conventional roofs and, in some aspects, compared to the influent water (e.g. rainfall; Teemusk and Mander, 2007; Speak *et al.*, 2014). Using greywater for irrigation of a green roof may decrease the quality of the runoff, although it may still be improved compared to the influent greywater itself, as discussed in Section 1.5.4. However, very few studies have examined the impact of greywater irrigation on runoff quality (Alfiya *et al.*, 2012; Sharvelle *et al.*, 2012), and there is no clear evidence regarding the ability of different plant types to improve the quality of the greywater and thus the quality of the runoff. This study therefore aims to investigate how the four different plant species may vary in their ability to provide runoff quality improvement on green roofs and how this service may be impacted when greywater is used for irrigation.

1.6.1 Research aims

The overarching aims of this research were therefore to understand how provision of stormwater management, and particularly the role of ET, can be maximised by appropriate plant selection. This would be achieved by using broadleaf species with high ET rates that may be suitable for use on green roofs compared to a traditionally used *Sedum*, whilst also investigating strategies for sustainable irrigation of these species. Six experiments and a modelling study were therefore set up aiming to:

- Understand how stormwater management provision is influenced by the varying leaf and canopy characteristics and ET rates of potential green roof species (Chapter 3);

- Investigate, in detail, the role of ET in stormwater management provision and how it is influenced by varying weather and substrate moisture conditions, enabling identification of optimal weather conditions for ET with each species (Chapter 4);
- Explore the potential of a simple ET-based model for scheduling irrigation of green roofs in order to maintain plant health and provision of ESs such as stormwater management and cooling (Chapter 5);
- Investigate any impacts of greywater on plant health and growth, provision of ESs and runoff water quality in order to assess its potential for use as a sustainable water source for supplementary green roof irrigation (Chapter 6).

1.6.2 Context of experimental setup and plant selection

Although this study takes an experimental and modelling approach to investigate the maximum potential of various species to provide stormwater management, particularly through ET, and the potential of greywater for sustainable irrigation of these species, plant choices are based on maximising the potential of urban vegetation, and green roofs in particular, to provide regulating ESs (such as stormwater management and cooling). As discussed in Section 1.1.1.1, green roofs provide a way for vegetation to be incorporated into urban areas without requiring additional space, whilst also offering insulation to the building in addition to providing a range of ESs. Planting choices on extensive green roofs have typically been dominated by succulent species, especially *Sedum*, due to the harsh environmental conditions (e.g. water deficit, high wind speeds and temperature extremes) on green roofs and their ability to survive without irrigation (Rowe *et al.*, 2014).

Recent studies, however, have indicated that other species may also be able to survive these harsh conditions (MacIvor and Lundholm, 2011; Nagase and Dunnett, 2013; Savi *et al.*, 2016), and the range of potential species is further expanded when supplementary irrigation is available (Dunnett and Nolan, 2004; Nagase and Dunnett, 2010; MacIvor *et al.*, 2013), as with semi-extensive green roofs. Furthermore, previous research at the University of Reading showed that some of these potential alternative broadleaf species were able to provide cooling to a significantly greater extent than *Sedum*, due to differing leaf and canopy attributes (e.g. leaf colour and pubescence and larger canopies) and their inherently higher ET rates (Blanuša *et al.*, 2013; Vaz Monteiro *et al.*, 2016a; 2017). Three of these broadleaf species, having already shown good cooling provision, were therefore selected for this study along with *Sedum* for comparison, with the aim of testing the maximum ability of a semi-extensive green roof planted with these species to also provide stormwater management. These broadleaf species are all low to medium growing perennial plants commonly found in UK gardens, and which represent the largest, most vigorous plant types likely to be supported on a semi-extensive green roof, thus maximising provision of ESs.

The setup of all experiments therefore reflected this aim to quantify the maximum potential of each species to provide stormwater management and to investigate the impact of irrigation with greywater on these plants. Experiments were thus carried out in controlled environmental conditions (i.e. inside a glasshouse or in controlled environment chambers). However, to replicate a semi-extensive green roof where possible, an industry standard green roof substrate was used in the majority of experiments and the substrate depth in all experiments was between 8 and 15 cm. To fully quantify the influence of the various plant species, a control treatment consisting of bare, unvegetated substrate was also used in all experiments.

Chapter 2

General materials and methods

2.1 Overview of experiments

Six experiments were carried out to address the research aims set out in Section 1.6.1. Experiments 1 – 4 were designed to investigate the ability of different plant species to maximise stormwater management provision on a green roof, through both interception and restoration of the substrate retention capacity. Experiments 5 and 6 studied the impacts of using greywater for irrigation on plant health, growth and provision of ecosystem services and on runoff water quality. Table 2.1 summarises all experiments; full details of materials, set-up and measurements can be found in the following sections.

Table 2.1: Overview of all experiments carried out in the study and the chapter(s) in which they are presented.

Expt.	Dates	Substrate	Treatments	Set-up	Chapter
1	24th March – 13th April 2014	Meadow Roof Medium; 11 cm depth	8x *Heuchera*, *Salvia*, *Stachys*, *Sedum*, control	Individual plants in 2 L containers	3
2	1st – 14th September 2015	Meadow Roof Medium; 8 cm depth	6x *Heuchera*, *Salvia*, *Stachys*, *Sedum*, control	Small canopies in 30 x 60 cm trays	3
3	12th – 19th April 2016	Peat-based compost; 15 cm depth	6x *Heuchera*, *Salvia*, *Stachys*, *Sedum*, control	Small canopies in 40 x 60 cm trays	3, 5
4	9th March – 30th April 2015	Meadow Roof Medium; 11 cm depth	6x *Heuchera*, *Salvia*, *Stachys*, *Sedum*, control	Individual plants in 2 L containers	4
5	22nd May – 18th July 2014	Meadow Roof Medium; 11 cm depth	16x *Heuchera*, *Salvia*, *Stachys*, *Sedum*, control; TW, GW	Individual plants in 2 L containers	6
6	22nd May – 13th July 2015	VC mix; 11 cm depth	22x *Heuchera*, *Salvia*, *Stachys*, *Sedum*, control; TW, GW	Individual plants in 2 L containers	6

2.2 Environmental conditions for experiments

All experiments were carried out at the University of Reading Whiteknights campus, Reading, UK. Experiments 1 – 3 and 5 – 6 took place in ventilated glasshouses to allow study of water inputs and usage without the interference of precipitation. Air temperature (T) and relative humidity (RH) were measured in the glasshouses every 30 minutes throughout all experiments using a Tinytag Plus 2 Data logger (Gemini Data Loggers, Chichester, UK), which was shielded from direct sunlight.

Experiment 4 was carried out in controlled environment (CE) growth cabinets so that the impact of specified environmental conditions on water uptake could be studied. Two Fisons 600G3/TL growth cabinets (Fisons Scientific Apparatus, Loughborough, UK), each with a growing area of 0.72 m^2, were used in the experiment. A day length of 16 hours (05:00 – 21:00 h) was chosen to replicate UK summertime conditions. This was provided by 13 Philips 40 W warm white fluorescent tubes, which provided a light intensity of 200 µmol m^{-2} s^{-1} (measured at the beginning of the experiment with an SKP 215 PAR Quantum Sensor; Skye Instruments, Powys, UK). There was no function for the growth cabinets to generate wind, but a vertical air flow of 0.2 m s^{-1} within the cabinet was provided by the air circulation system. Internal T and RH were recorded every minute by the cabinets' inbuilt logging systems. Target environmental conditions for simulated T/RH treatments are detailed in Section 4.2.1.

2.3 Plant material

In all experiments, three broadleaf perennial plant species/cultivars (*Heuchera micrantha* 'Obsidian', *Salvia officinalis* and *Stachys byzantina*) were compared to the succulent species *Sedum spurium*. For the purpose of this study, the cultivar 'Obsidian' was intended as a representative of the species *Heuchera micrantha*, and will therefore be referred to as a species hereafter. These three broadleaf species were selected for study as they have previously shown potential to provide a good cooling service and may be suitable for use on green roofs (Blanuša *et al.*, 2013; Vaz Monteiro *et al.*, 2016a). Since it has traditionally been used on green roofs due to its drought tolerance and low maintenance requirements, *Sedum* was included for comparison.

Photographs of all species studied are presented in Figure 2.1. *Salvia* and *Stachys* both have green/grey leaves with silver hairs, which are long and form a dense covering in *Stachys*, whilst leaf hairs are shorter on *Salvia* and leaf surfaces are rough. The *Salvia* canopy is bushy with upright woody stems whereas *Stachys* has a dense, ground-covering canopy. *Heuchera* is a vigorous subshrub with large, overlapping leaves that are dark purple with smooth, glossy surfaces. *Sedum* forms a dense, low-growing mat, with small green leaves that are smooth and succulent. The average evapotranspiration (ET) rate of *Sedum* is lower than the three broadleaf species (Vaz Monteiro, 2014).

Figure 2.1: Plant species studied in all of the experiments

In January 2014 and January 2015, *Heuchera* were obtained as two-year old plants from Coblands Nursery (Tonbridge, Kent, UK), which were maintained in a peat-based substrate in 2 L plastic containers. *Salvia*, *Stachys* and *Sedum* were propagated from cuttings in the winters of 2013/14, 2014/15 and 2015/16 for use in summer experiments. When transplanting into new substrates, as much of the old substrate as possible was removed from the roots of all species, although some peat-based compost was retained around the roots of *Heuchera* when transplanting into

Meadow Roof Medium (MRM; Section 2.4) as preliminary experiments suggested that it may not grow well in 100% MRM.

2.4 Growing media

Three different substrates were used in the experiments (see Appendix for properties of all substrates). To replicate 'real-life' conditions of a green roof, an industrial green roof substrate, Meadow Roof Medium (hereafter referred to as MRM; Vital Earth GB Ltd., Ashbourne, Derbyshire, UK) was used in Experiments 1, 2, 4 and 5. Due to changes in the manufacturing processes, it was not possible to obtain MRM in 2015, and a 'model' situation, using peat-based compost (Vitax Ltd., Leicestershire, UK), was therefore set up in Experiment 3.

MRM was chosen as a test substrate as it is a commercial green roof substrate manufactured and used in the UK, composed predominantly of crushed brick with added organic matter. This therefore represents 'real-life' green roof conditions and the water-retention characteristics and the behaviour of plants growing in this substrate are of practical interest. However, nutrient concentrations in the MRM are inherently high, resulting in high levels of phosphorus leaching from the substrate during the greywater (GW) experiment (Experiment 5). Additionally, the nutrient content added through GW application was small compared to the inherent substrate nutrient content. This made it difficult to analyse the uptake and storage of tracer nutrients in the substrate and plants, and to assess differences in runoff quality between treatments.

It was therefore decided to also test the impact of GW under 'model' conditions using a nutrient-poor substrate, so that the nutrient content added through GW application was an appreciable proportion of the total nutrients in the system. Thus, several substrate mixtures with varying nutrient concentrations were tested in a pilot study (data not shown) to formulate a substrate that was low but not deficient in nutrients, and would not be too free-draining. A 50:50 mix by volume of vermiculite and peat-based compost (hereafter referred to as VC mix) was identified as the most suitable substrate, and was used in Experiment 6. The VC mix was prepared at the time of planting by manually combining equal volumes of vermiculite (William Sinclair Horticulture Ltd., Lincoln, UK) and peat-based compost (Vitax Ltd., Leicestershire, UK) in a bucket and mixing thoroughly before filling containers. As nutrient concentrations in the VC mix were low, uptake and accumulation of the tracer nutrients in the substrate, plant tissues and runoff was easier to identify, thus allowing better assessment of differences between species and irrigation treatments. To enable quantification of all nutrient inputs to the plant/substrate during Experiment 6, no fertilisers were added to the VC mix either during planting or throughout the experiment. Irrigation with GW was the only additional nutrient input and therefore may have acted as a fertiliser; plants irrigated with tap water (TW) received no additional nutrients during the experiment.

2.4.1 Preliminary trials to characterise substrate moisture properties

Preliminary trials were carried out with each substrate at the start of the experimental seasons (March 2014 with MRM; March 2015 with peat-based compost; and May 2015 with VC mix), in order to determine the moisture characteristics of each substrate and determine daily plant water use. This information was then used to identify typical substrate moisture content (SMC) values under well-watered and dry conditions for each substrate, and to inform the irrigation volumes and scheduling in Experiments 5 and 6.

In the MRM and VC mix tests, three replicates of each species in 2 L containers, plus three control containers with bare, unvegetated substrate, were saturated to container capacity by submerging in water for 15 minutes and then draining for 30 minutes. Each container was then weighed and SMC was measured as described in Section 2.5.1. Thereafter, containers were weighed every 24 hours for 4 – 5 days to determine daily water loss from each container, and SMC was also measured daily. Containers received no further irrigation during this period. The substrate moisture characteristics of the peat-based compost used in Experiment 3 were tested in the same way, using 2 L control containers with bare, unvegetated substrate only. The mean daily water loss per container in each of the preliminary trials is presented in Table 2.2. It is worth noting that plants in the VC mix test were generally larger than those used in the MRM test, particularly *Sedum*, and tests were carried out at different times of the year (March for MRM and May for VC mix), which may partly account for the greater water uptake from the VC mix (in terms of absolute volumes), especially as water loss from bare, unvegetated substrate was similar.

SMC of the MRM tended to range between 0.300 and 0.400 $m^3 m^{-3}$ when the substrate was saturated and decreased to as low as 0.100 $m^3 m^{-3}$ after 4 or 5 days of drying, depending on species (data not shown). With the VC mix, SMC was around 0.550 – 0.600 $m^3 m^{-3}$ when the substrate was saturated and typically above 0.120 $m^3 m^{-3}$ after 5 days of drying, depending on species (data not shown). The SMC of unvegetated peat-based compost varied from 0.600 $m^3 m^{-3}$ when saturated to 0.500 $m^3 m^{-3}$ after 5 days of drying (data not shown). Based on the results of the preliminary tests, plants in all three substrates were considered 'well-watered' during Experiments 1 – 6 when SMC was > 0.250 $m^3 m^{-3}$, whilst SMC < 0.150 $m^3 m^{-3}$ was considered low.

Table 2.2: Mean daily water loss per 2 L container for each treatment in the three substrates. Data are the mean daily water loss from 3 replicate containers per species/control measured over 4 or 5 days following saturation, with associated standard error of the means (SEM).

Treatment	Mean (± SEM) daily water loss per 2 L container (mL)		
	Meadow Roof Medium	VC mix	Peat-based compost
Heuchera	56 (± 4.4)	67 (± 6.4)	-
Salvia	72 (± 2.6)	114 (± 11.5)	-
Stachys	68 (± 3.8)	117 (± 12.5)	-
Sedum	39 (± 1.7)	164 (± 17.9)	-
Control	52 (± 4.3)	53 (± 7.9)	43 (± 4.0)

2.5 Plant and substrate measurements

Plant and substrate measurements made in each experiment are summarised in Table 2.3; methods and procedures for each of the measurements are outlined in Sections 2.5.1 - 2.5.6, with specific details of timings and replication for each experiment described in relevant chapters.

Table 2.3: Summary of the plant and substrate parameters measured in each experiment.

Parameter	Stormwater management				Greywater	
	Expt. 1	Expt. 2	Expt. 3	Expt. 4	Expt. 5	Expt. 6
Substrate moisture content (SMC)	●	●	●	●	●	●
Substrate electrical conductivity (EC)					●	●
Evapotranspiration (ET)	●	●	●	●		●
Canopy size (height and diameter)	●	●	●	●	●	●
Leaf area	●	●	●	●		●
Root and shoot dry weights		●	●	●	●	●
Plant visual health and quality					●	●
Stomatal conductance to water vapour					●	●
Canopy temperature					●	●
Plant tissue/substrate chemical analysis					●	●

2.5.1 Substrate moisture content and electrical conductivity

Substrate moisture content (SMC) was measured in all experiments using a WET sensor connected to a HH2 Moisture Meter (Delta-T Devices, Cambridge, UK). In Experiments 1, 4, 5 and 6 two measurements were made in each 2 L container, and in Experiments 2 and 3 five measurements were made per tray, on each measuring occasion. The WET sensor was calibrated for use with the MRM substrate by Delta-T Devices, and was used on the 'organic' substrate setting with the VC mix and peat-based compost.

For Experiments 5 and 6, substrate electrical conductivity (EC) and temperature data, measured by the WET sensor simultaneously with SMC, were also generated. Since EC is dependent on temperature, all EC readings were corrected after measurement by manually applying a temperature compensation coefficient of 2% per °C: all EC values are thus reported at 25°C. A temperature correction coefficient of 2% $°C^{-1}$ was chosen as it is recommended as the default value by the WET sensor manufacturers, Delta-T Devices, for reporting EC at a standard temperature, and represents an average correction value for a range of substrate solutions.

2.5.2 Evapotranspiration

Evapotranspiration (ET) from all treatments was measured in Experiments 1, 2, 3, 4 and 6. Containers/trays were weighed every 24 hours using a CBK 32 bench checkweighing scale (Adam Equipment Ltd., Milton Keynes, UK) and daily ET was estimated as the weight loss per container/tray between two consecutive measurements. This was converted to ET depth (in mm) using Equation 1.1 (Section 1.3.5) by dividing the weight loss by the plot area.

2.5.3 Plant/canopy size and biomass

Several parameters were measured in all experiments to characterise canopy size. Plant/canopy height (measured from the substrate surface to the top of the tallest stem) and diameter (the average of two perpendicular measurements taken from above) were measured in all experiments. Leaf area was measured in Experiments 1, 2, 3, 4 and 6 using a leaf area meter with associated WinDIAS 3 Image Analysis System (Delta-T Devices, Cambridge, UK). In Experiments 1, 2, 4 and 6 all leaves from each plant/canopy were removed and their area measured. In Experiment 3, leaves were collected from a representative section of each tray (15 x 36 cm) and the measured leaf area was then scaled to tray size to give an estimate of the full canopy area. Additionally, in Experiment 3, leaf area density (i.e. cm^2 leaf area per cm^3 of canopy) was calculated by dividing total canopy leaf area by canopy volume.

Plants were harvested for biomass measurements in Experiments 2 – 6. Shoots and roots were separated and roots were carefully washed, removing as much substrate as possible. Shoots and roots were then dried in a ventilated oven at 70 ° C for 72 hours before being weighed with a Kern PCB 250-3 precision balance (Kern & Sohn, Balingen, Germany). In Experiment 3, roots and shoots from a representative area of each tray were harvested and results scaled up to describe the full canopy biomass. Additionally, fresh root volume was obtained in Experiment 3 by measuring the water displacement when roots were submerged in water in a measuring cylinder.

2.5.4 Plant health

Plant visual health was assessed throughout Experiments 5 and 6. Each plant was scored using a rating scale from 0 to 5 based on the visual plant health assessment system used by Sharvelle *et al.* (2012). Additionally, the number of dead leaves per plant was counted in both experiments (excluding *Sedum* in Experiment 6 due to counting difficulties), and total leaf numbers were also counted for *Salvia*, *Stachys* and *Heuchera*. Dead leaves were removed from all plants after counting in Weeks 4 and 6 in Experiment 5 and after every counting in Experiment 6 to enable easier counting and to make irrigation easier.

2.5.5 Leaf stomatal conductance to water vapour

Leaf stomatal conductance to water vapour (g_s) was measured during Experiments 5 and 6. Measurements were made at approximately the same time of day for each species using two young, fully expanded leaves on each plant. Measurements were made on one plant from each treatment alternately to account for any changes in environmental conditions throughout the day that might cause differences between treatments.

For *Heuchera*, *Salvia*, and *Stachys*, g_s was measured using an LCpro-SD infrared gas analyser (IRGA; ADC BioScientific Ltd., Hoddesdon, UK) with photosynthetic photon flux density supplemented to 1400 µmol m^{-2} s^{-1} using an external light source to ensure constant light levels throughout. When leaf sizes were too small to fill the whole chamber, approximate percentage coverage was visually estimated and g_s results were subsequently corrected during data analysis to give approximate g_s for 100% coverage. Owing to the very small leaf size of *Sedum*, an AP4 porometer (Delta-T Devices, Cambridge, UK) was used to measure g_s.

Although ideally the same equipment would have been used to measure the g_s all species, *Sedum* leaves were too small and too densely arranged to fit in the IRGA chamber, and the porometer was unsuitable for use with *Salvia* and *Stachys* as the humidity retained within the boundary layer of their hairy leaves resulted in inconsistent and unreliable readings. However, since the objective of this study was g_s comparison within rather than between species, the decision was made to use the porometer for *Sedum* and the IRGA for the broadleaf species.

2.5.6 Canopy temperature

In Experiments 5 and 6, canopy temperature was inferred from thermal images taken with an infrared imaging camera Thermo Tracer TH7800 (NEC San-ei Instruments Ltd., Tokyo, Japan). Plants were always positioned in the shade for at least 10 minutes prior to image taking to avoid sunlight variations; images of all plants were taken within one hour from the same distance and angle. Images were then analysed using NS9200 Report Generator software (NEC San-ei Instruments Ltd., Tokyo, Japan); canopy temperatures were determined in three representative areas for each plant and averaged to give a whole canopy temperature.

2.6 Setup of Experiments 1 – 4: Stormwater management

The experimental setup and preparation of plant materials for Experiments 1 – 4 are described in Sections 2.6.1 - 2.6.3 and 2.6.6. In Experiments 1 – 3, 'rainfall' was applied to all plants/canopies in a series of experimental runs in order to measure retention and runoff, whereas in Experiment 4 restoration of substrate retention capacity through ET was examined. Experimental runs in Experiments 1 – 3 consisted of a rainfall application to all plants/canopies under 'saturated' and 'unsaturated' conditions, as well as under 'dry' conditions in Experiment 1. The 'dry' run was conducted when the SMC fell below 0.150 m^3 m^{-3} for all containers – i.e. when the substrate would be considered 'dry', as determined in the preliminary tests described in Section 2.4.1. In 'saturated' runs, the substrate was pre-wetted to field capacity prior to rainfall application. In 'unsaturated' runs, rainfall was applied after a 72-hour antecedent dry period, with different plant treatments consequently having different SMCs due to differing ET rates.

Rainfall was simulated in Experiments 1 – 3 to ensure that constant volumes and/or intensities of rainfall were applied to all treatments. The simulators used in each experiment were tested extensively prior to the start of the experiments in order to determine suitable rainfall volumes and intensities and establish experimental procedures. Full details of the rainfall simulators used and the experimental procedure followed in Experiments 1 – 3 can be found in Sections 2.6.4 and 2.6.5 respectively. Experimental procedure for Experiment 4 is detailed in Section 4.2.2.

2.6.1 Experiment 1 setup: Rainfall retention and runoff with individual plants

In February/March 2014, eight plants of each of the four species were planted into 2 L containers with Meadow Roof Medium; each container was filled to 11 cm with MRM to ensure that substrate volumes were identical. Eight 2 L control containers with 11 cm of bare, unvegetated MRM were also prepared. Simulated rainfall was applied to each container three times over the course of the experiment, and restoration of substrate retention capacity (i.e. ET) was monitored between rainfall applications. Full details of each of the experimental runs can be found in Section 3.2.

Experiment 1

Treatments: 8 replicates of *Heuchera*, *Salvia*, *Stachys*, *Sedum* and control (bare substrate).

Measurements: SMC; plant height and diameter; leaf area; ET; volume of rainfall captured on the canopy; volume of runoff; volume of 'water lost due to dripping'.

2.6.2 Experiment 2 setup: Rainfall retention and runoff at canopy scale

Six replicate trays (30 x 60 x 8 cm) of each species, plus bare, unvegetated substrate, were prepared in July 2015, thus creating small canopies. All trays were filled to 8 cm with Meadow Roof Medium. *Salvia*, *Stachys* and *Sedum* had been propagated from cuttings in January 2015 and *Heuchera* were purchased as two-year-old plants. In order to create canopies with 100% coverage, 2, 4 or 6 plants were used per tray for *Heuchera*, *Stachys*, and *Salvia* and *Sedum* respectively. Three rainfall events were simulated for each tray, with restoration of substrate retention capacity between rainfall events also measured.

Experiment 2

Treatments: 6 replicates of *Heuchera*, *Salvia*, *Stachys*, *Sedum* and control (bare substrate).

Measurements: SMC; canopy height and diameter; leaf area; root and shoot dry weights; ET; volume of rainfall captured on the canopy; volume of runoff.

2.6.3 Experiment 3 setup: Canopy-scale stormwater management with an industry standard rainfall simulator

In February/March 2016, six replicates of each species were prepared, each consisting of a 32 L plastic tray (40 x 60 x 19 cm) with drainage holes drilled in the bottom and filled to approximately 15 cm with peat-based compost. Six control trays of bare, unvegetated substrate were also prepared. The number of plants per tray varied in order to achieve a full canopy, with 3 – 4 two-year-old plants per tray for *Stachys*, *Sedum* and *Heuchera* and 6 *Salvia* per tray, which had been propagated from cuttings in December 2015. Simulated rainfall was applied to each tray twice during the experimental period, and restoration of substrate retention capacity was also measured. Full details of each of the experimental runs are described in Section 3.2.

Experiment 3

Treatments: 6 replicates of *Heuchera*, *Salvia*, *Stachys*, *Sedum* and control (bare substrate).

Measurements: SMC; canopy height and diameter; leaf area; fresh root volume; root and shoot dry weights; ET; volume of rainfall captured on the canopy; volume of runoff.

2.6.4 Simulated rainfall

In Experiments 1 and 2, drip-system simulators were used. The application of water in this manner did not truly represent rainfall, but provided a quick and convenient method of applying water to the plants in order to quantify the volumes captured by different species. Based on the design described by Nagase and Dunnett (2012), rainfall simulators of this type were constructed for the experiments by drilling 1 mm-diameter holes in the bottom of a plastic box and inserting syringe needles (21G: 0.8 x 40 mm; Terumo UK Ltd., Surrey, UK) into the holes. These were sealed in place with Blu tack (Bostick Ltd.) to prevent water leaking out around the needles, and produced water droplets with consistent size and frequency. Reverse osmosis (RO) water was used for rainfall simulation with this type of simulator in Experiments 1 and 2 to prevent precipitates and air bubbles from mains tap water blocking the needles (Clarke and Walsh, 2007).

2.6.4.1 Experiment 1 simulator tests

Six small rainfall simulators were constructed for Experiment 1, using 1.6 L plastic boxes (internal dimensions 15.8 x 11.5 x 9.7 cm; Really Useful Products Ltd., Normanton, West Yorkshire, UK) each with 16 needles (Figure 2.2 A), which were 48 mm apart in rows 28 mm apart. Simulated rainfall covered a rectangular area of approximately 180 cm^2, which was just slightly smaller than the area of the 2 L containers thus ensuring that the total volume of water applied fell onto the plant/container. Simulators were supported approximately 60 cm above the ground, and one plant/container was positioned below each simulator for rainfall application (Figure 2.2 B).

Initial tests demonstrated that at least 200 mL of water was required to generate runoff from planted containers; 500 mL of rain was therefore applied to each container to ensure that there was enough runoff for accurate measurement. This was achieved by simulating rainfall for 10 minutes, with an initial water depth of 8 cm, which equated to a target rainfall intensity of 165 mm $hour^{-1}$. This very high rainfall intensity was chosen to reflect climate change projections of more intense precipitation events in the UK in the future (IPCC, 2013).

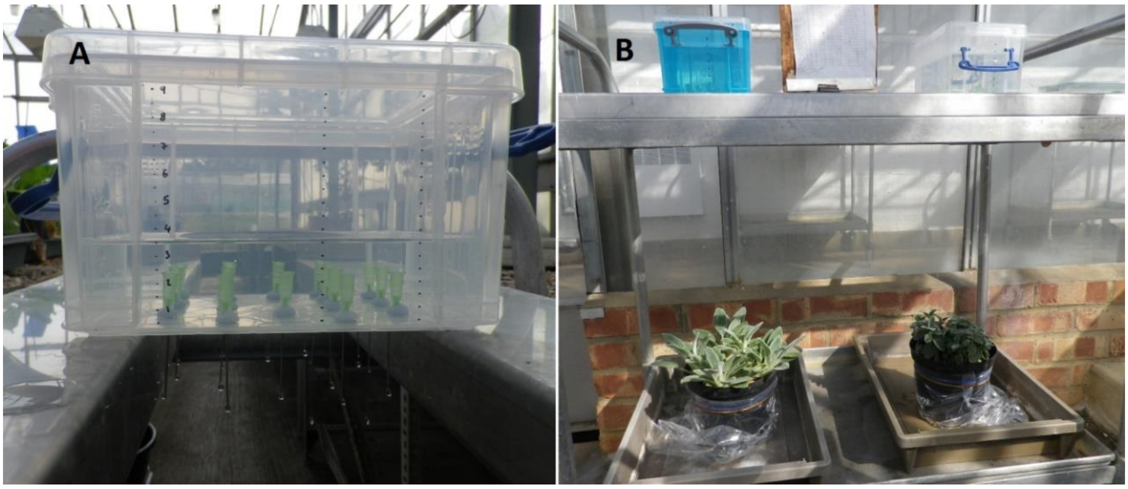


Figure 2.2: One of the six rainfall simulators used in Experiment 1 (A), and the position of the containers and trays below each simulator in the experimental runs (B).

The mean volume of simulated rainfall actually applied from each simulator in all of the experimental runs (as described in Section 2.6) was statistically similar (P = 0.820; LSD (5%) = 63.22; data not shown). There was little variation between simulators within each run, so all treatments received almost exactly the same volume of rainfall in each of the runs, allowing fair comparison of rainfall capture and runoff.

2.6.4.2 Experiment 2 simulator tests

For Experiment 2, three larger drip-system rainfall simulators were constructed using 32 L plastic boxes (internal dimensions 35 x 55 x 17 cm; Asda Stores Ltd., Leeds, UK). Each box had 72 needles arranged in 6 rows 45 mm apart (Figure 2.3 A), so that simulated rain fell in an area of 1925 cm^2, which covered all foliage. Simulators were supported on a mesh bench approximately 70 cm above the ground, and one tray was placed below each simulator for rainfall application (Figure 2.3 B). Trays were rolled in and out of position at the beginning and end of the rainfall application on a board, so that they were approximately 8 cm above the ground; the actual height of the simulators above the trays was therefore 62 cm.

Ideally, the rainfall intensity with this simulator would have been the same as in Experiment 1 to enable comparison of results at individual plant and canopy scales. However, with this experimental setup and needle configuration, which was partially dictated by the design of the mesh bench on which the simulators were supported, the maximum rainfall intensity that could be achieved was 115 mm hour^{-1}. The duration of rainfall was kept as 10 minutes, which equated to a target rainfall application of 3700 mL per tray. Testing of the simulators indicated that trays of bare substrate required application of at least 750 mL of water before runoff production began, and so 3700 mL was considered great enough to generate runoff even from planted trays.

Figure 2.3: One of the drip-system rainfall simulators used in Experiment 2 (A), and the position of the tray below the rainfall simulator during testing (B).

Actual volumes of water applied from each simulator during each experimental run (described in Section 2.6) varied, both between simulators and also between runs (data not shown). Average rainfall in all runs applied with simulator 1 was significantly lower than with simulator 3 (P = 0.033; LSD = 651.9), and the average volume from all simulators applied in the third run ('unsaturated') was significantly less than applied in the first run ('saturated') (P = 0.03; LSD =

648.7). The reduction in rainfall volume over the course of the experiment (i.e. between runs) could have been a result of the syringe needles becoming blocked with either air bubbles or debris in the water over time, despite the use of RO water, slowing the rate of dripping (Clarke and Walsh, 2007). As a result of this, only comparisons between treatments within each run were made. Additionally, the rainfall simulator used to test each treatment was varied in all experimental runs, so that rainfall from each simulator was applied to two replicates of each treatment in each run, and any differences in application volumes between simulators should therefore average out.

2.6.4.3 Experiment 3: Sprinkler rainfall simulator

In order to bring the characteristics of the simulated rainfall closer to those of natural rainfall, a sprinkler system based on the design described by Iserloh *et al.* (2012) and designed 'in house' by an irrigation specialist at RHS Garden, Wisley, was used to simulate rainfall in Experiment 3. The system consisted of a Lechler 460 608 nozzle attached by a 2 m length of hosing (Tricoflex) to a flow control, which was a series of pressure gauges and filters that ensured that the water flow and the characteristics of the droplets produced were constant. This was connected to the mains water supply by hosepipe, and 'rainfall' could be turned on and off directly on the simulator. The optimum flow pressure to achieve consistent rainfall in terms of droplet size and distribution was found to be 0.15 bars (15 kPa), and so this pressure setting was used for all rainfall simulations. The nozzle, hosing and simulator were fastened to an L-shaped timber support 2.4 m high and 1 m across (Figure 2.4), which was then secured to a metal pole in the glasshouse to keep the simulator stable and ensure that the rainfall always fell in the same area.

Trays were placed on a trolley and rolled into position under the rainfall (Figure 2.4 B), so that the actual height of the nozzle above the trays was 1.6 m; this is in line with the heights of other rainfall simulators cited in the literature, typically used in soil erosion and runoff studies, which vary between 0.7 and 3 m above the ground (e.g. Humphry *et al.*, 2002; Fister *et al.*, 2012). The height of the rainfall simulator determines the kinetic energy and terminal velocity of the water droplets produced; since the fall height is much lower than for actual rainfall, the velocity and energy of large drops in particular will be lower than in natural rainfall (Iserloh *et al.*, 2012).

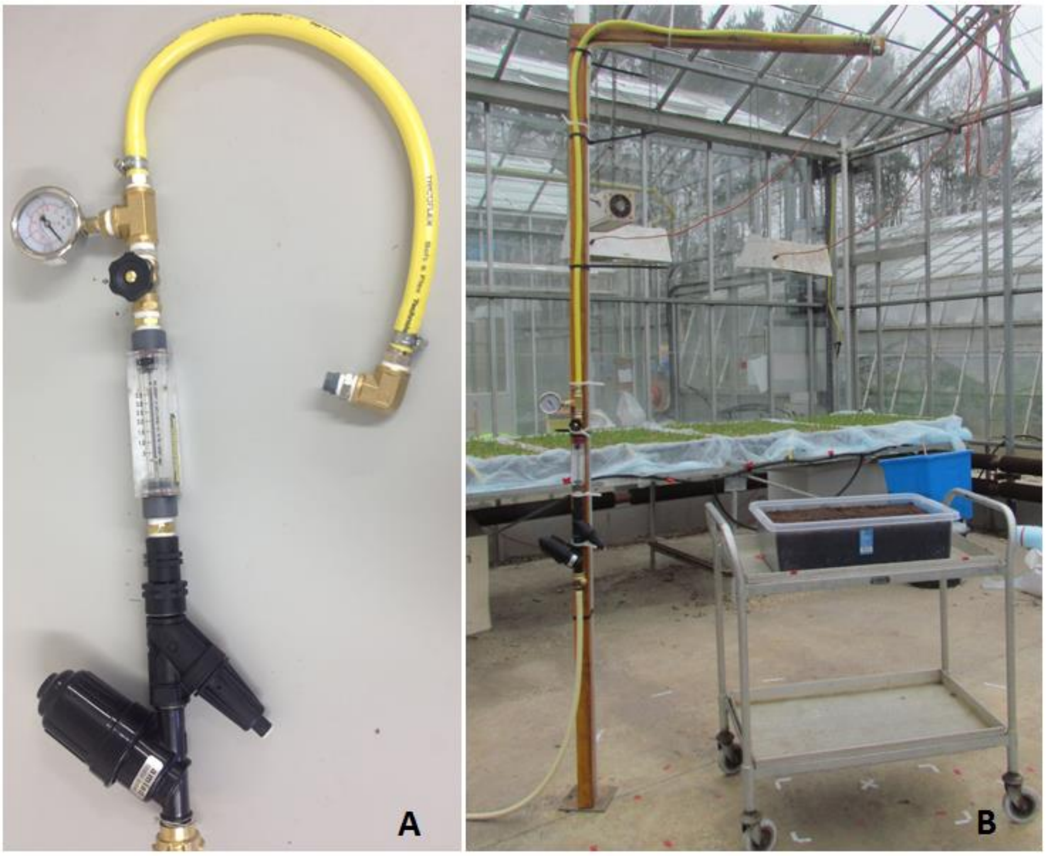


Figure 2.4: The sprinkler rainfall simulator used in Experiment 3, showing the pressure regulators and filters connected to the nozzle (A) and the experimental setup of the simulator secured to an L-shaped timber support with a tray positioned below the nozzle on a trolley for testing (B).

The spatial distribution of rainfall was found to vary and so tests were initially carried out to identify which position within the rainfall area could be used to ensure consistent rainfall intensity. Fifty-three numbered, empty buckets (24.2 cm diameter) were weighed and then positioned in concentric circles on the floor under the rainfall (Figure 2.5 A). Rainfall was simulated for 10 minutes with the flow pressure set to 15 kPa, and then all buckets were weighed again. The volume of water applied in each position was determined as the weight gain of each bucket, allowing spatial rainfall intensity to be mapped (Figure 2.5 B). Rainfall intensity was lowest directly below the nozzle and higher around the perimeter, similar to the spatial rainfall distribution described by Iserloh *et al.* (2012) and Fister *et al.* (2012) with the same nozzle type.

The area of buckets 1-2-6-7 (Figure 2.5 A) was identified as having the most consistent volume and intensity of rainfall in every rainfall simulation in further testing of the simulator, and this was therefore chosen as the position for the trays during the experiments. Unfortunately, no other areas were identified as having similar and consistent rainfall intensity, and so it was decided to test one tray at a time during the experiments, always in location 1-2-6-7 to ensure that all treatments were exposed to the same rainfall intensity. At trolley height (i.e. 1.6 m below the nozzle), the average rainfall intensity in the chosen location was consistently 28 mm hour^{-1}.

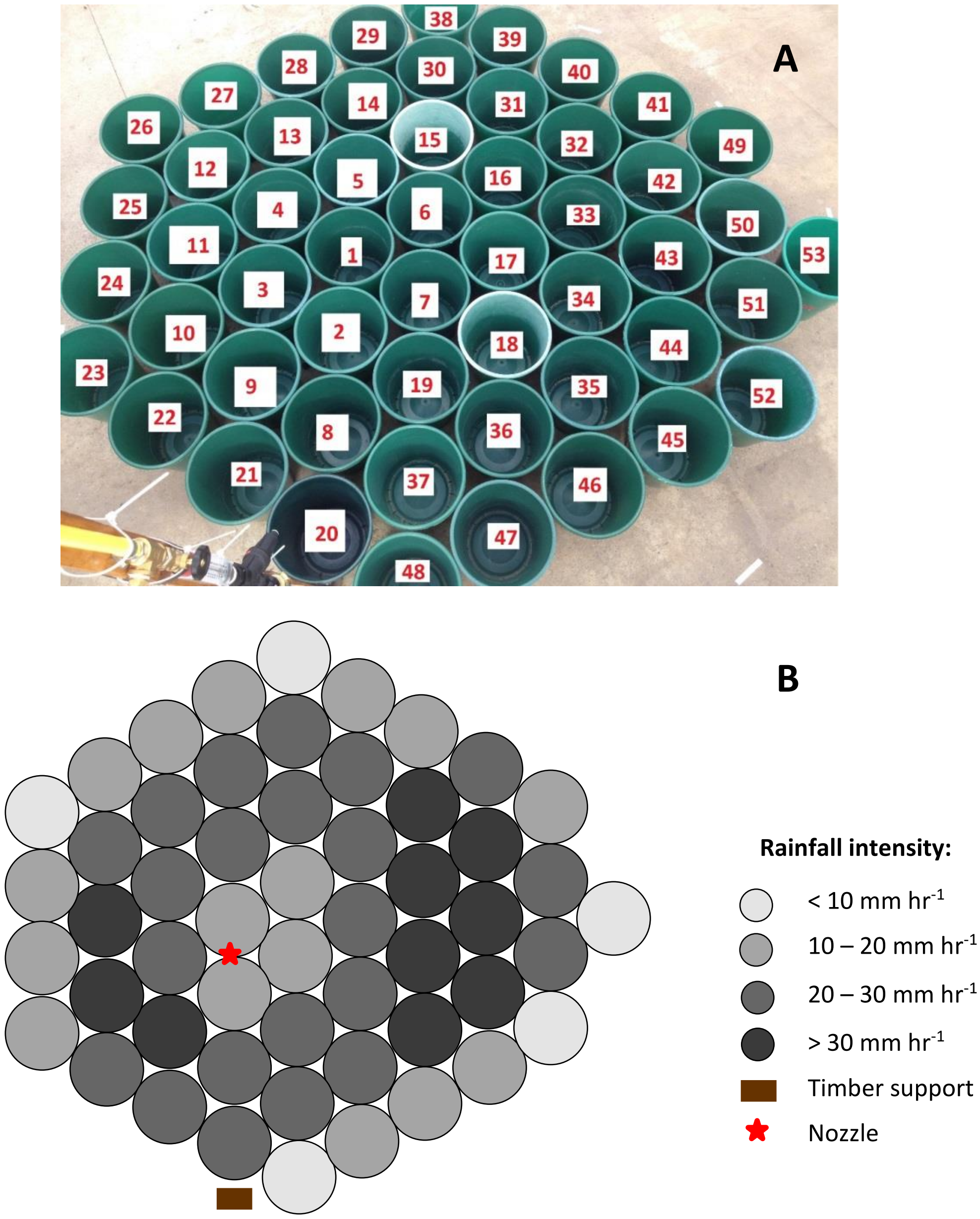


Figure 2.5: Setup of buckets (A) for the spatial rainfall distribution tests of the sprinkler simulator used in Experiment 3, and the 'mapped' rainfall intensities at ground level (B).

To further characterise the simulated rainfall, average raindrop size was measured using the flour pellet method described by Clarke and Walsh (2007). Flour was sieved into a tray to a depth of approximately 2 cm and lightly compressed, and the tray was then placed under the rainfall simulator at the selected height and position, and exposed to the rainfall for 5 seconds. After drying in the oven at 70°C for 24 hours, the raindrops formed pellets in the flour which were photographed. The diameters of all raindrops in three representative 4 x 4 cm areas were then measured using Image J software (National Institutes of Health, USA). Raindrop sizes ranged from 0.21 to 2.76 mm with the majority of droplets (70%) smaller than 1 mm diameter, similar to the simulated raindrops produced in other studies (e.g. Fister *et al.*, 2012; Iserloh *et al.*, 2012).

The time taken for runoff to be generated from trays with bare substrate was tested with the chosen settings, and found to vary between 2 and 8 minutes, depending on initial SMC. To ensure that adequate runoff was always generated from all planted treatments and all SMC conditions, it was therefore decided to simulate rainfall for 20 minutes for each tray. Since rainfall could only be applied to one tray at a time, this required rainfall duration meant that only 12 trays could be tested in a day. Each experimental run was therefore conducted over three consecutive days, testing 2 replicates from each treatment each day so that results were not affected by any differences in environmental conditions between days.

The actual volume of water applied on each day of each run of the experiment (as described in Section 2.6) was measured three times per day (beginning, middle and end of the experiment) by placing an empty tray of the same dimensions in position under simulated rainfall for 20 minutes (data not shown). The average volume of rainfall captured in the tray was similar in the 'saturated' and 'unsaturated' runs ($P = 0.154$; LSD = 148.1), although there were significant differences between experimental days in both runs ($P = 0.017$, LSD = 84.5 for the 'saturated' run and $P = <0.001$, LSD = 121.7 for the 'unsaturated' run). However, as two replicates per treatment were tested each day and there was very little variation in the volume of rainfall captured within each experimental day (data not shown), any differences in rainfall volume should average out for all treatments.

2.6.5 Rainfall application procedure (Experiments 1 – 3)

In each experiment there were five treatments: the four plant species and a control treatment of bare, unvegetated substrate. In addition, every time one replicate of each of the five treatments was tested, an empty tray was also placed under the rainfall to measure the volume of water simulated. All containers/trays were watered daily prior to the start of the experiments, and dead leaves were removed from all plants the day before each experiment started. In all runs, in all experiments, one container/tray was placed under each of the rainfall simulators at a time (Figure 2.2 - Figure 2.4); rainfall was therefore applied to six containers simultaneously in Experiment 1, three trays simultaneously in Experiment 2, and one tray at a time in Experiment 3. To account for differences that might be caused by any changes in environmental conditions throughout the experiments, one container or tray from each treatment were always tested simultaneously in Experiment 1 or alternately in Experiments 2 and 3.

In all experiments, containers or trays were weighed, antecedent SMC was measured and plant/canopy height and diameter were measured at the start of each run. To collect runoff from each treatment in Experiments 2 and 3, trays were placed inside a second tray of the same dimensions, thus ensuring that no rainfall fell directly into the second tray and so only runoff was captured. Wooden supports were used to raise the treatment trays so that there was space for runoff to collect in the second tray. In Experiment 1, a distinction was made between runoff – i.e. water that passed through the container and leached out again – and 'water lost due to dripping' from the canopy – i.e. rainfall that bounced or dripped from the canopy or substrate surface onto surrounding surfaces and therefore did not enter the plant/substrate system. Runoff was collected by placing each container inside a plastic bag (resealable food and freezer bags: 260 x 300 mm) and securing with an elastic band. The containers were then stood in trays (38.5 x 28.6 cm) to collect any 'water lost due to dripping' from the canopy. Since the rainfall simulators used in Experiment 1 did not cover an area larger than the containers, no rainfall fell directly into these trays.

After the pre-determined rainfall duration (10 minutes in Experiments 1 and 2 and 20 minutes in Experiment 3), containers were left to drain until runoff stopped; this took approximately 10, 20 and 30 minutes in Experiments 1, 2 and 3 respectively. Volumes of water captured in the runoff trays (or bag in Experiment 1, plus the 'water lost due to dripping' in the tray) were then measured using measuring cylinders. Each container or tray was weighed again, and SMC measurements were made as before.

At the end of each experiment, plants were harvested for leaf area and biomass measurement, as described in Section 2.5.3. In Experiment 1, four plants of each species were harvested after the 'unsaturated' run, and the remaining four plants per species were harvested after the 'saturated' run. In Experiment 2, four replicates of each species were harvested at the end of the experiment, after all runs had been completed, and in Experiment 3 representative sections of all trays were harvested at the end of the experiment.

2.6.6 Experiment 4 setup: Plant-environment interactions in restoration of substrate retention capacity

Individual plants in 2 L containers filled to a depth of 11 cm with MRM, as well as control containers with 11 cm of bare, unvegetated substrate were used in Experiment 4. Two year-old *Heuchera* plants were transplanted into the MRM at the beginning of February 2015. *Salvia*, *Stachys* and *Sedum* plants were already planted in 2 L containers in MRM prior to the start of the experiment, having been transplanted the previous year. There were six replicates of each treatment, and plants of similar size and health with maximum substrate coverage were selected.

Three containers of each treatment were transferred into each CE growth cabinet (see Section 2.1) at the start of each experimental trial, apart from trial 4 where only two replicates per treatment were tested at once due to the use of a dehumidifier (which was required to bring RH into the required range) limiting the space inside the cabinet. Environmental conditions and details of all the individual trials are described fully in Section 4.2.1. Containers were randomly arranged within the cabinet and measurements were made for 4 or 5 days, depending on environmental conditions and SMC.

Experiment 4

Treatments: 6 replicates of *Heuchera*, *Salvia*, *Stachys*, *Sedum* and control (bare substrate).

Measurements: SMC; plant height and diameter; leaf area; root and shoot dry weights; ET.

2.7 Setup of Experiments 5 and 6: Greywater for irrigation

Plants of each species were transplanted into 2 L containers filled with 11 cm of substrate (MRM in Experiment 5 or VC mix in Experiment 6) 3 – 4 weeks before each experiment started. In Experiment 5 there were 16 plants of each species plus 16 control containers of bare, unvegetated MRM; in Experiment 6 there were 22 containers for each treatment, including containers with unvegetated VC mix. *Salvia* and *Stachys* were propagated from cuttings in February 2014 and January 2015 for Experiments 5 and 6 respectively and *Sedum* plants were cut back during the winter so that they were actively growing during the experiments. Two year-old *Heuchera* plants were split before transplanting so that they were of comparable size to plants of the other species. In both experiments, four additional plants of each species were also prepared at the same time, to be harvested at the start of each experiment for baseline values.

In both experiments, all species/controls were divided into two irrigation treatments: tap water (TW) and greywater (GW). There were therefore 8 TW replicates and 8 GW replicates of each species/control in Experiment 5, and 11 TW and 11 GW replicates of each species/control in Experiment 6. In both experiments, containers were placed inside the glasshouse with TW and GW treatments of each species positioned together to ensure they were exposed to the same environmental conditions (e.g. shading) so that any differences between treatments at the end of the experiment could be attributed solely to differences in the irrigation they received.

In Experiment 6, at the end of 6 weeks, the treatments were further divided into two groups for different experimental testing: five containers of each treatment (i.e. 5 TW replicates and 5 GW replicates of each species/control; hereafter referred to as 'runoff quality' containers) were used to test the ability of plants to improve runoff quality; the remaining 6 TW and 6 GW replicates of each species/control (hereafter referred to as 'ET assessment' containers) were used to quantify ET.

Experiment 5

Treatments: *Heuchera*, *Salvia*, *Stachys*, *Sedum* and control (bare substrate: MRM) – 8 replicates with TW irrigation and 8 replicates with GW irrigation.

Irrigation regime: Irrigation volumes were always identical for all containers in all treatments.

Measurements: SMC; substrate and runoff EC; plant growth (height and diameter); plant health; g_s; canopy temperature; leaf area; root and shoot dry weights; nutrient concentrations in roots, shoots, substrate and runoff.

Experiment 6

Treatments: *Heuchera*, *Salvia*, *Stachys*, *Sedum* and control (bare substrate: VC mix) – 11 replicates with TW irrigation and 11 replicates with GW irrigation.

Irrigation regime: Irrigation volumes were based on average water use per species, and differed between species/control; TW/GW volumes were always identical within species.

Measurements: SMC; substrate and runoff EC; plant growth (height and diameter); plant health; g_s; canopy temperature; ET; leaf area; root and shoot dry weights; nutrient concentrations in roots, shoots, substrate and runoff.

2.7.1 Synthetic greywater

A synthetic greywater was used for the GW irrigation treatment in both experiments so that the chemical and physical properties of the GW were pre-determined to an industry standard recipe. This ensured that the composition and properties of the greywater were consistent throughout the experiment and that the results obtained were replicable. The GW prepared for these experiments followed the recipe formulated by Diaper *et al.* (2008) (Table 2.4) to represent GW from the bathroom and laundry.

Table 2.4: Components of the synthetic greywater mixed for Experiments 5 and 6, based on the recipe formulated by Diaper *et al.* (2008); ingredient amounts per 100 L are as stated by Diaper *et al*. (2008).

Ingredient	Product Used	Amount of product (g)		
		per 100 L	per 21 L (Expt. 5)	per 25 L (Expt. 6)
Moisturiser	'Simple rich moisturiser'	1.00	0.21	0.25
Toothpaste	'Colgate Advanced White'	3.25	0.68	0.81
Deodorant	'Sure (Women) Crystal Invisible'	1.00	0.21	0.25
Vegetable Oil	'Co-Op' Sunflower Oil	0.70	0.15	0.18
Hand Wash	'Imperial Leather'	72.00	15.12	18.00
Laundry	'Ariel Actilift'	15.00	3.15	3.75
Na_2SO_4	BDH Chemicals Ltd (Poole, UK)	3.50	0.74	0.88
$NaHCO_3$	BDH Chemicals Ltd (Poole, UK)	2.50	0.53	0.63
Na_2PO_4	BDH Chemicals Ltd (Poole, UK)	3.90	0.82	0.98
Boric Acid	May and Baker Ltd. (Dagenham, UK)	0.14	0.03	0.07*

*** Boric acid concentration was doubled in Experiment 6 (compared to the Diaper *et al*. (2008) formulation) due to difficulty detecting boron in Experiment 5.**

GW was mixed up in batches (typically 21 L in Experiment 5 and 25 L in Experiment 6), which were used for irrigation for a maximum of one week and stored below 4°C between uses. All ingredients were measured out into a small beaker using a precision balance and topped up to 150 mL with mains tap water. This was then mixed at 50°C for 10 minutes with a magnetic stirrer hotplate (Fisher Scientific UK Ltd., Loughborough, UK), after which the mixture was transferred to a large beaker, topped up to 1500 mL with tap water and stirred for a further 20 minutes. The mixture was then poured into a 25 L plastic bucket and diluted with tap water up to 21 or 25 L whilst vigorously mixing manually. Tap water and the mixed GW were both sampled for chemical analysis each time a new GW batch was mixed and their pH and electrical conductivity (EC) were measured using a pH meter (Hanna Instruments, Leighton Buzzard, UK) and the WET sensor respectively.

2.7.2 Irrigation regimes

Irrigation volumes and timings for both experiments were determined based on the results of the substrate moisture tests described% in Section 2.4.1. The aim was to maintain SMC within the 'well-watered' range (determined to be > 0.250 m^3 m^{-3}) to prevent plant function becoming compromised due to water stress, whilst also preventing any runoff being generated. This strategy was chosen to ensure that none of the GW chemicals leached from any of the containers so that total nutrient inputs could be accurately determined and there could be fair comparison between treatments.

Different approaches to achieving this aim were employed in Experiments 5 and 6: in Experiment 5, the same volume of water (TW or GW) was used for irrigation of all treatments so that every container received an identical quantity of nutrients. However, due to differences in ET rates between species (and the bare substrate), this approach proved difficult in keeping SMC high in some treatments whilst also preventing runoff generation from others. Therefore, in Experiment 6 a different approach was used, in which irrigation volumes differed for each species/control based on their water use, but were kept identical within species/control. With this strategy, it was possible to keep SMC within the 'well-watered' range for all treatments without producing runoff from any containers. Although this meant that species received different quantities of nutrients over the course of the experiment, this was considered to be a satisfactory solution, since comparison between species was not the primary objective of Experiment 6. In both experiments, identical volumes of TW and GW were always used within the same plant treatment, and water was applied directly to the substrate to avoid any potential damage to the plants through direct contact of greywater on the foliage (Misra *et al.*, 2010).

At the start of Experiment 5, the SMC of all treatments was in the region of 0.300 m^3 m^{-3} (data not shown), which is considered high for the MRM (as determined from substrate moisture tests in Section 2.3.1). Based on this high SMC and the average daily plant water use identified in preliminary tests (Section 2.4.1), each container was initially irrigated with 80 mL of TW or GW approximately every two days. As a result of warming weather and the decision to employ regulated deficit irrigation to avoid generation of runoff from any of the containers, SMC gradually decreased over the first 3 weeks of the experiment. Irrigation volumes were therefore increased to 100 mL approximately 5 times per week to reduce drought stress to plants whilst also continuing to prevent runoff generation, allowing SMC to stabilise in the range 0.100 – 0.200 m^3 m^{-3}. There were, however, increasing differences in SMCs between treatments, due to irrigating with fixed volumes which did not take into account the varying ET rates of each species. Control containers, which contained MRM and no vegetation, generally maintained higher SMC in the range 0.200 – 0.250 m^3 m^{-3}. All containers received the same volume of TW or GW for irrigation over the course of the experiment.

At the start of Experiment 6, the SMCs of all containers were within the 'well-watered' range identified in substrate moisture tests (Section 2.4.1), and irrigation volumes were initially set at 150 mL of TW or GW per container 5 times per week. Over the first 10 days of the experiment, the SMC of planted treatments gradually declined, at varying rates depending on their ET rates, whilst control SMC remained above 0.400 m^3 m^{-3}. Irrigation volumes were therefore adjusted to reflect this, with *Salvia*, *Stachys* and *Sedum* receiving higher volumes than *Heuchera* and control for approximately 3 weeks. In the final week of the experiment, *Heuchera* irrigation volumes were increased and matched those of *Salvia*, *Stachys* and *Sedum*, whilst control still received lower volumes. All planted treatments generally maintained SMC above 0.200 m^3 m^{-3} and control containers maintained SMC above 0.300 m^3 m^{-3} for the majority of the experiment (see Chapter 6).

2.7.3 Total nutrient inputs to containers during experiments

Over the 8 weeks of Experiment 5, all containers were irrigated with a total volume of 3180 mL of either TW or GW. This equated to an average nutrient input of 0.3 or 16.5 mg of phosphorus and 0.13 or 1.53 mg of boron per container with TW or GW irrigation respectively. During the 6 weeks of Experiment 6, control containers each received a total of 3070 mL of TW or GW, *Heuchera* containers received 4520 mL each, and *Salvia*, *Stachys* and *Sedum* containers all received 5450 mL of either TW or GW. The average nutrient inputs per container in Experiment 6 are presented in Table 2.5.

Table 2.5: Average nutrient input total per container during the 6 weeks of Experiment 6. Phosphorus and boron values for tap water treatments are estimated maximums as nutrient concentrations were reported as 'less than' values by NRM.

Treatment		**Average total received per container (mg)**		
		Phosphorus	**Boron**	**Sodium**
Tap water	*Heuchera*	0.9	0.09	73.7
	Salvia	1.1	0.11	88.8
	Stachys	1.1	0.11	88.8
	Sedum	1.1	0.11	88.8
	Control	0.6	0.06	50.0
Greywater	*Heuchera*	22.1	3.39	484.1
	Salvia	26.7	4.09	583.7
	Stachys	26.7	4.09	583.7
	Sedum	26.7	4.09	583.7
	Control	15.0	2.30	328.8

2.7.4 Chemical analyses

Chemical analysis was carried out on harvested roots, shoots, substrate and runoff in Experiments 5 and 6. Dried root and shoot samples were prepared for chemical analysis by adding liquid nitrogen and grinding into a fine powder with a pestle and mortar. All samples were analysed for boron (B) and phosphorus (P) content, plus sodium (Na) in Experiment 6, at NRM Laboratories (Bracknell, UK); procedures followed to determine P, B and Na concentrations (as specified by NRM) were as follows.

Samples of MRM from Experiment 5 were dried and sieved to 2 mm; available phosphorus was extracted using a 0.5 M sodium bicarbonate solution, the blue colour of which was measured spectrophotometrically to determine the concentration of available P, whilst the concentration of hot water extractable boron was determined by Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP-OES). A full suite of analysis was carried out on the VC mix samples from Experiment 6, including measurement of P, B, Na, calcium (Ca) and magnesium (Mg) concentrations. Nutrients were extracted by adding a weight of sample equivalent to a volume of 60 mL (determined by substrate bulk density) to 300 mL of deionised water; this was shaken for 1 hour at 250 rpm at 22°C, and then all nutrient concentrations were determined by ICP-OES.

Root and shoot samples were ashed at 550°C to destroy all organic matter then dissolved in hydrochloric acid, and water samples were digested in nitric acid; the concentrations of B, P and Na were then analysed by ICP-OES in all plant and water samples.

2.8 Statistical analysis

All statistical analysis was carried out using GenStat 16th edition software (VSN International Ltd., Hemel Hempstead, UK). Analysis of variance (ANOVA) was used in all experiments to assess the effects of various treatments on different parameters. Normality assumptions and variance levels were checked for homogeneity and data were transformed where necessary; square or square root transformations were chosen for each dataset as appropriate, as described in relevant chapters, so that the distribution of the transformed data residuals was normal. Variables are reported as a mean for each treatment with associated Least Significant Difference (LSD), which was used to assess significant differences between treatments at 5% significance level. In the case of unbalanced ANOVAs, the maximum LSD (at 5% significance) was reported.

2.8.1 Analysis of stormwater management data

In Experiments 1 – 3, the volume of water captured on the plant/substrate ‘complex’ was assumed to be equal to the weight gain of each container/tray after rainfall had been applied. For each application of rainfall in Experiments 1 – 3, ANOVA was used to assess the effect of different plant species on the volume of rainfall captured on the plant/substrate ‘complex’, the volume of runoff, and, in Experiment 1, the volume of ‘water lost due to dripping’. Linear regressions combining all species were also carried out for each experimental run to test the relationship between antecedent SMC, ET prior to rainfall application, plant height, plant diameter, leaf area, leaf area density, canopy volume, shoot and root dry weights and fresh root volume with the volume of water retained on the plant/substrate ‘complex’ or the volume of runoff.

In Experiments 1 – 4, ANOVA was used to assess significant differences between species in water uptake from the substrate following a rainfall event or saturation (i.e. ET rates). In Experiment 4, ANOVA was also used to assess the effect of the varying environmental conditions on the ET rates of each species. Additionally, linear regressions were carried out on data from Experiment 4 to assess the significance of any relationships between the uptake of water from the substrate and environmental conditions (antecedent SMC, air temperature, RH, vapour pressure deficit), combining data from all experimental trials for each individual species/control.

2.8.2 Analysis of greywater data

In Experiments 5 and 6, ANOVA was used to assess any differences in plant growth, substrate EC, canopy temperature and stomatal conductance between TW and GW treatments for each species/control. In addition, in Experiment 6 the effect of irrigation treatment on the measured ET was also assessed. For all parameters, differences between TW and GW treatments were assessed at each measurement point over the course of each experiment, except canopy temperature in Experiment 5 which was only measured at the end of the experiment. ANOVA was also used to test for significant differences between the TW and GW treatments in the concentrations of B, P and Na measured in the substrate, roots, shoots and runoff of each treatment in both experiments. Additionally, significant differences between the species/control in terms of B, P and Na concentrations in roots, shoots, substrate and runoff were assessed.

Chapter 3

The effect of vegetation type on green roofs' capacity to provide stormwater management

3.1 Introduction

Surface flooding in urban areas is likely to become more common due to further increases in urbanisation (i.e. replacement of natural materials and vegetation with impervious surfaces) and a likely increase in the frequency of intense precipitation events in the UK predicted by climate change models (IPCC, 2013). Urban vegetation, including green roofs, can help to mitigate the flood risk by delaying, prolonging and reducing the volume of runoff compared to conventional urban roofs and surfaces. The main mechanisms through which vegetation on green roofs provide stormwater management are: direct interception on vegetation surfaces during rainfall; infiltration and storage of water in the substrate; and subsequent evapotranspiration (ET) from the green roof during dry periods (Stovin *et al.*, 2012). The retention performance of green roofs depends on the characteristics of rainfall events (intensity, depth, duration) and climate (Voyde *et al.*, 2010a), as well as properties of the roof itself (e.g. slope; Getter *et al.*, 2007) and the substrate and vegetation types (Beecham and Razzaghmanesh, 2015; Brandão *et al.*, 2017).

The substrate has frequently been acknowledged as the most important store of water (VanWoert *et al.*, 2005), and retention of rainfall by a green roof has therefore been shown to depend on substrate characteristics, such as the type, depth and age of substrate (Mentens *et al.*, 2006; Getter *et al.*, 2007), and its properties including water-holding capacity, porosity and antecedent substrate moisture content (SMC) (Volder and Dvorak, 2014; Stovin *et al.*, 2015). Based on these factors, the substrate is able to retain a finite maximum volume of water during a rainfall event (defined as the substrate's retention capacity), after which any further water added will become runoff (Sims *et al.*, 2016).

The presence of vegetation is known to significantly increase the retention performance of a green roof compared to bare substrate alone (Voyde *et al.*, 2010a). Furthermore, significant differences in retention have been identified with different plant types (Nagase and Dunnett, 2012; Whittinghill *et al.*, 2015), resulting from differences in both canopy capture and restoration of substrate retention capacity through ET. Direct interception of rainfall on the vegetation canopy has been shown to provide up to an additional 4% retention, depending on species

(MacIvor and Lundholm, 2011), with characteristics such as canopy structure, size and density, leaf morphology and root structure thought to influence interception capacity (Nagase and Dunnett, 2012). Species tested to date primarily include succulent species, grasses and forbs (Lundholm *et al.*, 2010; Nagase and Dunnett, 2012). There is little information available regarding the ability of larger plants with different canopy structures, such as broadleaf species, to provide stormwater management on a green roof.

The contribution of interception to long-term retention performance is, however, generally considered minor compared to the role of the vegetation in restoring substrate retention capacity through ET (Stovin *et al.*, 2015). Species with high ET rates are able to restore the substrate retention capacity faster, thus allowing greater storage of water in the substrate during subsequent rainfall events (Stovin *et al.*, 2013). Green roof planting choices have typically been based on survival without irrigation and hence species that are able to withstand substrate moisture deficits (i.e. succulents such as *Sedum*) are frequently used; likewise, the majority of green roof rainfall retention studies use succulent species. However, these species have inherently low ET rates, thus restricting the restoration of substrate retention capacity, and have typically been found to provide lower overall retention than other species (Dunnett *et al.*, 2008; Whittinghill *et al.*, 2015). As very few studies have tested non-succulent species (primarily grasses and forbs; Dunnett *et al.*, 2008; Lundholm *et al.*, 2010), the ability of species with higher ET rates to provide stormwater management has not yet been fully investigated.

3.1.1 Study aims

It is clear that vegetation characteristics, such as canopy, leaf and root characteristics as well as ET rate, can influence the retention performance of a green roof, and species choice will therefore impact the stormwater management provision by the green roof. However, the majority of studies continue to test only succulent species, despite the fact that the low ET rates of these species are known to limit their retention ability. Furthermore, only a limited range of plant types have been investigated to date, with little variation in canopy characteristics or ET rates. The experiments described in this chapter therefore adopted a more theoretical framework to investigate the maximum potential of plants to provide stormwater management and the mechanisms through which it is provided, using broadleaf species with high ET rates and larger, more complex canopy structures with varying leaf traits (e.g. presence of leaf hairs). The objectives of this chapter were therefore:

- To identify the contribution of the vegetation itself to rainfall retention in addition to the retention provided by the substrate;
- To investigate the impact of species selection on the retention performance of a green roof, by comparing traditionally used *Sedum* to alternative, significantly more physiologically active, broadleaf species;
- To investigate how varying canopy and leaf morphologies, root system sizes and ET rates influence retention performance through canopy interception and restoration of substrate retention capacity.

3.2 Materials and Methods

Three glasshouse experiments were carried out using simulated rainfall to quantify the volume of water that could be retained by plants with differing canopy characteristics and to examine the role of plants in restoring a substrate's retention capacity following a rainfall event. The basic setup of all experiments is described in Section 2.6. However, although every effort was made to ensure that rainfall was applied consistently to all treatments in all simulated rainfall events, there was considerable variation in the depth of rainfall applied in each simulated rainfall event and during each experimental run in Experiment 2. This resulted in relatively large variability of results, even within treatments, with low statistical significance. The general trends observed were very similar to the results of Experiment 3, however, in which rainfall application was consistent and more representative of natural rainfall. Therefore, Experiments 1 and 3 only are presented in this chapter, being representative of individual plants and small canopies respectively.

A summary of the setup and details of Experiments 1 and 3 is presented in Table 3.1, and timelines of simulated rainfall applications in both experiments are given in Figure 3.1 and Figure 3.2. Full details of the plant materials and substrates used are described in Sections 2.3 and 2.4.

Rainfall was simulated to ensure consistency in the rainfall depth and intensity applied to each treatment within each experiment; full details of the rainfall simulators used in each experiment can be found in Section 2.6.4. The average characteristics of the simulated rainfall events in each run of Experiments 1 and 3 are presented in Table 3.2. The experimental procedure and all measurements made in the experiments are described in Sections 2.6.5 and 2.5 respectively.

Table 3.1: Summary of Experiments 1 and 3.

	Experiment 1	Experiment 3
Dates	24th March – 13th April 2014	12th – 19th April 2016
Set-up	Individual plants in 2 L containers with 11 cm of Meadow Roof Medium	Small canopies in 40 x 60 cm trays with 15 cm of peat-based compost
Treatments	8x *Heuchera*, *Salvia*, *Stachys*, *Sedum*, control	6x *Heuchera*, *Salvia*, *Stachys*, *Sedum*, control
Rainfall simulator	Drip-system	Sprinkler
Measurements	SMC; plant height and diameter; leaf area; ET; volume of rainfall captured on the canopy; volume of runoff; volume of 'water lost due to dripping'	SMC; canopy height and diameter; leaf area; ET; fresh root volume; root and shoot dry weights; volume of rainfall captured on the canopy; volume of runoff

Table 3.2: Average characteristics of simulated rainfall events in each experimental run in Experiments 1 and 3.

Experimental run	Average characteristics of simulated rainfall events		
	Amount (mm)	**Duration (minutes)**	**Intensity (mm hr^{-1})**
Experiment 1			
'Dry' *	26.5	10	159.2
'Saturated' ^	28.8	10	172.6
'Unsaturated' #	28.8	10	172.9
Experiment 3			
'Saturated' ^	9.3	20	27.9
'Unsaturated' #	8.9	20	26.6

*** 'Dry' run was conducted when substrate moisture content fell below 0.150 m^3 m^{-3} for all containers (i.e. substrate would be considered 'dry'; see Section 2.4.1).**

^ In 'saturated' runs, substrate was pre-wetted to field capacity before rainfall application.

 # In 'unsaturated' runs, rainfall was applied after a 72-hour antecedent dry period, with different plant treatments consequently having different SMCs due to differing ET rates.

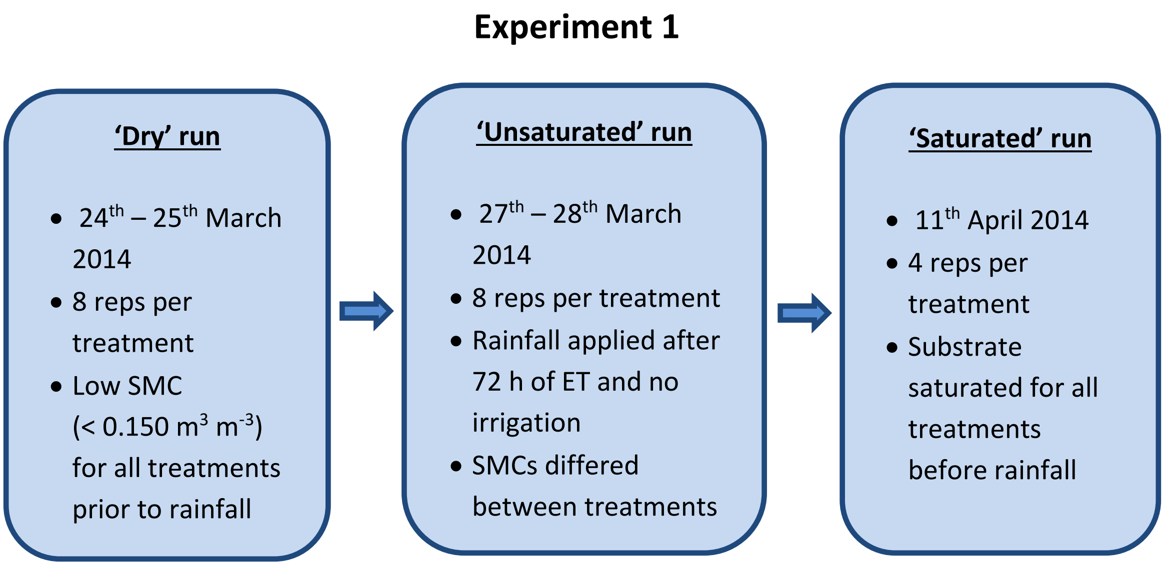


Figure 3.1: Timeline of simulated rainfall events in Experiment 1.

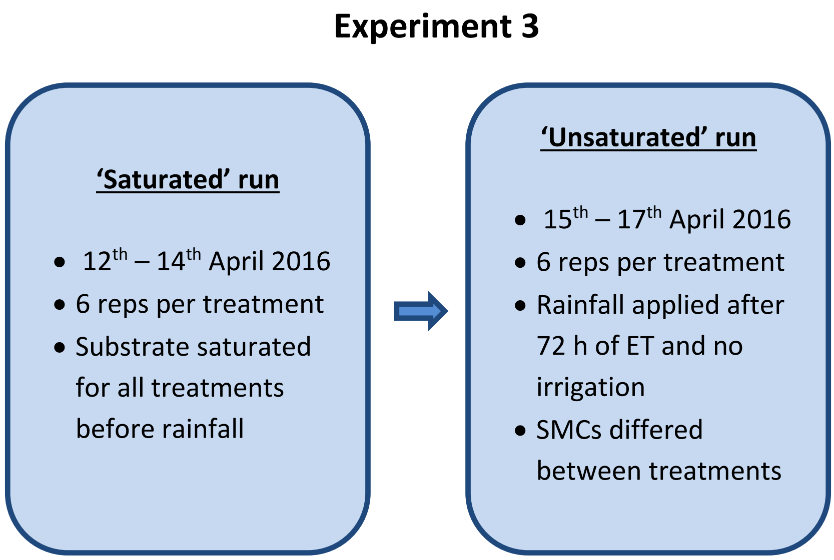


Figure 3.2: Timeline of simulated rainfall events in Experiment 3.

3.2.1 Retention on the canopy

To quantify the volume of water directly captured on the canopy, the substrate of all treatments was saturated to container capacity prior to rainfall application in Experiments 1 and 3, so that no further storage was available in the substrate and antecedent SMC was high. Rainfall was then applied in these 'saturated' conditions in both experiments.

To saturate the substrate, all containers/trays were submerged in water for 10 or 30 minutes in Experiments 1 and 3 respectively. Containers/trays were then allowed to drain to field capacity (i.e. until dripping stopped) for a further 10 – 15 minutes in Experiment 1 and two hours in Experiment 3. Simulated rainfall was then applied to each container/tray in the manner described in Section 2.6.5, for the pre-determined duration, as stated in Table 3.2.

In both experiments, antecedent SMC was measured before rainfall application, with two measurements per container in Experiment 1 and five measurements per tray in Experiment 3. Containers/trays were also weighed before and after rainfall, and the volume of water captured on the canopy was taken to be the weight gain of each container/tray after rainfall application. The volume of runoff from each container/tray was also measured, and in Experiment 1 the volume of 'water lost due to dripping' from the canopy was also measured, as described in Section 2.6.5.

3.2.2 Retention on the whole canopy/substrate 'complex'

To quantify the volume of water that could be retained on the whole canopy/substrate 'complex', in both experiments simulated rainfall was applied to all treatments following an antecedent dry period of 72 hours, during which no further irrigation was received. The retention capacity of each treatment's substrate was therefore restored at a natural rate during this time, dependent on the ET rate of each species, resulting in differing antecedent SMCs for each treatment at the onset of rainfall. Applications of rainfall in these conditions are hereafter referred to as 'unsaturated' runs. The volume of water retained on the canopy/substrate 'complex' was determined as the weight gain of the container/tray after rainfall. Runoff from each container/tray was also measured in both experiments, and 'water lost due to dripping' from the canopy was measured in Experiment 1.

Additionally, in Experiment 1 rainfall was applied to all treatments in 'dry' conditions – i.e. SMC < 0.150 m^3 m^{-3}, which was identified as low SMC for the Meadow Roof Medium substrate based on preliminary moisture tests (see Section 2.4.1), as well as being the SMC at which significant reduction in leaf stomatal conductance would occur for the plant species used (Vaz Monteiro *et al.*, 2016a; 2017). To accomplish this, daily irrigation of all treatments was stopped a week before the start of the experiment, after which the SMC of all containers was measured daily and plants were irrigated with small volumes of water as required to maintain plant health without increasing SMC above 0.150 m^3 m^{-3}. Simulated rainfall was applied as described in Section 2.6.5 once the SMC of all treatments was below 0.150 m^3 m^{-3}.

3.2.3 Restoration of substrate retention capacity

The rate of restoration of the substrate retention capacity following rainfall or saturation is dependent on the ET rate. To quantify this, daily ET from each container/tray was measured for up to 72 hours following rainfall in all experimental runs of Experiments 1 and 3. During this time, containers/trays remained in the glasshouse but received no irrigation. SMC was measured and all containers/trays were weighed every 24 hours.

3.2.4 Data analysis

The volume of water retained on the canopy or canopy/substrate 'complex', the volume of runoff and the volume of 'water lost due to dripping' from the canopy were all converted to depths (mm) by dividing by plot area (Eq. 1.1; Section 1.3.5), and expressed as a proportion of the total rainfall applied to each container/tray (%). As all applied rainfall was accounted for in Experiment 1, the total rainfall applied to each container was calculated as the sum of the water captured on the canopy (or canopy/substrate 'complex'), as runoff and as 'water lost due to dripping'. In Experiment 3, the total rainfall applied to each tray was calculated based on the average volume of water collected in empty trays on each day of the experiment, which was then scaled to reflect the surface area of each individual canopy to determine the volume of rainfall that fell onto each specific canopy. To account for the effect of different canopy sizes between species, the absolute volume of water retained on the canopy in 'saturated' conditions in each experiment was expressed relative to canopy leaf area. Daily ET in the days following rainfall was calculated as the weight loss from each tray/container in each 24-hour period, which was then converted to depth (mm). All measurements of daily ET were also expressed relative to total canopy leaf area.

Statistical analyses were performed as described in Section 2.8. All data relating to 'water lost due to dripping' from the canopy in all runs of Experiment 1 were normalised using square root transformations prior to analysis. Additionally, runoff data from 'unsaturated' conditions in Experiment 1 were normalised using a square transformation. All other data satisfied normality assumptions and did not require transformations before analysis.

3.3 Results

3.3.1 Experimental setup

Antecedent SMC for each treatment prior to the application of rainfall in ‘dry’, ‘saturated’ and ‘unsaturated’ conditions in Experiments 1 and 3 are presented in Table 3.3. The differences in SMC values between Experiments 1 and 3 are a result of the different substrates used in each experiment (Meadow Roof Medium in Experiment 1 and peat-based compost in Experiment 3).

Table 3.3: Mean antecedent SMC of all treatments prior to rainfall application in ‘dry’, ‘saturated’ and ‘unsaturated’ conditions in Experiments 1 and 3.

Treatment	**Mean antecedent SMC (m^3 m^{-3})**				
	Expt. 1 (Meadow Roof Medium)			**Expt. 3 (peat-based compost)**	
	'Dry' *	**'Saturated' ^**	**'Unsaturated' #**	**'Saturated' ^**	**'Unsaturated' #**
Heuchera	0.139	0.256	0.093	0.579	0.516
Salvia	0.133	0.256	0.111	0.596	0.486
Stachys	0.123	0.264	0.097	0.630	0.488
Sedum	0.133	0.299	0.180	0.604	0.519
Control	0.132	0.286	0.175	0.580	0.535
LSD (d.f.)	**0.0280** (39)	**0.0231** (19)	**0.0154** (39)	**0.0271** (29)	**0.0363** (29)

*** ‘Dry’ run was conducted with SMC < 0.150 m^3 m^{-3} for all containers.**

^ In ‘saturated’ runs, substrate was pre-wetted to field capacity before rainfall application.

 # In ‘unsaturated’ runs, rainfall was applied after a 72-hour antecedent dry period.

In ‘unsaturated’ conditions in both experiments there were significant differences in SMC between treatments (Table 3.3) as a result of differing ET rates (see Figure 3.5). In Experiment 1, SMCs of all three broadleaf species (*Heuchera*, *Salvia* and *Stachys*) were significantly lower than the SMCs of *Sedum* and the unvegetated control (P < 0.001), whilst in Experiment 3, the SMCs of only *Salvia* and *Stachys* were significantly lower than the control (P = 0.045). There were also differences in SMC between treatments in ‘saturated’ conditions in both experiments, possibly due to different rooting densities between species, affecting the water-holding capacity of the substrate. However, all treatments were saturated to container capacity and SMCs were all within the 'well-watered' ranges identified for both substrates in Section 2.4.1. In 'dry' conditions in Experiment 1, the SMCs of all treatments were statistically similar.

Measured plant/canopy parameters for the plants used in Experiments 1 and 3 are presented in Table 3.4. In Experiment 1, all plants measurements were made once at the time of the 'dry' and 'unsaturated' runs and again during the 'saturated' run due to a two-week gap; plants were measured once during Experiment 3.

3.3.2 Retention on the canopy

The proportion of the total rainfall retained on the plant canopy in 'saturated' conditions varied significantly between species in both experiments (Figure 3.3 A). With individual plants in Experiment 1, *Salvia* and *Sedum* retained the most water (5.1 and 3.4% of the total rainfall respectively). The larger canopies in Experiment 3 retained a much higher proportion of the total rainfall, with *Sedum* and *Stachys* retaining the most water (17.1 and 13.1% respectively). In both experiments, *Heuchera* retained the least rainfall and was not significantly different to the bare substrate control treatment. In 'dry' conditions in Experiment 1, in which all treatments had similarly low antecedent SMC and differences in retention should therefore reflect canopy interception, observed trends were similar to Experiment 1 'saturated' conditions, with *Salvia* retaining significantly more rainfall on the canopy/substrate 'complex' than *Stachys* (46.0% compared to 36.0%; LSD = 8.31) (data not shown).

To account for differences in individual canopy sizes, the volume of water retained on the canopy in 'saturated' conditions in Experiments 1 and 3 was calculated relative to the total leaf area (Figure 3.3 B). Trends were typically the same as for retention percentage in each experiment, with significant differences between species still apparent. Additionally, regression models identified significant positive relationships between the volume of water retained on the canopy in the 'saturated' run of Experiment 3 and shoot dry weight (adjusted R^2 = 0.45; $P < 0.001$) and leaf area density (adjusted R^2 = 0.38; $P < 0.001$), whilst there was no relationship with canopy height (adjusted R^2 = 0.02; P = 0.227) (data not shown).

Table 3.4: Average plant/canopy parameters per container/tray in Experiments 1 and 3, with associated standard error of the means (SEM). For Experiment 1, data are a mean of 8 replicates per species for the 'dry' and 'unsaturated' runs (apart from leaf area which is the mean of 4 replicates) and 4 replicates per species for the 'saturated' run. For Experiment 3, data are the mean of 6 replicate trays per species.

Species	Mean (± SEM) canopy height (cm)	Mean (± SEM) canopy diameter (cm)	Mean (± SEM) leaf area (cm^2)	Mean (± SEM) shoot dry weight (g)	Mean (± SEM) fresh root volume (cm^3)
Expt. 1 - 'Dry' * & ''Unsaturated' #					
Heuchera	17.4 (± 0.8)	25.3 (± 0.8)	1031 (± 29.5)	-	-
Salvia	9.9 (± 0.4)	17.9 (± 0.6)	699 (± 21.2)	-	-
Stachys	9.5 (± 0.3)	23.5 (± 0.8)	735 (± 50.0)	-	-
Sedum	6.2 (± 0.3)	17.1 (± 0.6)	681 (± 78.4)	-	-
Expt. 1 - 'Saturated' ^					
Heuchera	16.4 (± 0.8)	31.1 (± 1.3)	1142 (± 143.3)	-	-
Salvia	12.5 (± 0.5)	24.5 (± 1.4)	1001 (± 175.1)	-	-
Stachys	13.9 (± 0.2)	24.3 (± 1.2)	797 (± 27.5)	-	-
Sedum	7.2 (± 0.4)	18.4 (± 1.0)	825 (± 101.8)	-	-
Experiment 3					
Heuchera	14.0 (± 0.2)	52.6 (± 1.1)	6943 (± 775.2)	57.1 (± 7.3)	320 (± 36.1)
Salvia	18.8 (± 0.5)	74.6 (± 1.6)	18564 (± 687.5)	125.2 (± 6.9)	603 (± 41.1)
Stachys	19.1 (± 1.0)	76.2 (± 2.4)	20760 (± 871.3)	141.9 (± 5.2)	437 (± 52.0)
Sedum	13.6 (± 0.4)	62.1 (± 0.7)	13586 (± 884.7)	111.0 (± 4.6)	203 (± 25.5)

*** 'Dry' run was conducted with SMC < 0.150 $m^3\ m^{-3}$ for all containers.**

^ In 'saturated' runs, substrate was pre-wetted to field capacity before rainfall application.

 # In 'unsaturated' runs, rainfall was applied after a 72-hour antecedent dry period.

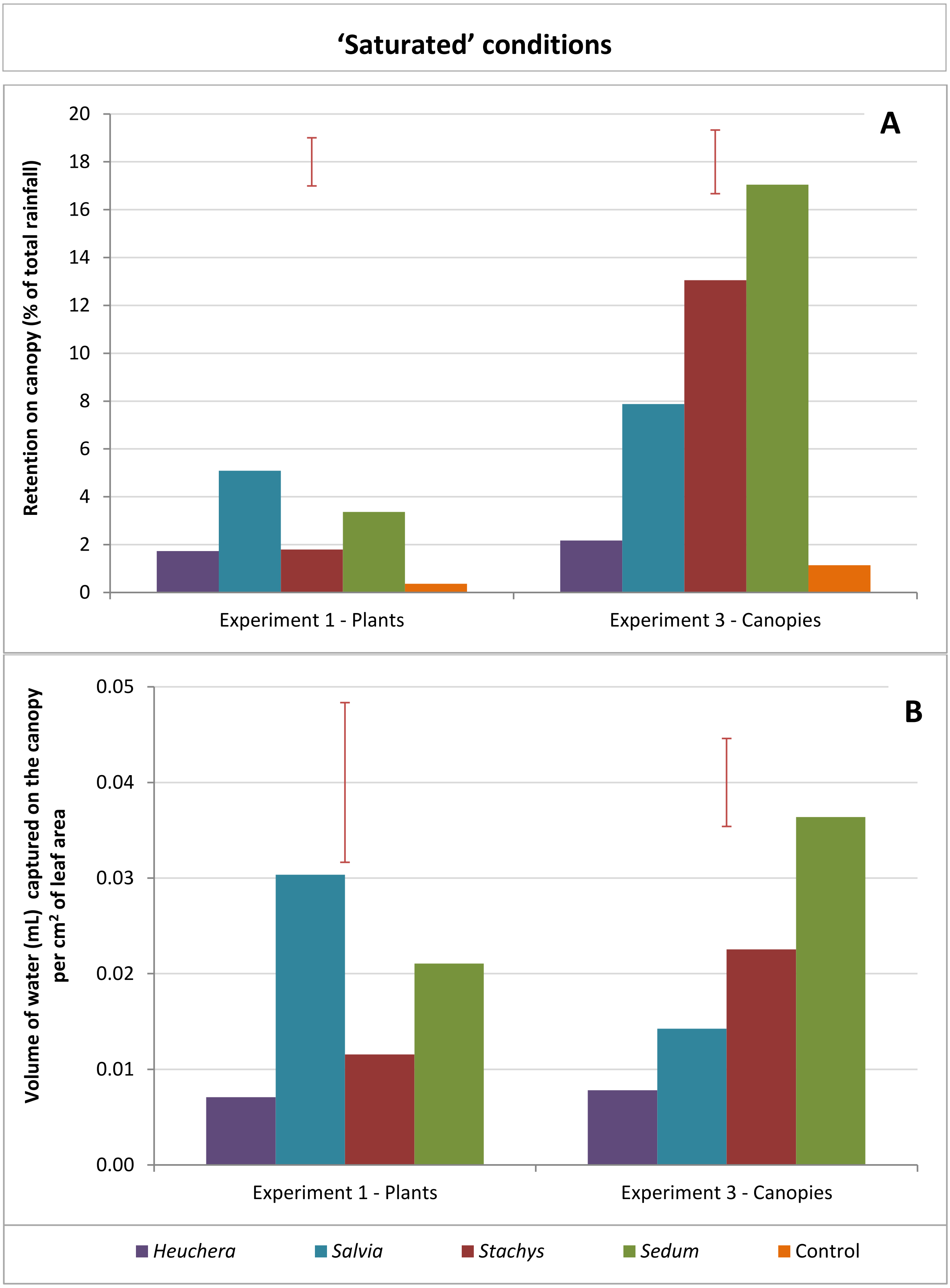


Figure 3.3: Mean rainfall retention on the canopy (A) and retention relative to leaf area (B) in 'saturated' conditions in Experiments 1 and 3. Data are means of 4 or 6 replicate containers/trays per species in Experiments 1 and 3 respectively, with associated LSDs (5%); red bars indicate statistical differences between the means of each experiment respectively.

There were also significant differences between treatments in runoff depth in 'saturated' conditions in both experiments (Table 3.5). In Experiment 1, significantly less runoff was produced with *Heuchera* than with the bare substrate control treatment (17.2 compared to 22.7 mm) whilst all other species produced similar depths (20 – 21 mm). However, in Experiment 1, 'water lost due to dripping' from the canopy of *Heuchera* accounted for over 20% of the total rainfall, which was significantly more than with *Salvia* and the control. With larger canopies in Experiment 3, significantly greater runoff was produced with *Heuchera* than with *Salvia*, *Stachys* and *Sedum* ($P < 0.001$). With the bare substrate control treatment, the entire volume of rainfall applied was lost as runoff.

Table 3.5: Mean runoff from each container/tray in 'saturated' conditions in Experiments 1 and 3 and 'water lost due to dripping' from the canopy in Experiment 1, expressed as depths and proportions of the total rainfall. Analysis of the 'water lost due to dripping' data was carried out on square root transformed data (LSD (5%) was 1.235; P = 0.208); letters indicate statistical differences between the means of each experimental run.

'Saturated' conditions ^	Experiment 1				Experiment 3	
	Runoff		'Water lost due to dripping'		Runoff	
Treatment	**Depth (mm)**	**% of rainfall**	**Depth (mm)**	**% of rainfall**	**Depth (mm)**	**% of rainfall**
Heuchera	17.2	77.7	4.7 ^{b}	20.5	8.6	92.7
Salvia	20.8	92.1	0.6 ^{a}	2.8	6.4	69.0
Stachys	20.5	91.6	1.5 ^{ab}	6.6	6.5	70.5
Sedum	20.4	89.5	1.5 ^{ab}	7.1	6.3	68.1
Control	22.7	95.9	0.8 ^{a}	3.7	9.7	100.0
LSD (d.f.)	**4.59** (19)	-	- (19)	-	**0.74** (29)	-

^ In 'saturated' runs, substrate was pre-wetted to field capacity before rainfall application.

3.3.3 Retention on the whole canopy/substrate 'complex'

In 'unsaturated' conditions (i.e. following a 72-hour antecedent dry period), there were significant differences in the proportion of total rainfall retained on the whole canopy/substrate 'complex' in both experiments (Figure 3.4). With individual plants in Experiment 1, the three broadleaf species retained significantly more water within the canopy and substrate than *Sedum* and the control ($P < 0.001$), with *Salvia* retaining almost twice as much as the control (50.7% compared to 28.6% respectively). With larger canopies in Experiment 3, differences between treatments were more pronounced, with *Salvia* and *Stachys* retaining significantly more rainfall within the canopy/substrate 'complex' than all other treatments ($P < 0.001$), and over 3 times more than the control. Retention with *Stachys* was also 2.5 times greater than with *Heuchera*, which retained a relatively small proportion of the rainfall (28.5%), similar to the control (20.5%).

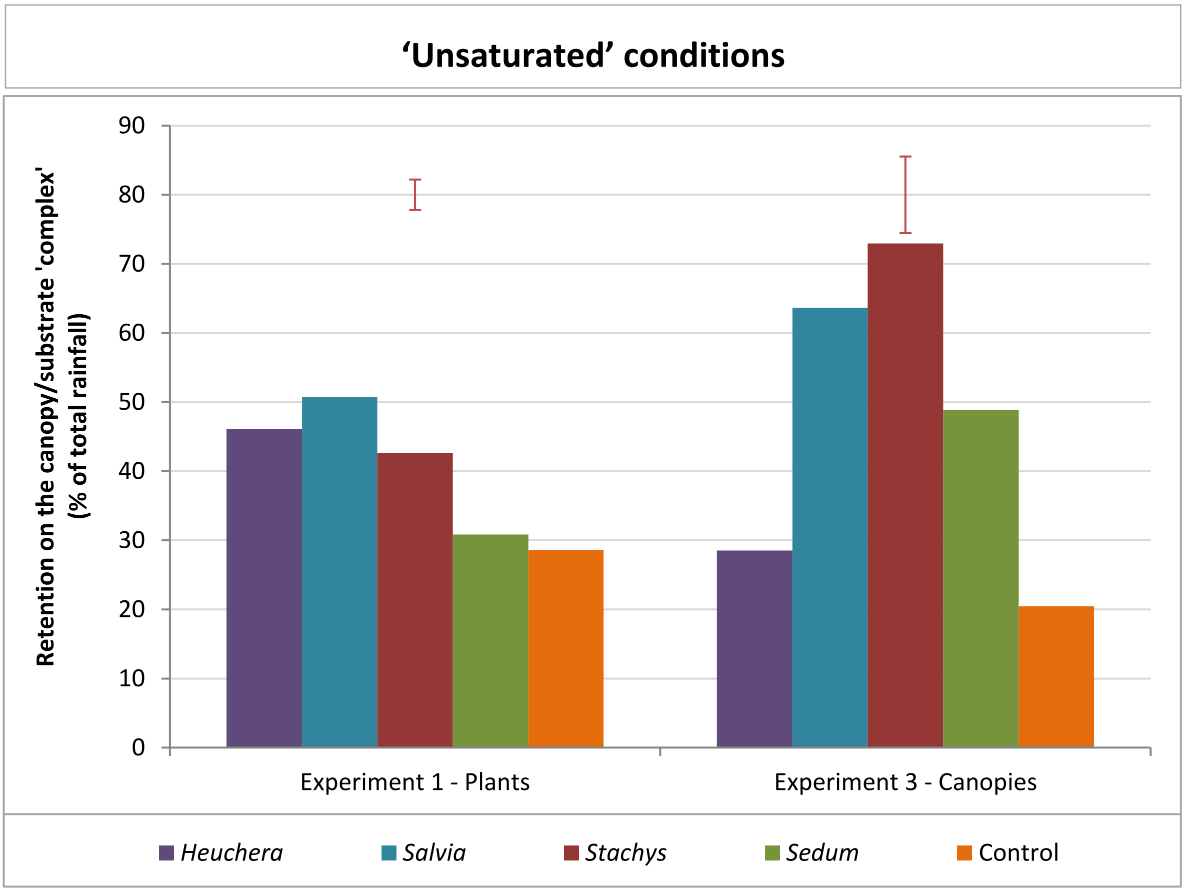


Figure 3.4: Mean rainfall retention on the canopy/substrate 'complex' in 'unsaturated' conditions (i.e. following a 72-hour antecedent dry period) in Experiments 1 and 3. Data are means of 8 or 6 replicate containers/trays per treatment in Experiments 1 and 3 respectively with associated LSDs (5%); red bars indicate statistical differences between the means of each experiment respectively.

There were also significant differences between treatments in the depth of runoff produced in 'unsaturated' conditions in both experiments (Table 3.6). With individual plants in Experiment 1, significantly more runoff was produced with *Sedum* and the control than with the other species ($P < 0.001$). As with 'saturated' conditions, *Heuchera* produced the least runoff (8.7 mm) but the 'water lost due to dripping' from the canopy was also significantly greater than all other treatments ($P < 0.001$), accounting for over 15% of the total rainfall. Conversely, with larger canopies in Experiment 3, *Heuchera* produced significantly more runoff than all other species (5.9 mm; $P < 0.001$), whilst *Salvia* and *Stachys* produced the least runoff (1.2 and 1.4 mm respectively). The bare substrate control produced significantly more runoff than all species, accounting for 84.2% of the total rainfall.

Table 3.6: Mean runoff from each tray/container in 'unsaturated' conditions in Experiments 1 and 3 and 'water lost due to dripping' from the canopy in Experiment 1, expressed as depths and proportions of the total rainfall. Analyses of runoff and 'water lost due to dripping' data from Experiment 1 were carried out on square and square root transformed data respectively (LSDs (5%) were 38.89 and 0.423; P < 0.001 for both); letters indicate statistical differences between the means of each experimental run.

'Unsaturated' conditions [#]	Experiment 1				Experiment 3	
	Runoff		'Water lost due to dripping'		Runoff	
Treatment	**Depth (mm)**	**% of rainfall**	**Depth (mm)**	**% of rainfall**	**Depth (mm)**	**% of rainfall**
Heuchera	8.7 [a]	38.4	3.5 [b]	15.5	5.9	67.1
Salvia	11.0 [a]	47.7	0.4 [a]	1.6	1.2	12.3
Stachys	13.0 [b]	56.8	0.1 [a]	0.5	1.4	15.2
Sedum	15.9 [c]	69.0	0.0 [a]	0.2	3.4	38.1
Control	16.5 [c]	71.3	0.0 [a]	0.1	7.5	84.2
LSD (d.f.)	- (39)	-	- (39)	-	**1.25** (29)	-

[#] **In 'unsaturated' runs, rainfall was applied after a 72-hour antecedent dry period.**

Regression models between the volume of runoff produced per tray in Experiment 3 (in both the 'saturated' and 'unsaturated' runs) and potential explanatory variables identified a strong positive and statistically significant relationship with antecedent SMC (adjusted $R^2 = 0.76$; $P < 0.001$) (data not shown). However, there was no correlation between runoff and any plant parameters (canopy height and diameter, leaf area, leaf area density, shoot and root dry weights or fresh root volume), with adjusted R^2 values typically below 0.02 and not statistically significant (data not shown).

3.3.4 Restoration of substrate retention capacity

Daily ET from each container/tray, measured between the 'dry' and 'unsaturated' runs in Experiment 1 and between the 'saturated' and 'unsaturated' runs in Experiment 3, is presented in Figure 3.5. All containers/trays were assumed to be at field capacity at the start of the measuring periods as they followed simulated rainfall events. Cumulative ET after 72 hours varied significantly between treatments in both experiments, with *Salvia* and *Stachys* always losing significantly more water than *Sedum* and the control ($P < 0.001$). Furthermore, regression models indicated that cumulative ET in the 72-hour dry period prior to rainfall application in the 'unsaturated' run of Experiment 3 had a strong, statistically significant relationship with both rainfall retention on the canopy/substrate 'complex' and runoff (adjusted $R^2 = 0.94$ and 0.91 respectively; $P < 0.001$; Figure 3.6). With individual plants in Experiment 1, *Heuchera* ET was high, similar to *Salvia*, with a loss of 11.0 mm after 72 hours (Figure 3.5 A). Conversely, in Experiment 3, *Heuchera* had very low ET, similar to the control, with a loss of just 5.9 mm in 72 hours (Figure 3.5 B). However, when expressed per leaf area to take account of differing canopy sizes, ET losses with *Heuchera* were similar to *Salvia* and *Stachys* in all experiments, whilst water uptake by *Sedum* was significantly lower (data not shown).

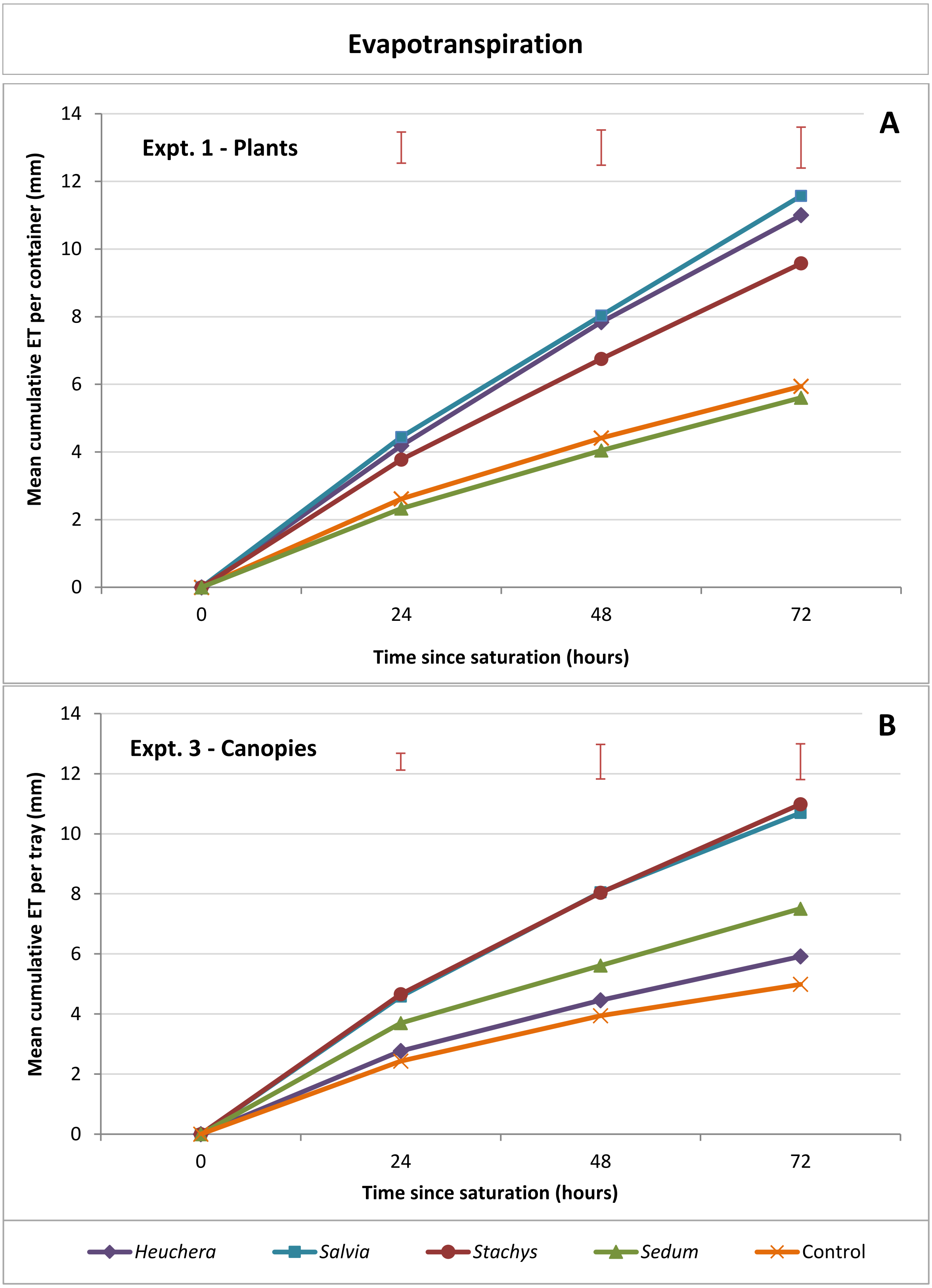


Figure 3.5: Mean cumulative evapotranspiration (ET) from each container/tray for 72 hours following saturation in Experiment 1 (A) and Experiment 3 (B). Data are means of 8 or 6 replicate containers/trays per treatment in Experiments 1 and 3 respectively, with associated LSDs (5%); red bars indicate statistical differences between the means at each time point.

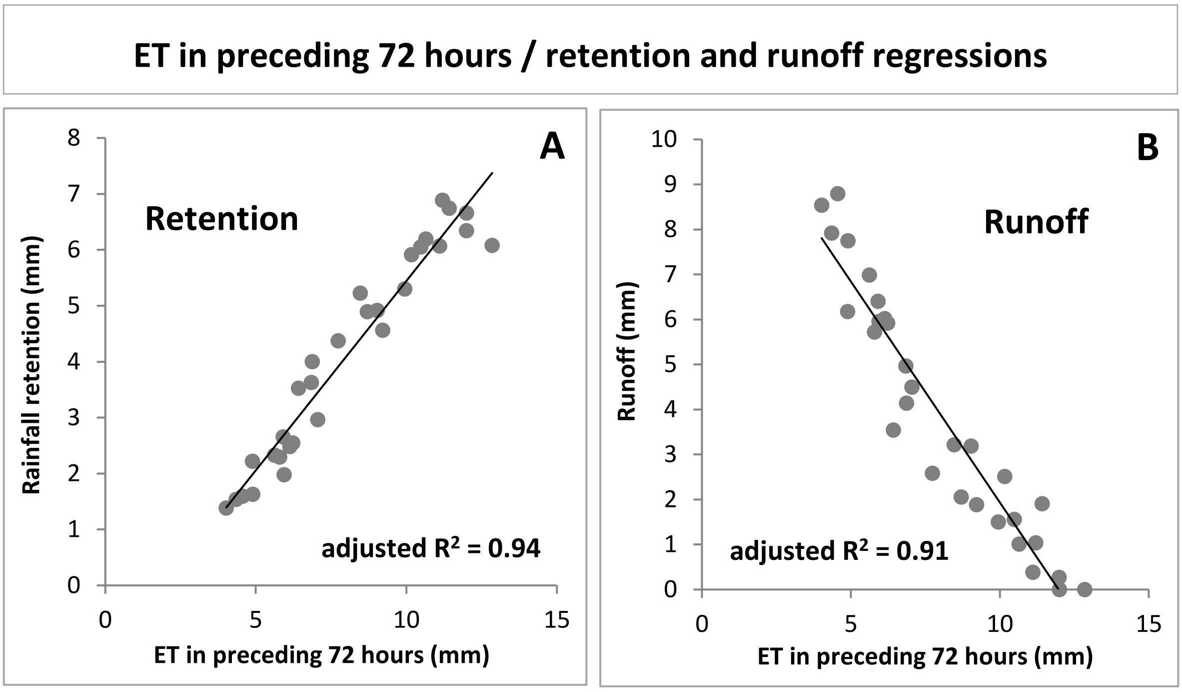


Figure 3.6: Regression models showing the relationship between total ET in the 72-hour antecedent dry period prior to rainfall application in the 'unsaturated' run of Experiment 3 and rainfall retention on the canopy/substrate 'complex' (A) and runoff (B). Analysis was carried out on all species combined.

3.4 Discussion

This chapter examined the potential of four plant species to provide stormwater management on a green roof by retaining rainfall in the substrate and on the canopy, thereby reducing the volume of runoff from the roof and mitigating the risk of urban flooding.

3.4.1 Species differences in rainfall retention and runoff reduction

Rainfall retention by vegetated treatments in all experiments varied from 1.7 to 72.9% of the total rainfall per rainfall event, depending on species, antecedent SMC and rainfall characteristics. Several studies have also noted widely ranging retention in individual storm events (e.g. 0 - 100 % retention; Stovin *et al.*, 2012) and attribute this variation mainly to the size of the rainfall event and the antecedent weather conditions. Indeed, the inverse relationship between storm size (depth, duration and intensity) and green roof retention (or runoff) is well documented (e.g. Villarreal and Bengtsson, 2005; Whittinghill *et al.*, 2015; Carpenter *et al.*, 2016), as larger storms saturate the substrate beyond field capacity, resulting in runoff production. Rainfall intensity and depth were substantially higher in Experiment 1 than Experiment 3 (average depth of 28.8 compared to 9.1 mm respectively), which could partially explain the overall higher retentions observed in Experiment 3 (average retention of 31.8% for vegetated treatments compared to 22.8% in Experiment 1). Rainfall depth greater than 10 mm is generally considered to be a heavy storm, following the classification proposed by Getter *et al.* (2007).

In addition to the scale of the experiments (individual plants compared to small canopies), the substrate type and depth also differed between experiments. The substrate used in Experiment 1 was an industry standard, free-draining green roof substrate which would be expected to have different drainage properties to the organic-rich, peat-based compost used as the 'model' setup in Experiment 3. Indeed, Dunnett *et al.* (2008) observed lower runoff from a natural, more organic soil compared to a synthetic green roof substrate, although some other studies have found no significant differences in rainfall retention percentages between green roofs with differing substrate types (Voyde *et al.*, 2010a; Fassman-Beck *et al.*, 2013). Since the objective of the presented experiments was to assess the retention capabilities of the different plant species rather than focussing on different substrates, comparison between treatments within each experiment is still valid. It should also be noted that in Experiments 1 – 3, retention and runoff were both measured directly, whereas published studies typically measure only runoff and then calculate retention as the remaining portion of rainfall; comparison of results should therefore be treated with caution.

As expected, rainfall retention by the bare substrate control treatment was significantly lower than by vegetated treatments, ranging from 0.4 to 28.6% in all rainfall events in Experiments 1 and 3, depending on antecedent SMC. In 'unsaturated' conditions, up to 22.1% more rainfall was retained by vegetated treatments compared to bare substrate in Experiment 1 (with *Salvia*) and up to 52.4% more in Experiment 3 (with *Stachys*). This highlights the importance of vegetation, and is similar to results of several other studies, in which vegetated treatments have retained significantly more rainfall than bare substrate treatments (e.g. Volder and Dvorak, 2014; Beecham and Razzaghmanesh, 2015; Stovin *et al.*, 2015), indicating that the addition of vegetation can improve the retention performance of a green roof above that of bare substrate alone.

In addition to the significant difference in retention between vegetated and control treatments, there were also significant differences between the species tested in this study, with overall average retention with *Salvia* (31.8%) and *Stachys* (32.6%) almost double the retention with *Heuchera* (19.6%), and also significantly higher than with *Sedum* (25.0%) in Experiments 1 and 3. These differences were more pronounced in 'unsaturated' conditions than 'saturated' conditions, as a result of varying ET rates, and thus available substrate storage, in addition to differences in canopy capture (see Sections 3.4.2 and 3.4.3).

Although there is clear evidence that vegetation contributes significantly to green roof retention, the majority of green roof stormwater retention studies use *Sedum*s or other succulent species as vegetated treatments, and do not attempt to account for potential differences that may be a result of different vegetation types. Additionally, there have been few studies directly researching the effects of different vegetation types on retention performance (e.g. Berghage *et al.*, 2007; Lundholm *et al.*, 2010; Whittinghill *et al.*, 2015; Heim *et al.*, 2017) or the mechanisms that enable particular species to surpass others in their retention performance. A few studies have found that *Sedum*s retain significantly less water than other species (Dunnett *et al.*, 2008; Nagase and Dunnett, 2012; Whittinghill *et al.*, 2015), whereas Stovin *et al.* (2015) found no difference in annual retention between *Sedum* spp. and Meadow Flowers. These differences in results could be due to the length and setup of the studies, as Stovin *et al.* (2015) note that there were seasonal variations in plant cover with Meadow Flowers during their 4-year study, whereas *Sedum* maintained a full, dense cover throughout. Likewise, Heim *et al.* (2017) reported similar retention with *Sedum* and another native succulent, *Rhodiola rosea*, likely resulting from differences in plant cover throughout the study (69 – 97% for *Sedum* compared to 26 – 36% for *R. rosea*), and suggest that the retention performance of *R. rosea* may increase if coverage increased, since this species has higher water use (Wolf and Lundholm, 2008). Additionally, climatic variation between seasons influences ET rates and hence restoration of substrate retention capacity, resulting in significantly different retention/runoff at different times of the year (Mentens *et al.*, 2006). Since Experiments 1 and 3 were carried out during late spring/early summer, retention would likely be lower during the winter, and the observed retention during the experiments is therefore probably an overestimate of the cumulative annual retention that would be experienced on a green roof with these species.

Dunnett *et al.* (2008) and Nagase and Dunnett (2012) identified significant relationships between the volume of runoff produced and plant characteristics (including height, diameter, and root and shoot dry weights), and other studies have attributed greater retention or runoff reduction with denser vegetative cover and larger plants with greater canopy complexity (Teemusk and Mander, 2007; Whittinghill *et al.*, 2015). Similarly, Lundholm *et al.* (2010) suggest that planting a mix of species rather than a monoculture will create a more complex canopy architecture that may consequently be able to intercept and retain more water. However, regression models between the volume of runoff produced in Experiment 3 and potential explanatory canopy variables (canopy height and diameter, shoot and root dry weights, and leaf area) were not significant and all produced low adjusted R^2 values (typically less than 0.02; data not shown), indicating that plant characteristics alone were not predictive of the runoff produced.

The results of Experiments 1 and 3 highlight the impact of varying ET rates between species on their ability to retain rainfall and thus reduce runoff. It is clear from the results of all experiments that species with high ET rates (i.e. the broadleaf species) were able to restore the retention capacity of the substrate more than species with low ET rates (*Sedum*), resulting in significantly lower antecedent SMC at the onset of rainfall in 'unsaturated' conditions and thus greater rainfall retention in the substrate/canopy 'complex'.

3.4.2 The role of the evapotranspiration in rainfall retention

The additional retention provided by vegetated treatments compared to bare substrate results from a combination of direct canopy interception of rainfall (discussed in Section 3.4.3) as well as the role of the vegetation in restoring the substrate's retention capacity through ET between rainfall events. This water loss from the substrate through ET is generally considered to be of greater importance than canopy interception (Stovin *et al.*, 2015) since it is clear that the substrate itself represents the majority of a green roof's water storage capacity (VanWoert *et al.*, 2005; Dunnett *et al.*, 2008). This was clearly highlighted in the results of Experiment 1, in which a substantially higher proportion of the total rainfall was captured on the canopy/substrate 'complex' in 'dry' conditions compared to 'saturated' conditions (e.g. 50.7% retention compared to 5.1% respectively with *Salvia*), where the only difference between the two rainfall applications was that antecedent SMC was low in the 'dry' run whereas the substrate was saturated to field capacity at the beginning of the 'saturated' run.

ET is therefore recognised as a key factor determining a green roof's retention performance (Stovin *et al.*, 2012), which is also evident in the results of these experiments. For example, although *Sedum* was one of the top performing species in terms of canopy capture in 'saturated' conditions in Experiments 1 and 3, water retention on the whole canopy/substrate 'complex' was significantly lower than most other species in 'unsaturated' conditions, probably as a result of its low ET rate limiting the restoration of the substrate's water retention capacity. Indeed, the overall effectiveness of *Sedum* compared to other species in rainfall capture is often considered to be limited by its low ET rate (Nagase and Dunnett, 2012). Moreover, regression models identified strong relationships between both rainfall retention and runoff in the 'unsaturated' run of Experiment 3 and ET in the preceding 72 hours, with adjusted R^2 values of 0.94 and 0.91 respectively ($P < 0.001$). These results indicate that retention and runoff are both strongly dependent on ET in the preceding dry period, highlighting the importance of restoration of the substrate's water retention capacity in overall retention performance. Furthermore, the advantage of species with high ET rates, and thus their ability to maximise stormwater management provision on a green roof, is clearly evident.

In the 3 days with no irrigation following a rainfall event, there were significant differences between treatments in water uptake and consequently SMCs in all experiments, resulting from varying ET rates. *Salvia* and *Stachys* had significantly higher ET rates than *Sedum* and the control treatment in all experiments, typically taking up around twice as much water from the substrate in 72 hours. Consequently, the water retention capacity of the substrate is likely to have been restored twice as much with these species, theoretically doubling the water storage availability in the substrate for a subsequent rainfall event. Water uptake by *Heuchera* varied between experiments, with high ET rates similar to *Salvia* and *Stachys* in Experiment 1 but low ET rates, similar to the control and significantly lower than *Sedum*, in Experiment 3. However, under the conditions of these experiments this variation was probably due to differences in canopy sizes, as water uptake expressed relative to leaf area indicates that the ET rate of *Heuchera* was similar to those of *Salvia* and *Stachys*, and significantly higher than that of *Sedum* in all experiments (data not shown).

These findings are consistent with previous studies, in which the presence of vegetation has been shown to increase substrate moisture losses compared to bare substrate alone (Voyde *et al.*, 2010b) and succulent species such as *Sedum* were generally found to deplete substrate moisture slower than herbaceous species (Poë *et al.*, 2015). Additionally, species with very dense vegetative cover, such as *Sedum*, may retain moisture in the substrate for longer by preventing evaporation from the substrate surface (Wolf and Lundholm, 2008).

Species differences in ET, and hence water retention capacity of the substrate, became more pronounced over time in all experiments: for example, in Experiment 3 water loss with *Stachys* was 2.3 mm greater than with the control after 24 hours, whilst the difference was 6.0 mm after 72 hours of drying. This suggests that the advantage of one species over others and over bare substrate would become greater with longer periods of dry weather between rainfall events. This pattern was also identified in the first few days of drying (6 – 14 days) in several other studies (e.g. Berghage *et al.*, 2007; Voyde *et al.*, 2010b). However, beyond this time the cumulative water uptake of different treatments was observed to converge so that the available substrate retention capacity became similar for all treatments (Poë *et al.*, 2015). This is probably a result of decreasing ET rates over time as substrate moisture becomes limited (Stovin *et al.*, 2013), particularly in broadleaf species with initially high ET rates, which quickly deplete substrate moisture. The cumulative retention provided by green roofs will therefore be greatest when rainfall events are spread out in time, allowing restoration of the substrate retention capacity through ET between storms (Berghage *et al.*, 2007). However, the advantage of broadleaf species with high ET rates, such as *Stachys*, over those with low ET rates, such as *Sedum*, is likely to be the greatest in the first few days following rainfall, when there are the greatest differences between ET losses and thus restoration of the substrate's water retention capacity.

In Experiment 3, there was a highly significant relationship between antecedent SMC and the volume of runoff produced from vegetated treatments (adjusted $R^2 = 0.76$; $P < 0.001$), indicating that antecedent SMC, as well as ET in the preceding dry period, can be an important indicator of potential rainfall retention on a green roof. Retention in 'unsaturated' conditions was directly related to the antecedent SMCs of each treatment at the onset of rainfall, in all experiments. Due to the varying ET rates of each treatment during the preceding 72-hour dry period, antecedent SMCs varied significantly between treatments, with SMCs of the control treatments always similar to *Sedum* and significantly higher than *Salvia* and *Stachys*. This was similar to other studies, in which antecedent SMC was significantly higher in bare substrate treatments than vegetated treatments at the onset of rainfall (e.g. Volder and Dvorak, 2014). This indicated that greater substrate water storage would be available with *Salvia* and *Stachys* during the rainfall event in 'unsaturated' conditions, which was observed in all experiments as retention was significantly higher with *Salvia* and *Stachys* compared to *Sedum* and the control. Rainfall retention under natural environmental conditions on a green roof is therefore clearly related to the available water storage in the substrate (and thus antecedent SMC), which in turn is dictated by ET losses in the preceding dry period.

3.4.3 The role of the canopy in rainfall retention

The contribution of the canopy itself to rainfall retention was generally small compared to the role of the substrate, which is in line with the results of other studies – for example, MacIvor and Lundholm (2011) found that canopy interception contributed up to 4% of the total rainfall retention, depending on species. Similarly, in 'saturated' conditions, in which retention was solely dependent on the canopy since the substrate was already saturated to field capacity, vegetated treatments retained up to 5% more rainfall than bare substrate in Experiment 1 (with *Salvia*) and up to 16% more (with *Sedum*) in Experiment 3. There were also significant differences in retention between species in all experiments, with greater differences observed between species with the larger canopies in Experiment 3. This additional retention provided by the canopy would be important at times when antecedent SMC is high at the onset of rainfall, for example when storms occur close together and there is little time for restoration of substrate retention capacity between rainfall events, or during cooler and wetter weather or seasons. In these situations, canopy interception may be the sole mechanism for retention, and so having a species capable of high canopy retention is essential.

Although very few studies have investigated retention with different vegetation types, plant characteristics such as canopy height, diameter and density, and waxy or hairy leaves were identified as factors that may affect the amount of rainfall retained on vegetation (Nagase and Dunnett, 2012). Regression models between retention on the canopy and potential explanatory plant characteristics in the ‘saturated’ run of Experiment 3 identified significant correlations for shoot dry weight ($P < 0.001$) and leaf area density ($P < 0.001$). However, in all experiments there were still significant differences between species when retention was expressed relative to leaf area to account for potential variation due to plant size. The differences in rainfall retention on the vegetation may therefore also be due to differing canopy structures and leaf morphologies (e.g. presence/absence of leaf hairs, leaf shape) that are not adequately described by any of the variables measured in these experiments.

Sedum typically formed a very dense canopy composed of many upright branches with small, succulent leaves and rosettes, which together provided a large area for capturing water and may account for its high retention in all experiments. Furthermore, the stems of *Sedum* contributed greatly to the overall canopy density (up to 20% of the total canopy area in Experiment 3; data not shown), and as they were not included in leaf area measurements, this may account for the high relative volume of water captured per leaf area. Indeed, when stems were included in calculations, the leaf area density of *Sedum* increased from 0.43 to 0.53 $cm^2\ cm^{-3}$, whilst the leaf area density of the other species all increased by only 0.01 $cm^2\ cm^{-3}$ (data not shown). *Salvia* also formed a dense, closed canopy in all experiments, made up of several layers of horizontally aligned leaves, which are hairy with rough surfaces. This provided good coverage of the substrate whilst also allowing water to penetrate down through the leaf layers, providing a large surface area for water capture. Additionally, the rough, hairy, horizontal leaves were able to retain water droplets, even when they coalesced.

Stachys has large and particularly hairy leaves, which were able to retain water efficiently on their surfaces. This was evident in Experiment 3 when the larger canopies were full and dense and rainfall covered the whole canopy area, retaining 13.1% of the total rainfall. However, with individual plants in Experiment 1, *Stachys* was one of the poorest performing species tested, retaining only 1.8% of the total rainfall applied. This may have been partly due to the structure of the canopy, as *Stachys* branches tended to grow at an oblique angle, meaning that the centre of the canopy was relatively sparse, often leaving a large area of the substrate exposed. Additionally, the simulated rainfall in Experiment 1 only covered a rectangular area of approximately 180 cm^2, which often resulted in some of the *Stachys* canopy being outside of the rainfall area; due to the sparse centre of the *Stachys* canopies, this tended to result in a relatively large proportion of the rainfall falling directly onto the exposed substrate.

Heuchera typically formed a large canopy with good substrate coverage, although canopy cover was slightly lower than other species in Experiment 3 (approximately 90%). However, both the structure of the *Heuchera* canopy and characteristics of its leaves resulted in significantly lower rainfall retention than other species in all experiments. The large leaves, which are smooth and horizontally-aligned, formed an almost continual layer that raindrops bounced and dripped off of, preventing water infiltrating through the canopy and reaching the substrate surface. These leaf and canopy characteristics resulted in the large volume of 'water lost due to dripping' from the canopy with *Heuchera* (20.5% of the applied rainfall in 'saturated' conditions), measured in Experiment 1. Consequently, runoff from *Heuchera* was lower than the other treatments (77.7% in 'saturated' conditions), despite the fact that only a small proportion of the total rainfall was retained on the canopy (1.7%). The 'water lost due to dripping' from the canopy in this way is an important parameter to consider, since runoff from a green roof will not be delayed or reduced as much if a large proportion of the rainfall drips off of the vegetation onto surrounding surfaces. However, the 'water lost due to dripping' from individual plants measured in Experiment 1 is likely to be an overestimate compared to larger canopies, including a full green roof, as the edge effect is exaggerated with individual plants. Additionally, it is clear that runoff alone may not be an accurate parameter to measure the stormwater management capabilities of a green roof, as it does not take into account the volume of 'water lost due to dripping' from the canopy.

3.5 Key conclusions

- Species selection for green roofs has an impact on the stormwater management service that can be provided, as there are significant differences between species in terms of both canopy capture and restoration of substrate retention capacity following rainfall, depending on the ET rate and the canopy characteristics of each species.
- Substrate is the major store for water and antecedent SMC is therefore a key factor in stormwater management with green roofs. However, under the experimental conditions of this study canopies themselves retained up to 17% of the total rainfall, depending on

species, and can therefore make a substantial contribution to rainfall retention on a green roof.

- There was a strong relationship between ET, rainfall retention and runoff reduction in 'unsaturated' conditions, when plants were allowed to freely transpire during an antecedent dry period of 72 hours, suggesting that greater restoration of substrate retention capacity through enhanced ET is the most important contribution of vegetation to retention performance. Species with high ET rates are therefore able to provide the greatest stormwater management service. Experimental results suggest that the advantage of species with high ET rates is likely to be greatest in the first few days following rainfall when differences in ET losses between species are greatest.
- The ability of the canopy to intercept and retain rainfall is likely to become more important when antecedent SMC is constantly high, for example in cool, wet weather or when rain storms are close together.
- *Sedum* provided good canopy capture in 'saturated' conditions but was slow to restore the substrate retention capacity due to its low ET rate, which consequently resulted in one of the lowest retention and highest runoff volumes of all the species tested in 'unsaturated' conditions.
- *Stachys* and *Salvia* provided good canopy capture and were also able to restore the substrate retention capacity quickly due to their high ET rates; these species were therefore able to retain the most rainfall and reduce runoff the most in 'unsaturated' conditions.

Chapter 4

The impact of different simulated summertime temperature and humidity scenarios on plants' water use: links with restoration of the substrate's water retention capacity

4.1 Introduction

The role of green roofs in mitigating urban flooding, through delay and reduction of runoff, is well documented. The substrate is generally regarded as the most important part of a green roof system in terms of its stormwater management capabilities, since the bulk of the rainfall is stored in the substrate (VanWoert *et al.*, 2005; Dunnett *et al.*, 2008). The substrate has a finite retention capacity, which varies with substrate type, depth, porosity and water-holding properties. Removal of water from the substrate through evapotranspiration (ET) between storms allows a greater volume of water to be stored by the system in the next rainfall event (Stovin *et al.*, 2012), up to the maximum retention capacity of the substrate, after which any water added will become runoff (Sims *et al.*, 2016). Vegetation is acknowledged to play a vital role in increasing the retention potential of a green roof over and above that of bare substrate alone (Voyde *et al.*, 2010a), mainly as result of the additional contribution of plant transpiration to total ET in dry periods. This was also clearly highlighted in Chapter 3, where experiments revealed that rainfall retention on the canopy/substrate 'complex' following a 3-day antecedent dry period was strongly related to cumulative ET, and consequently antecedent substrate moisture content (SMC), during the dry period (see Sections 3.3 and 3.4.2).

Significant differences in rainfall retention have been identified with different plant species (Nagase and Dunnett, 2012; Whittinghill *et al.*, 2015), as well as in the experimental results presented in Chapter 3, highlighting the importance of species choice for maximum provision of stormwater management. However, few studies have directly examined the role of different species in restoring substrate retention capacity through ET (e.g. Berghage *et al.*, 2007; Poë *et al.*, 2015), and green roof ET has rarely been quantified (Voyde *et al.*, 2010b). Additionally, the vast majority of plant species examined to date, in terms of both ET and overall retention, have been succulents such as *Sedum* (e.g. Voyde *et al.*, 2010b; Farrell *et al.*, 2012; Berretta *et al.*, 2014).

Although these species have traditionally dominated green roof planting choices due to their ability to survive without irrigation, they also have inherently low ET rates (Vaz Monteiro *et al.*, 2017), which restrict restoration of substrate retention capacity and limit their ability to provide rainfall retention (Nagase and Dunnett, 2012). Species with high ET rates are likely to restore the substrate retention capacity faster and to a greater extent in dry periods between storms, so that a greater retention capacity is available for rainfall storage in subsequent storms, even when they occur close together. However, the ability of species with high ET rates to restore substrate retention capacity during dry periods through ET has not yet been examined.

Rainfall retention performance of green roofs has been observed to vary between locations and between seasons (Speak *et al.*, 2013; Sims *et al.*, 2016), which is likely to be a result of the varying environmental conditions and their influence on ET. Indeed, Sims *et al.* (2016) studied identical green roofs (in terms of substrate type and depth, configuration and vegetation treatments) in three different climatic regions of Canada to attempt to isolate the influence of climatic variables on green roof retention performance. They found that higher ET between storms on the roof in a semi-arid climate resulted in greater restoration of substrate retention capacity than on the roof located in a maritime climate, leading to an overall retention of 75.2% compared to 43.4% (Sims *et al.*, 2016); rainfall totals were similar in both locations, suggesting that the influence of climate on ET plays an important role in overall retention performance.

The main climatic parameters influencing ET are solar radiation, air temperature and humidity, and wind speed (Allen *et al.*, 1998). Radiation provides the primary energy supply for the evaporation process; temperature provides a small additional energy source, whilst also reducing the energy required for the process (Tan *et al.*, 2015). High wind speeds increase ET by reducing the thickness of the boundary layer, thus reducing boundary layer resistance to water vapour, and by promoting turbulent mixing of the atmosphere, which allows saturated air above the evaporating surface to be replaced with drier air (Tan *et al.*, 2015). The humidity gradient between the saturated air in the leaf and the relatively drier external air drives the removal of water vapour from the evaporating surface and is described by vapour pressure deficit (VPD), which is a function of air temperature and humidity (Allen *et al.*, 1998). The rate at which water vapour from the evaporating surfaces is transferred to the air, controlled by all of these climatological variables, influences a green roof’s ability to restore substrate retention capacity between storms and thus the proportion of a subsequent rainfall event that can be retained (Poë *et al.*, 2015).

Very few studies have examined the influence of climatic variables on the ET rates of green roof species (Berretta *et al.*, 2014; Poë *et al.*, 2015; Sims *et al.*, 2016), especially whilst keeping all other factors constant (e.g. vegetation type, substrate type and depth, season and duration of study). These studies typically observed greater ET in summer compared to spring conditions (Berretta *et al.*, 2014; Poë *et al.*, 2015) and in dry compared to humid climates (Sims *et al.*, 2016), resulting from higher VPD in warm and dry conditions driving faster ET. This suggests that, in a UK summer, green roofs would be able to provide greater rainfall retention when conditions are predominantly hot and dry (i.e. high temperature and low humidity). However, over a long dry period (28 days; Poë *et al.*, 2015), the higher ET rates in summer conditions declined after the first 12 days due to low SMC, becoming lower than spring ET for the remainder of the study. Moreover, these studies primarily tested the effect of varying climates on *Sedum* species, which are widely acknowledged to be adapted to drought conditions through leaf succulence and the ability to switch to Crassulacean Acid Metabolism (CAM) photosynthesis in order to conserve and prolong water supplies (Farrell *et al.*, 2013). However, other species, including broadleaf species with high ET rates, may not utilise water conservation strategies, and there is evidence that photosynthesis, and therefore transpiration, can continue at a higher rate even when substrate moisture is low (Cameron *et al.*, 2006; Voyde *et al.*, 2010b). This could be advantageous for a green roof's overall rainfall retention performance, as the substrate retention capacity would be restored to a greater capacity more quickly with broadleaf species as a result of their high ET rates. Thus, a larger volume of rainfall could be stored in the substrate in subsequent rainfall events, even if they occur very close together. Moreover, this suggests that species could be selected based on a green roof's location and predominant summer weather conditions in order to maximise the provision of stormwater management, as different species may have optimal climatic conditions for ET and thus restoration of substrate retention capacity.

Since the maintenance of ET at its maximum potential rate depends on a constant supply of water to the evaporating surface (Verhoef and Egea, 2013), the actual rate of ET declines over time if no supplementary irrigation is supplied, as available substrate moisture becomes increasingly restricted (Stovin *et al.*, 2013). This daily ET decrease has been observed in succulent species during long drying periods (e.g. 4 weeks) in glasshouse and controlled environment experiments (Voyde *et al.*, 2010b; Poë *et al.*, 2015), with the ET rates of vegetated treatments often eventually becoming similar to or lower than unvegetated treatments. Additionally, experimental results presented in Chapter 3 indicated that for species with higher ET rates (i.e. broadleaf species such as *Stachys*), this decline in daily ET may occur much faster as a result of substrate moisture being depleted faster, thus restricting subsequent ET. This suggests, therefore, that these species may only have an advantage over succulents or bare substrate, in terms of restoring substrate retention capacity and allowing greater storage of water in subsequent rainfall events, for a relatively short time after a rainfall event, when SMC is not restricted. However, this decline in the ET over time with decreasing SMC has not yet been fully examined and quantified for species with high transpiration rates in the context of green roof ecosystem services (ESs) provision.

4.1.1 Study aims

There is therefore a need to characterise the behaviour of species with high ET rates in terms of the impact of varying climates on ET rates and their responses to drying substrate, in order to identify optimum environmental conditions for ET and thus provision of stormwater management service. The experimental trials presented in this chapter adopted a theoretical framework to investigate the maximum ability of species with high ET rates to restore substrate retention capacity under varying environmental conditions (air temperature (T) and relative humidity (RH) in different combinations; hereafter referred to as T/RH treatments) and as substrate moisture is depleted. Trials were therefore conducted under controlled environmental conditions to ensure that other parameters (such as solar radiation and wind speed) remained constant, using broadleaf species with high ET rates relative to *Sedum* to identify the optimum T and RH conditions that promote the greatest restoration of substrate retention capacity. The objectives of this chapter were therefore:

- To investigate the impact of varying air temperature and humidity on the ET rates of different species, in order to identify optimum environmental conditions for each species in terms of restoring substrate retention capacity;
- To investigate the response of each species to drying substrate (i.e. decreasing SMC) in terms of ET rates, and the impact of any water conservation strategies on the species' ability to restore substrate retention capacity.

4.2 Materials and Methods

A controlled environment (CE) experiment was carried out to examine how ET, and thus the rate of restoration of substrate retention capacity, varies between species in different T/RH treatments. A summary of the experimental setup for Experiment 4 is presented in Table 4.1. Full details of the plant materials and substrates used in the experiments are described in Sections 2.3 and 2.4 and all measurements were made as described in Section 2.5.

Table 4.1: Summary of Experiment 4.

	Experiment 4
Dates	9th March – 30th April 2015
Set-up	Individual plants in 2 L containers with 11 cm of Meadow Roof Medium
Treatments	6x *Heuchera*, *Salvia*, *Stachys*, *Sedum*, control
Measurements	SMC; plant height and diameter, leaf area, root and shoot dry weights, ET

4.2.1 Restoration of substrate retention capacity under different environmental conditions

Experiment 4 consisted of a series of 5 successive trials in CE growth cabinets, each with different environmental settings to examine how ET rates of each species, and thus the rate of restoration of substrate retention capacity, varied in different T/RH treatments. The experimental setup of Experiment 4 was described in Section 2.6.6. There were five treatments in all trials: the four plant species (*Heuchera*, *Salvia*, *Stachys* and *Sedum*) plus a bare substrate control. Each trial was carried out in two or three parts (referred to as Parts a, b and c), due to space limitations in the CE cabinets only allowing a maximum of 3 replicates per treatment (half the total number) to be tested at a time. Moreover, in trial 4 (‘dry’) only 2 replicates of each treatment fitted inside the cabinet at a time, as a Honeywell HDE010E dehumidifier (Honeywell International Inc., Kaz Europe SA, Switzerland), which was capable of maintaining a set RH of 40%, was placed inside the CE cabinet to achieve the target RH. Trial 4 therefore took place in three successive parts with 2 replicates per species/control tested each time.

The target environmental settings for the five trials were chosen to simulate a range of potential summertime T/RH scenarios that could be experienced in the UK. Trials are hereafter referred to as 'warm', 'hot', 'cool', 'dry' and 'humid', based on their target T and RH (Table 4.2); target vapour pressure deficit (VPD) was calculated from the target T and RH for each treatment (using Equations 5.12 and 5.13; see Section 5.2.2). The actual mean T and RH recorded in the CE cabinets during each part of each trial are presented in Table 4.3, along with the calculated actual VPD. General environmental conditions of the CE growth cabinets were described in Section 2.1.

Table 4.2: Target air temperature (T) and relative humidity (RH) settings and calculated target vapour pressure deficit (VPD) for the controlled environment cabinets during each T/RH trial.

Trial	T/RH summertime scenario	Target temperature (°C)		Target relative humidity (%)	Target mean VPD (kPa)
		Day	Night		
1	**'Warm'**	22	14	60	0.85
2	**'Hot'**	28	16	60	1.12
3	**'Cool'**	18	10	60	0.66
4	**'Dry'**	22	14	40	1.27
5	**'Humid'**	22	14	80	0.42

4.2.2 Experimental procedure

Setup details of all trials are summarised in Table 4.3, along with the mean actual environmental conditions recorded in the CE cabinets during each trial. Fluctuations in actual T and RH inside the cabinets during experimental trials resulted in almost identical average VPDs during the 'hot' and 'dry' trials (1.34 and 1.33 kPa respectively) and during the 'cool' and 'humid' trials (0.53 and 0.55 kPa respectively). At the start of each trial, containers were saturated to container capacity by submerging in water for 15 minutes and then leaving to drain to field capacity for approximately 1 hour. Five containers (one of each species/control) were saturated simultaneously. Each container was then weighed and two SMC measurements were made before randomly placing all containers inside the growth cabinets. Containers remained in the cabinets for the remainder of the trial, and were removed every 24 hours for weighing and SMC measurement. To ensure survival of all plants and avoid irreversible damage, trials were ended when the SMC of any species fell below 0.100 $m^3 m^{-3}$, which was considered low for the Meadow Roof Medium (MRM) based on substrate moisture tests (see Section 2.4.1). Containers were then removed from the cabinets and placed in a glasshouse where they were watered daily and allowed to recover for at least 3 days before the start of the next trial.

Plant height and diameter were also measured at the start of every trial. Once all trials had been completed, four plants of each species were randomly selected for harvesting, and leaf area and root and shoot dry weights were measured.

Table 4.3: Details of the setup of each experimental trial and the actual temperature (T), relative humidity (RH) and calculated vapour pressure deficit (VPD) recorded in the controlled environment (CE) cabinets during each part of each T/RH trial.

T/RH summertime scenario	Trial/ part	Plant replicates tested	Mean temperature (°C)		Mean RH (%)	Mean VPD (kPa)
			Day	Night		
'Warm'	**1a**	1-3	20.9	14.4	61.7	0.92
	1b	4-6	19.5	15.3	63.7	0.96
'Hot'	**2a**	1-3	26.8	16.3	54.3	1.44
	2b	4-6	24.3	18.3	61.9	1.24
'Cool'	**3a**	1-3	15.3	9.7	78.0	0.43
	3b	4-6	16.9	10.3	72.4	0.62
'Dry'	**4a**	1-2	22.4	14.8	42.8	1.40
	4b	3-4	22.4	15.1	42.2	1.31
	4c	5-6	22.5	15.2	41.3	1.29
'Humid'	**5a**	1-3	20.5	13.7	78.7	0.53
	5b	4-6	21.9	14.0	79.1	0.57

4.2.3 Data analysis

All statistical analyses were performed as described in Section 2.8. Daily ET was calculated as the weight loss from each container in each 24 hour period, which was converted to depth (in mm) by dividing by plot area (using Eq. 1.1; Section 1.3.5). To account for the effect of different canopy sizes, ET in the first 24 hours after saturation was expressed relative to leaf area for all species under all environmental conditions.

4.3 Results

Although water loss from bare substrate control containers was solely through evaporation, for simplicity, the term 'evapotranspiration' (ET) is used from here on to describe water loss from containers of all species/control.

4.3.1 Plant parameters

The average plant height and diameter of each species measured at the beginning of each T/RH trial are presented in Table 4.4. Due to the length of time taken for each trial and mechanical problems with the CE cabinets, trials 4 and 5 ('dry' and 'humid') were conducted approximately 5 – 6 weeks after trial 1 ('warm'). Plant height and diameter generally increased over the course of the experiment, and therefore plants were larger in the later trials. Leaf area and shoot and root dry weights of harvested plants, measured at the end of the experiment after all trials had been completed, are presented in Table 4.5.

Table 4.4: Average plant height and diameter of each species during each environmental trial, with associated standard error of the means (SEM). Data are means of 6 replicates per species.

Species	Average (± SEM) plant height and diameter during each experimental trial (cm)				
	'Warm'	'Hot'	'Cool'	'Dry'	'Humid'
Heuchera					
Height	16.7 (± 0.4)	20.0 (± 0.7)	21.1 (± 0.7)	20.7 (± 0.6)	21.1 (± 0.7)
Diameter	30.5 (± 0.8)	30.6 (± 1.0)	33.3 (± 2.0)	38.2 (± 1.2)	38.2 (± 1.4)
Salvia					
Height	15.9 (± 0.6)	17.4 (± 0.7)	21.1 (± 0.8)	23.8 (± 0.5)	23.3 (± 0.4)
Diameter	31.7 (± 1.5)	34.0 (± 0.9)	37.2 (± 1.7)	41.5 (± 1.3)	41.9 (± 0.7)
Stachys					
Height	15.1 (± 0.4)	16.4 (± 0.3)	19.2 (± 0.6)	21.0 (± 1.2)	20.6 (± 0.8)
Diameter	42.2 (± 1.0)	41.5 (± 0.8)	44.8 (± 1.0)	46.2 (± 1.0)	49.5 (± 1.3)
Sedum					
Height	14.2 (± 0.9)	14.9 (± 0.8)	15.6 (± 0.5)	15.5 (± 0.3)	16.6 (± 0.8)
Diameter	34.8 (± 1.4)	34.2 (± 1.0)	37.9 (± 0.8)	37.9 (± 1.0)	37.0 (± 1.2)

Table 4.5: Average leaf area and shoot and root dry weights per plant of each species with associated standard error of the means (SEM), measured at the end of all experimental trials. Data are means of 4 replicates per species.

Species	Mean (± SEM) leaf area (cm^2)	Mean (± SEM) shoot dry weight (g)	Mean (± SEM) root dry weight (g)
Heuchera	1956 (± 301.5)	21.6 (± 2.1)	11.6 (± 0.6)
Salvia	2627 (± 250.9)	29.6 (± 1.5)	9.3 (± 0.8)
Stachys	4600 (± 279.6)	35.1 (± 1.3)	12.1 (± 1.1)
Sedum	2086 (± 36.2)	29.9 (± 1.7)	4.5 (± 0.6)

Cumulative ET after 96 hours for each species/control in each environmental trial is presented in Table 4.6. ET results from Experiments 1 and 3 indicated that cumulative differences between species/control became more pronounced over time (see Section 3.3.4), and thus cumulative ET after 96 hours is presented here in order to compare maximum differences. Although the 'cool' and 'humid' trials continued for a further 24 hours, for fair comparison cumulative ET after 96 hours in all trials was examined. The contribution of plant transpiration as a percentage of total ET (i.e. if ET = 100% and evaporation from bare substrate = 40% of ET, then plant transpiration = 60% of total ET) is also presented in Table 4.6.

Table 4.6: Mean cumulative ET per container in 96 hours for each species/control in each T/RH trial. Data are means of 6 replicates per treatment with associated LSDs (5%). Numbers in brackets indicate the contribution of plant transpiration to the total ET (%).

Treatment	Mean cumulative ET in 96h (mm) and contribution of plant transpiration to total ET (%) in each of the experimental trials				
	'Warm'	'Hot'	'Cool'	'Dry'	'Humid'
Heuchera	20.92 (51)	24.30 (49)	16.79 (56)	24.12 (51)	17.17 (60)
Salvia	26.31 (61)	29.58 (58)	22.28 (67)	30.29 (61)	24.43 (72)
Stachys	28.16 (63)	31.83 (61)	25.95 (72)	30.69 (61)	24.90 (72)
Sedum	12.29 (16)	16.03 (22)	11.95 (38)	18.77 (37)	12.75 (46)
Control	10.35 (-)	12.47 (-)	7.39 (-)	11.84 (-)	6.89 (-)
LSD (d.f. = 29)	**2.485**	**1.896**	**2.124**	**2.021**	**2.127**

There were significant differences in cumulative ET between species/control in all T/RH treatments (P < 0.001), with the same patterns observed in all trials: *Stachys* and *Salvia* had the highest ET, followed by *Heuchera* and then *Sedum*, whilst the bare substrate control had the lowest ET in all trials. ET from the control was particularly low compared to planted treatments in the 'cool' and 'humid' trials, approximately 3.5 times lower than with *Stachys* compared to 2.5 times lower in the 'warm', 'hot' and 'dry' trials. This was also evident from the percentage of total ET provided by plant transpiration, which was highest in the 'cool' and 'humid' treatments for all species. The contribution of plant transpiration with *Sedum* was also high in the 'dry' treatment.

To attempt to account for any differences in ET that may have resulted from varying canopy sizes, mean water loss in the first 24 hours after saturation in each T/RH trial was expressed relative to leaf area for each species (Figure 4.1). Data were expressed this way only for well-watered conditions (i.e. the first 24 hours after saturation) so that ET was not restricted by drying substrate with any species (Section 4.3.3). Differences in relative water loss between species were only significant in the 'warm' and 'humid' treatments (P = 0.004 and 0.009 respectively), with significantly higher water loss per unit leaf area with *Heuchera* compared to *Sedum* in both treatments, and also compared to *Stachys* in the 'humid' treatment. However, since leaf area was only measured once after all trials had been completed, plant growth over the course of the experiment is not accounted for. Results are therefore only an indication of relative water loss per unit area for each species, and are only used for comparison of species within each trial rather than across all trials.

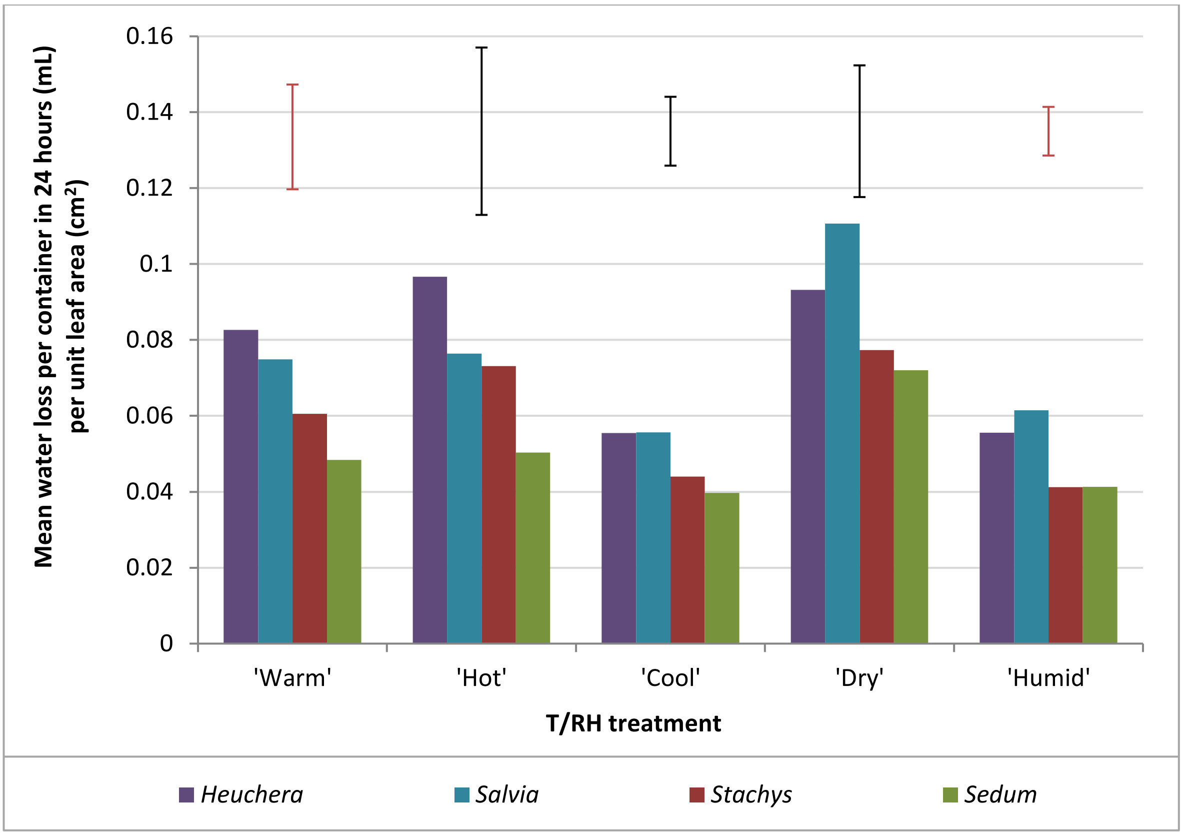
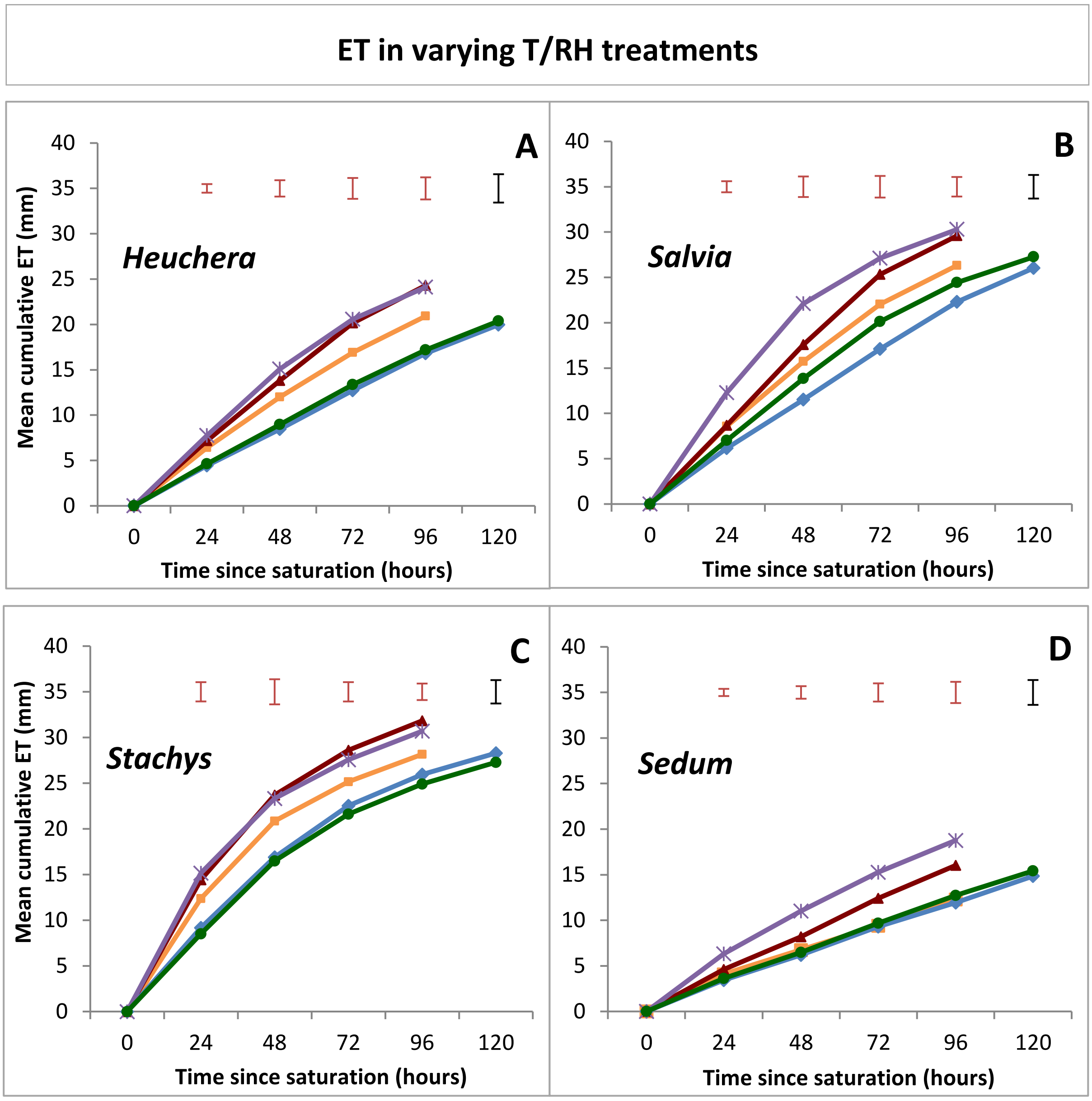


Figure 4.1: Mean water loss per container in the first 24 hours after saturation expressed relative to leaf area for each species in each T/RH trial. Data are means of 4 replicates per species with associated LSDs (5%); red bars indicate statistical differences between species within each T/RH treatment.

4.3.2 Evapotranspiration under varying temperature and humidity

To examine the effect of varying temperature and RH on ET rates, cumulative ET over the course of each trial for each species/control is presented in Figure 4.2. Within all species/control, there were significant differences in cumulative ET between T/RH treatments ($P < 0.001$). Treatments with high VPD (i.e. 'hot' and 'dry') always had significantly greater ET than treatments with low VPD (i.e. 'cool' and 'humid') with all species/control, typically close to double in the first 24 hours. Observed ET patterns for all T/RH treatments were similar with *Heuchera*, *Stachys* and control Figure 4.2 A, C and E), where cumulative ET was statistically similar in the 'hot' and 'dry' treatments and in the 'cool' and 'humid' treatments. Cumulative ET in the 'warm' treatment was between these two extremes and typically significantly different from all other treatments. With *Heuchera* and control, the differences in cumulative ET between treatments generally increased over time (e.g. for control the difference between 'dry' and 'humid' was 1.91 mm at 24 hours and 5.58 mm at 96 hours). However, this was not the case with *Stachys*, where ET differences between treatments were up to 6.67 mm at 24 hours, and remained at around 7 mm for the remainder of the trials. Daily ET rates were more similar in all T/RH treatments after the first 24 hours, gradually becoming lower in the 'warm', 'hot' and 'dry' treatments compared to the 'cool' and 'humid' treatments (data not shown).

With *Salvia*, there were significant differences in cumulative ET between the 'hot' and 'dry' treatments for the first 48 hours and between the 'cool' and 'humid' treatments between 24 and 72 hours ($P < 0.001$; Figure 4.2 B). By 96 hours, these differences were no longer observed, and the patterns of cumulative ET in all of the treatments became similar to those of *Heuchera*, *Stachys* and control. The maximum difference in cumulative ET between treatments ('cool' and 'dry') with *Salvia* increased in the first 48 hours from 6.12 to 10.61 mm but then decreased again, reaching 8.01 mm after 96 hours. There were also significant differences between the 'hot' and 'dry' treatments for the whole length of the trials with *Sedum* ($P < 0.001$; Figure 4.2 D), whilst cumulative ET in the 'warm' treatment was statistically similar to the 'cool' and 'humid' trials. Differences in cumulative ET between T/RH treatments became progressively larger over time, increasing from 2.89 mm difference at 24 hours (between 'cool; and 'dry') to 6.82 mm difference at 96 hours.



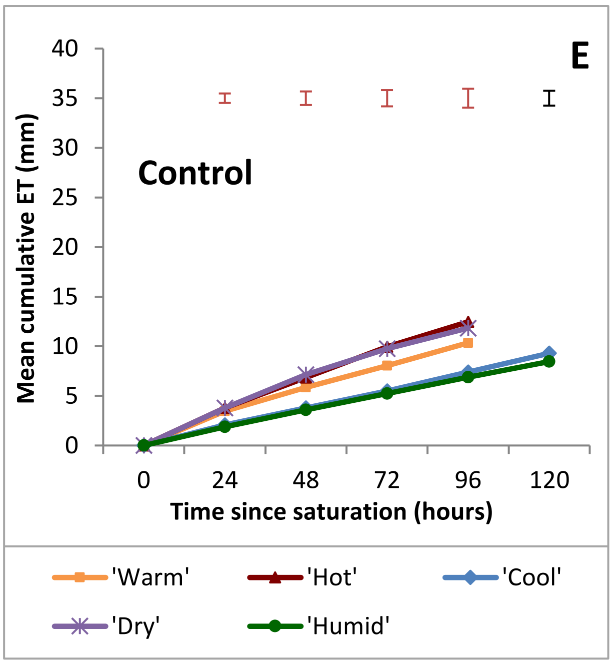


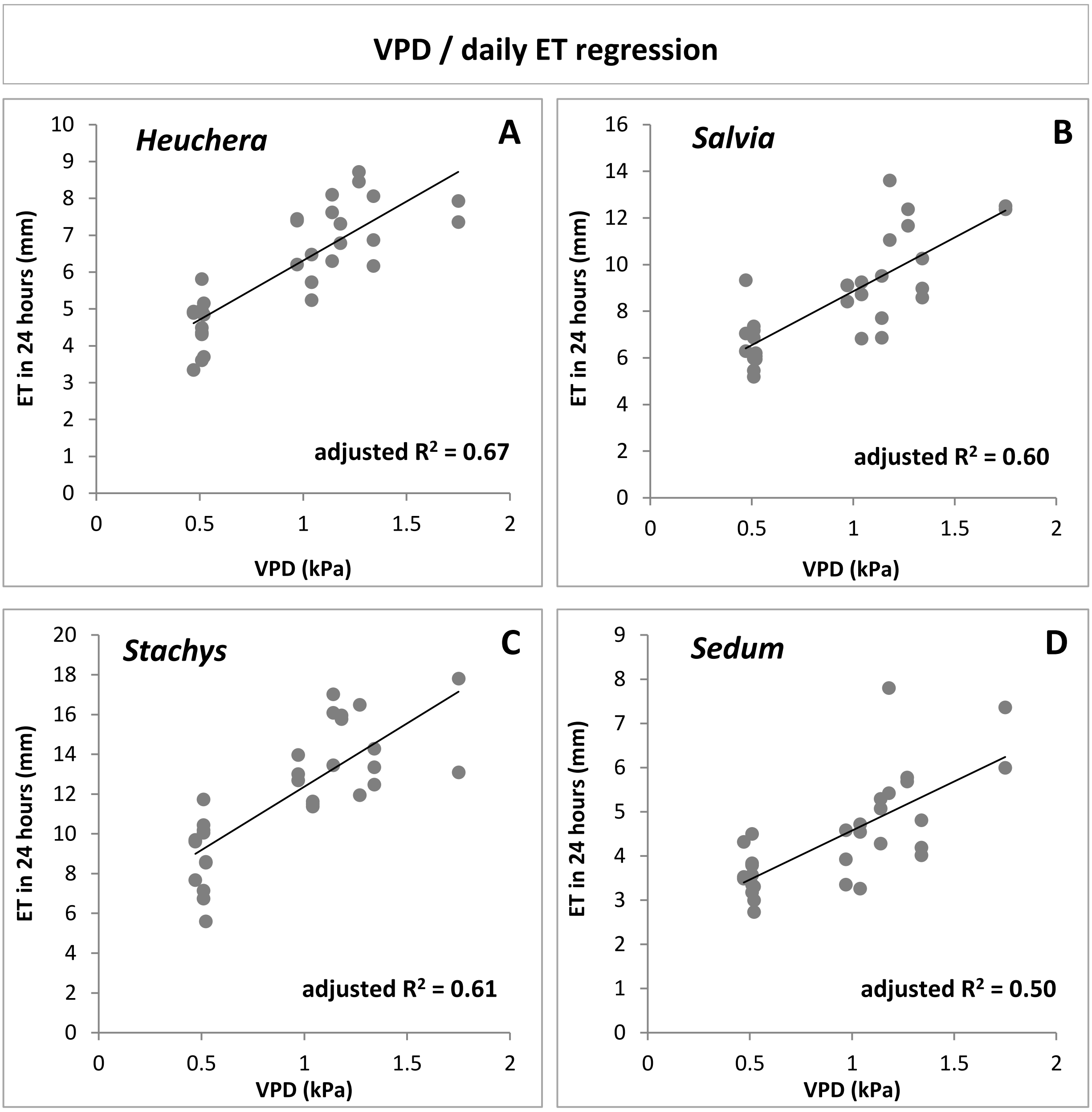
Figure 4.2: Average cumulative ET per container over the course of all T/RH trials for *Heuchera* (A), *Salvia* (B), *Stachys* (C), *Sedum* (D) and control (E). Data are means of 6 replicates per species/control with associated LSDs (5%); red bars indicate statistical differences between the means of each trial.

Regression models indicated that there was a fairly strong relationship (adjusted R^2 values between 0.47 and 0.67; Figure 4.3) between ET under well-watered conditions (i.e. in the first 24 hours after saturation when ET is not limited by decreasing SMC) and VPD for all species/control, particularly for *Heuchera*, *Salvia* and *Stachys*. Low ET in the first 24 hours was also strongly related to high RH (adjusted R^2 values between 0.50 and 0.71; data not shown), whereas the relationship between ET and air temperature was weaker for all species/control (adjusted R^2 values between 0.21 and 0.38; data not shown).

4.3.3 Effect of drying substrate on ET rates of different species

To examine the effect of drying substrate on ET, the daily ET rates of each species/control in the 'warm' treatment, along with associated SMCs at the start of each 24-hour period, are presented in Figure 4.4. Average daily VPD, which was relatively uniform for each day, is also displayed to illustrate any possible variation in the environmental conditions in the CE cabinets (Figure 4.4 A). Although absolute volumes of water lost per container differed in each T/RH treatment for each species/control, daily ET exhibited a similar decline in each T/RH treatment for all species/control; the 'warm' treatment is therefore presented here as representative of the average ET decline observed. Saturated SMCs of *Salvia* and *Stachys* were somewhat higher than for *Heuchera*, *Sedum* or control in all trials, which is likely to be a result of differing root densities affecting the water-holding capacity of the substrate. However, containers of all species/control were saturated to container capacity and SMCs were all within the well-watered range identified in Section 2.4.1 at the start of each trial.

ET and SMC of all species/control declined after Day 1. For *Stachys* the decline in daily ET was initially rapid, declining by around 4 mm day^{-1} each day (from 12.36 mm day^{-1} on Day 1 to 4.31 mm day^{-1} on Day 3), before appearing to slow, decreasing by only 1.32 mm day^{-1} on Day 4. *Stachys* SMC also declined rapidly in the first 2 days, from 0.548 m^3 m^{-3} when saturated to 0.214 m^3 m^{-3} after 2 days; after this time SMC decreased more gradually. A similar pattern was also observed in all other environmental trials (data not shown), with the decline in SMC and daily ET typically faster in the 'hot' and 'dry' treatments (reduction in daily ET of 5 – 6 mm day^{-1} on average) and slower in the 'cool' and 'humid' treatments (reduction of around 2 mm day^{-1}). *Stachys* ET was initially significantly higher than all other species/control ($P < 0.001$) but declined to such an extent that by Day 4 it was similar to *Sedum.* This pattern was also observed in all other T/RH trials: in the 'hot' and 'dry' trials *Stachys* daily ET was similar to *Sedum* by Day 3, whereas in the 'cool' trial it took until Day 5 for ET rates to become similar (data not shown).



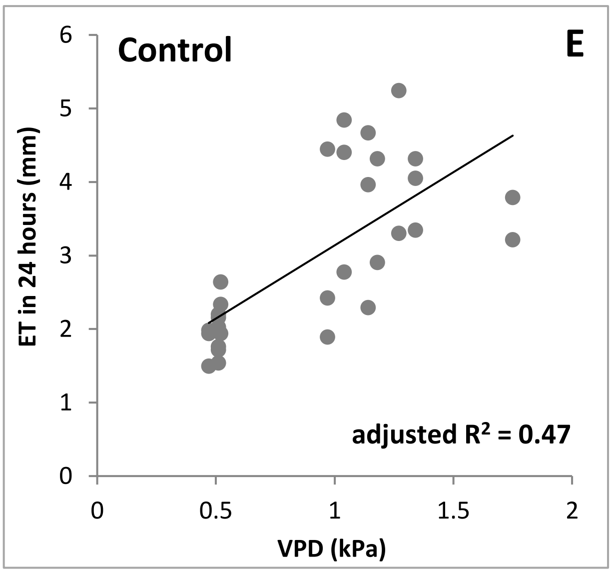


Figure 4.3: Regression models showing the relationship between VPD and daily ET under well-watered conditions (i.e. the first 24 hours after saturation) in all T/RH treatments combined for *Heuchera* (A), *Salvia* (B), *Stachys* (C), *Sedum* (D) and control (E).

The declines in both daily ET and SMC were much slower with *Sedum* and the control, with daily ET for both treatments reducing by only 1.17 mm day^{-1} from Day 1 to Day 4. In the 'cool' and 'humid' treatments, daily ET decreased by an average of only 0.76 and 0.24 mm day^{-1} from Day 1 to Day 5 for *Sedum* and the control respectively (data not shown). However, in the 'dry' treatment daily ET with *Sedum* decreased by 2.84 mm day^{-1} from Day 1 to Day 4 (data not shown).

Regression models indicated that the SMC at the start of each day could be a good indicator of the daily ET rate, depending on species/control (Figure 4.5). There was a particularly strong and significant relationship between SMC and ET for *Stachys* in all treatments (adjusted R^2 = 0.76; $P < 0.001$), whilst the relationship was weak for *Sedum* (adjusted R^2 = 0.01; $P = 0.100$) and the control (adjusted R^2 = 0.02; $P = 0.052$). However, the correlation between SMC and daily ET was typically higher in the 'dry' treatment for all species/control, with adjusted R^2 values of 0.34, 0.40, 0.64, 0.87 and 0.93 for *Sedum*, control, *Heuchera*, *Salvia* and *Stachys* respectively.

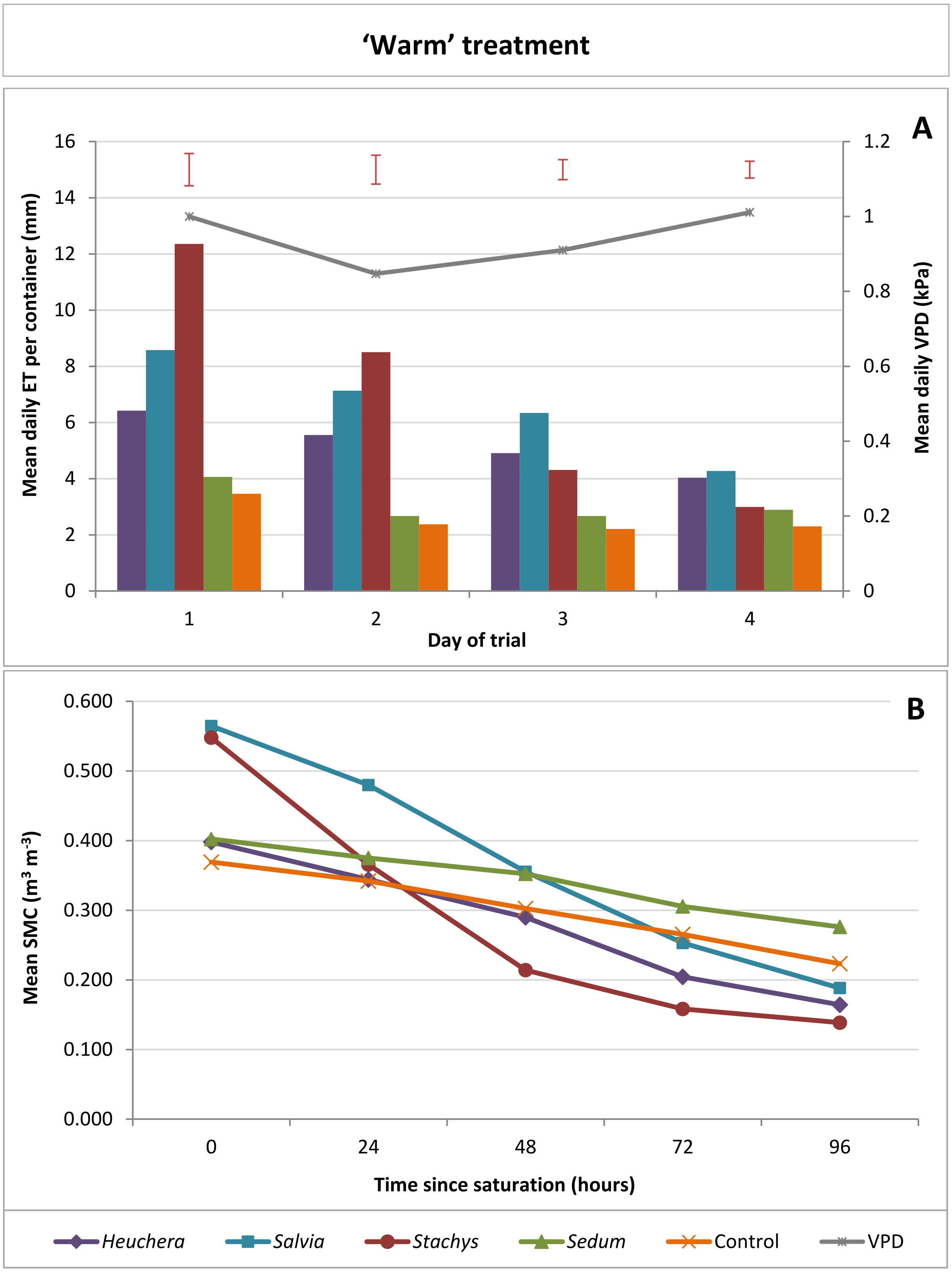


Figure 4.4: Average daily ET per container in the 'warm' trial, with mean VPD measured in the CE cabinets on each day of the trial (A), and associated average SMC of each species/control at the start of each 24-hour period (B). Data are means of 6 replicates per treatment with associated LSDs (5%); red bars indicate statistical differences between the means of species/control on each day of the trial.

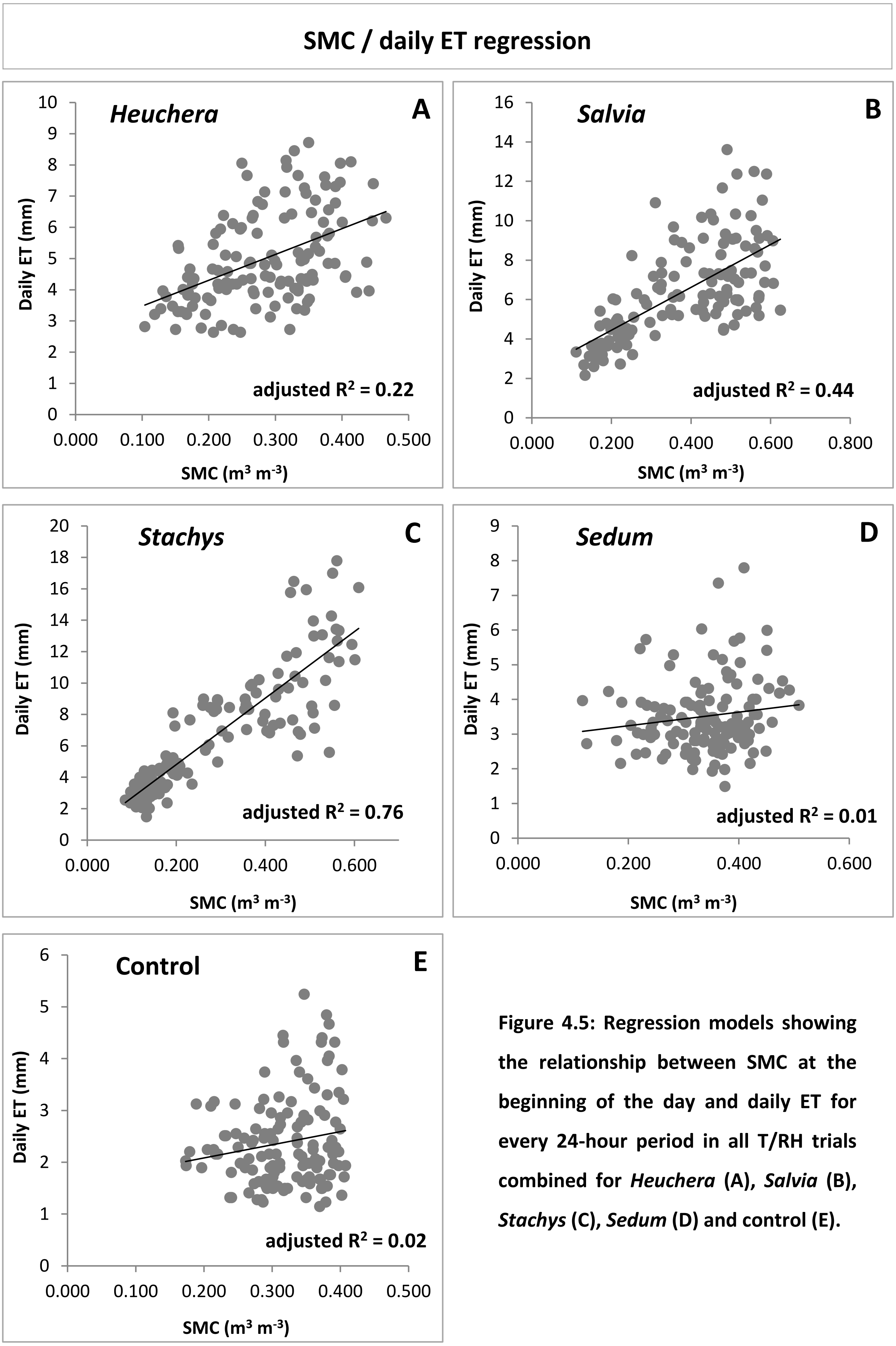


Figure 4.5: Regression models showing the relationship between SMC at the beginning of the day and daily ET for every 24-hour period in all T/RH trials combined for *Heuchera* (A), *Salvia* (B), *Stachys* (C), *Sedum* (D) and control (E).

4.4 Discussion

This chapter examined in depth the influence of varying temperature (T) and relative humidity (RH) conditions (T/RH treatments) and decreasing substrate moisture content (SMC) on the evapotranspiration (ET) rates of four plant species in the context of ET as a proxy for restoration of substrate retention capacity on a green roof, thus allowing greater rainfall retention in subsequent storms.

4.4.1 Species differences in ET rates in all climatic scenarios

Removal of moisture from the substrate through ET between storms restores the retention capacity of the substrate for rainfall retention in subsequent rainfall events (Stovin *et al.*, 2012). Varying ET rates of different species are therefore of interest as they determine the extent and speed of substrate retention capacity recharge. In the presented experiment, cumulative ET in 96 hours without irrigation ranged from 6.89 mm (control; 'humid' treatment) to 31.83 mm (*Stachys*; 'hot' treatment). The same pattern of differences between species/control was observed in all T/RH treatments for cumulative ET in 96 hours, with *Salvia* and *Stachys* always having significantly higher ET than all other species/control, whilst ET with *Heuchera* was significantly greater than *Sedum*, and control ET was significantly lower than all other species. When using stomatal conductance (g_s) as an indicator of ET, a similar pattern was observed in an earlier study with these species in outdoor plots (Vaz Monteiro *et al.*, 2017), with *Salvia* and *Stachys* having greater g_s than *Heuchera*, and *Sedum* g_s the lowest.

These results highlight the importance of species selection for optimal provision of ESs such as stormwater management on a green roof, as cumulative ET was significantly higher in all T/RH treatments with the broadleaf species, especially *Stachys* and *Salvia*, compared to *Sedum* or bare substrate. Thus, it appears that maximum rainfall retention performance on a green roof (as a result of restoration of substrate retention capacity through ET) would always be achieved with *Stachys* and *Salvia*, regardless of the predominant summertime weather conditions. Additionally, cumulative ET with *Sedum* was significantly higher than with bare substrate, in all T/RH treatments (apart from 'warm'), similar to results of other studies (Berghage *et al.*, 2007; Voyde *et al.*, 2010b). This indicates that, although the low ET rate of succulent species may limit their potential for stormwater management provision (Nagase and Dunnett, 2012), the presence of *Sedum* on a green roof enables greater rainfall retention than bare substrate alone.

ET values (both daily and cumulative) for *Sedum* were similar to those reported for succulent species in other studies, which typically range from around 1 to 3 mm day^{-1}, depending on species, SMC and weather conditions (Voyde *et al.*, 2010b; Berretta *et al.*, 2014). However, ET rates of the broadleaf species were substantially higher in all simulated T/RH summertime scenarios, with daily ETs under well-watered conditions of up to 7.76, 12.27 and 15.17 mm day^{-1} for *Heuchera*, *Salvia* and *Stachys* respectively in the 'dry' treatment. Significant differences in ET between different species have previously been identified (e.g. Berghage *et al.*, 2007; Farrell *et al.*, 2012), but these have typically been between a variety of succulent species and so ET differences were generally small. There was also substantial variation in daily ET within the broadleaf species, with the ET rate of *Stachys* plants double that of *Heuchera* under well-watered conditions. However, these differences were not apparent when water loss was expressed relative to canopy leaf area, indicating that although daily ET with *Stachys* was significantly greater when individual mature plants were considered, ET per unit leaf area was similar with all broadleaf species. Results of the presented experiment clearly highlight the superior ability of species with high ET rates to remove water from the substrate following rainfall, thus having the potential to restore the substrate retention capacity to a much greater extent than with succulent species even in just 24 hours, and allowing storage of a larger volume of rainfall in the next storm.

The presence of vegetation increases the ability of a green roof system to restore the substrate retention capacity above that of bare substrate alone, as was observed in the presented experiment, due to the additional contribution of plant transpiration (Voyde *et al.*, 2010a). The proportion of total cumulative ET after 96 hours provided by plant transpiration (see Section 4.3.1) was large, particularly for the broadleaf species (e.g. up to 60% for *Heuchera* and 72% for *Salvia* and *Stachys*, all in the 'humid' treatment), clearly demonstrating the importance of vegetation over and above bare substrate. Contribution to ET through plant transpiration was smaller with *Sedum*, especially in the 'warm' and 'hot' treatments where it was around 3 times less than *Stachys*. This again highlights the advantage of species with high transpiration rates compared to species with low ET rates such as *Sedum*, and the greater restoration of substrate retention capacity that can be achieved with these species. Voyde *et al.* (2010b) reported a plant contribution to ET of 34% with *Sedum* under well-watered conditions, decreasing to 29% of the total ET when low SMC restricted plant transpiration, as evaporation from the substrate is known to dominate ET when water supply becomes restricted (Castiglia Feitosa and Wilkinson, 2016). A similar result was obtained for *Sedum* in Experiment 4, with an average plant transpiration contribution of 32% in all trials, where *Sedum* transpiration is not thought to have been restricted by low SMC at any time during the relatively short trials. Furthermore, the contribution of plant transpiration to total ET was particularly large in low VPD treatments (‘cool’ and ‘humid’), which was likely due to limited evaporation from the bare substrate and a more abundant water supply (i.e. higher SMC) in vegetated treatments in these conditions (Voyde *et al.*, 2010b). The benefit of having vegetation on a green roof, compared to bare substrate, may therefore be the most valuable under cool, wet summertime conditions, substantially increasing restoration of substrate retention capacity, and hence overall retention performance, of the system.

4.4.2 Effect of varying temperature and humidity on ET rates

The main meteorological parameters controlling ET are solar radiation, air temperature and humidity, and wind speed (Allen *et al.*, 1998). Climatic variables that influence ET rates will affect the overall retention performance of a green roof (Sims *et al.*, 2016), by controlling the extent to which the substrate retention capacity is restored between rainfall events and thus the volume of water that can be retained in the next storm. Hence, green roof retention has been found to vary between seasons (Mentens *et al.*, 2006; Berghage *et al.*, 2007; Speak *et al.*, 2013) and between locations with different climates (Sims *et al.*, 2016). The artificial conditions inside the CE cabinets differed somewhat to natural atmospheric conditions outdoors, as radiation and wind speed were very low, which is likely to have restricted ET; measurements are therefore likely to be conservative estimates compared to natural environmental conditions.

Although every effort was made to achieve the target climatic settings in the CE cabinets, average vapour pressure deficit (VPD), which describes the vapour pressure gradient between the leaf and the air and drives ET, was similar in the ‘hot’ and ‘dry’ treatments (1.34 and 1.33 kPa respectively) and in the ‘cool’ and ‘humid’ treatments (0.53 and 0.55 kPa respectively). Since all other atmospheric parameters (i.e. radiation and wind speed) were constant in the CE cabinets throughout all T/RH trials, ET results in the ‘hot’ and ‘dry’ and in the ‘cool’ and ‘humid’ treatments were probably more similar than if the target range of VPDs had been achieved.

Relative differences in cumulative ET between T/RH treatments were similar for each species/control, and there were significant differences between treatments with all species/control. Cumulative ET in the ‘hot’ and ‘dry’ trials (i.e. high VPD) was always significantly greater than in the ‘cool’ and ‘humid’ trials (i.e. low VPD) with all species/control. This was expected as high VPD would induce greater ET, and indicates that a higher percentage of rainfall could be retained in the substrate in the ‘hot’ and ‘dry’ treatments, with all species and the control, if a rainfall event occurred at any time during the drying period. Low ET rates measured in other studies with cool, humid conditions have been found to limit the restoration of substrate retention capacity between rainfall events, thus keeping antecedent SMC high and resulting in lower overall retention performance of the green roof (Stovin *et al.*, 2012; Speak *et al.*, 2013; Volder and Dvorak, 2014). Indeed, a study with identical green roofs in a maritime climate (i.e. low VPD; Halifax, Nova Scotia) and a semi-arid climate (i.e. high VPD; Calgary, Alberta) found that, despite having similar annual rainfall totals, retention was 43.4% and 75.2% respectively, as a result of greater ET between storms in Calgary restoring the substrate retention capacity to a greater extent (Sims *et al.*, 2016). Other studies have also observed higher ET rates in warmer compared to cooler conditions, when substrate moisture was not restricted (Berretta *et al.*, 2014; Poë *et al.*, 2015). Moreover, Voyde *et al.* (2010a) hypothesised that low radiation and high RH during their study restricted ET between rainfall events and thus limited the available retention capacity of the substrate during individual storms.

With *Stachys*, *Heuchera* and control, cumulative ETs were similar in the 'hot' and 'dry' treatments and the 'cool' and 'humid' treatments, in line with the similar VPDs experienced in the CE cabinets during these trials. However, cumulative ET in the 'dry' treatment was significantly higher than in the 'hot' treatment for the first 48 hours with *Salvia* and for the whole length of the trials with *Sedum*. This suggests that these plants would therefore perform best on a green roof (i.e. provide greater rainfall retention) following dry periods with low RH and moderate temperatures. Additionally, cumulative ET in the 'humid' treatment was significantly higher than in the 'cool' treatment between 48 and 72 hours with *Salvia*. It is, however, possible that these differences could partially be a result of plant growth over the course of the experiment, as the 'dry' and 'humid' trials were conducted 2 – 4 weeks later than the 'hot' and 'cool' trials, due to the length of each trial component. Indeed, the average height and diameter of *Salvia* in particular increased between trials, whilst *Sedum* growth was relatively modest.

Daily ET with *Sedum* was fairly constant throughout the 'hot' trial (average of 4 mm day^{-1} each day), which was consistent with the steady ET rates also observed in the 'warm', 'cool' and 'humid' trials (data not shown). Conversely, in the 'dry' trial there was a greater decline in daily ET with *Sedum*, decreasing from an initially high 6.34 mm day^{-1} on Day 1 to 3.50 mm day^{-1} on Day 4 (data not shown). It is possible that the higher air temperatures during the 'hot' trial may have induced *Sedum* to utilise water conservation strategies (e.g. by switching to CAM photosynthesis; Farrell *et al.*, 2012), whilst the more moderate temperatures in the 'dry' trial did not. This could have been a response to either increased leaf temperature (as stomatal conductance (and thus ET) has been strongly linked to leaf temperature for a range of species, including succulents; Vaz Monteiro *et al*, 2016a) or heat stress experienced by the root system as substrate temperatures increased (Savi *et al.*, 2016). Indeed, *Sedum* substrate temperatures under well-watered conditions (after 24 hours) were moderately higher in the 'hot' treatment, averaging 22.7°C compared to 20.9°C in the 'dry' treatment (data not shown). Although there are a range of environmental factors that may trigger facultative CAM plants to switch to CAM photosynthesis, some *Sedum* species (e.g. *S. album*) are known to be particularly sensitive to temperature (Starry *et al.*, 2014), possibly due to a stronger influence of environmental conditions on leaf temperatures due to the lower leaf succulence (and thus thinner leaves) in these species (Farrell *et al.*, 2012; Rayner *et al.*, 2016; Vaz Monteiro et al, 2016a).

Higher VPD in the CE cabinets was strongly linked to greater daily ET under well-watered conditions (i.e. the first 24 hours after saturation), particularly for the species with high ET rates (adjusted R^2 = 0.61, 0.60 and 0.67 for *Stachys*, *Salvia* and *Heuchera* respectively). Similarly, greater ET was also strongly linked to lower RH (adjusted R^2 values between 0.50 and 0.71). Conversely, the relationship between daily ET under well-watered conditions and average daily air temperature was weaker, with adjusted R^2 values between 0.21 (*Sedum*) and 0.38 (*Heuchera*), suggesting that humidity may have a greater influence on ET than air temperature. Indeed, Voyde *et al.* (2010b) identified a correlation between RH and ET, where the daily ET rate under well-watered conditions was 2.3 mm when mean RH was 64% and only 1.1 mm when mean RH was 93%.

4.4.3 The effect of drying substrate on ET rates

The saturated SMCs of *Stachys* and *Salvia* were greater than for *Heuchera*, *Sedum* and control in all trials, possibly due to differences in rooting densities between species affecting the maximum retention capacity of the substrate (Nagase and Dunnett, 2012; Berretta *et al.*, 2014). However, SMC of all species/control declined over the course of the trials, with *Stachys* and *Salvia* SMC decreasing rapidly due to their high ET rates so that after 96 hours their SMCs were similar to *Heuchera* and significantly lower than *Sedum* SMC in all treatments except 'dry', in which *Sedum* was similar.

For ET to continue at its maximum potential rate, water must be continually supplied to the evaporating surfaces (i.e. the substrate or leaf surfaces; Verhoef and Egea, 2013). As SMC declines over time after wetting, the water supply to the evaporating surfaces becomes increasingly restricted, causing ET rates to fall (Stovin *et al.*, 2013). This was clearly observed in all T/RH trials in the presented experiment, with daily ET declining concurrently with SMC, depending on species/control, and there was a strong relationship between antecedent SMC at the beginning of each day and ET in the subsequent 24 hours identified for species with the highest ET rates (*Stachys* and *Salvia*: adjusted R^2 = 0.76 and 0.44 respectively). Indeed, daily ET with *Stachys* declined rapidly over time in all trials, particularly in the first 3 days after saturation (e.g. from 15.17 day^{-1} on Day 1 to 4.22 mm day^{-1} on Day 3 in the 'dry' treatment), probably as a result of reduced availability of substrate moisture (SMC declined from 0.495 to 0.109 m^3 m^{-3} over the same period). Consequently, by Day 3 *Stachys* ET was lower than *Heuchera* and *Salvia* ET (significantly so in the 'hot', 'dry' and 'warm' trials) and similar to *Sedum* ET; by the end of all trials, the daily ET rate of *Stachys* was approaching that of the control. These results imply that the majority of a green roof's substrate retention capacity would be restored very quickly (in the first 2 – 3 days following rainfall) with species with high transpiration rates, thus enabling the green roof to store a large volume of water in subsequent rainfall events that occur relatively close together.

Since the daily ET of these species declined whilst those with lower ET rates did not, the available substrate retention capacity would become more similar with all species (and control) after this time, indicating that the advantage of species with high ET rates (e.g. *Stachys*) over species with lower ET rates (e.g. *Sedum*) would be greatest in the first 2 – 3 days following rainfall. A similar decline in daily ET rates and a convergence of the cumulative ETs of different species were observed with succulent species in other studies (Berghage *et al.*, 2007; Voyde *et al.*, 2010b; Poë *et al.*, 2015), although typically over a much longer period of time (28 days), which may account for why this was not observed for all species/control in the short duration of these trials.

In all T/RH treatments, declines in SMC and daily ET with *Stachys*, and to a slightly lesser extent *Salvia*, were accompanied by wilting (Figure 4.6), presumably indicating low leaf water status with these species in response to drought conditions. Cameron *et al.* (2006) observed similar behaviour with *Forsythia* under severe regulated deficit irrigation, and suggested that vigorous species may continue to photosynthesise at maximum potential (based on available light), thus maintaining high stomatal conductance even when water deficit is high and plants become stressed. Similarly, (Voyde *et al.*, 2010b) noted that *Disphyma australe* did not adapt to drought stress during drying, instead depleting plant water content in order to maintain higher transpiration rates, and thus resulting in plant wilting. It is likely, therefore, that *Stachys* and *Salvia* may continue to photosynthesise, and thus transpire, at their full potential whilst light is available, quickly depleting substrate moisture and resulting in a rapid decline in subsequent ET and also leaf water status. Indeed, the g_s of these species, an indicator of ET, has previously been found to only be significantly reduced when SMC falls below 0.150 – 0.200 m^3 m^{-3} (Blanuša *et al.*, 2013; Vaz Monteiro et al, 2016a). Additionally, once *Stachys* became wilted the plants formed a very dense cover over the substrate (Figure 4.6 B), probably restricting evaporation from the substrate surface and further reducing overall ET.

Wilting of *Stachys* and *Salvia* plants was, however, temporary and they recovered quickly when irrigated at the end of each trial, with no permanent damage evident. It is therefore likely that these species could provide good rainfall retention on a green roof as long as supplementary irrigation is provided in periods of drought to ensure plant survival and continuation of high ET rates. Although the substrate retention capacity available for water storage during the next rainfall event can only be restored by a finite amount, maintaining high ET rates is advantageous for the provision of additional ecosystem services (ESs), particularly cooling (Vaz Monteiro *et al*, 2016a). Results of this experiment suggest that irrigation would be required after an average of 3 - 4 dry days, depending on T and RH conditions, in order to maintain plant health and high ET rates with *Stachys*.

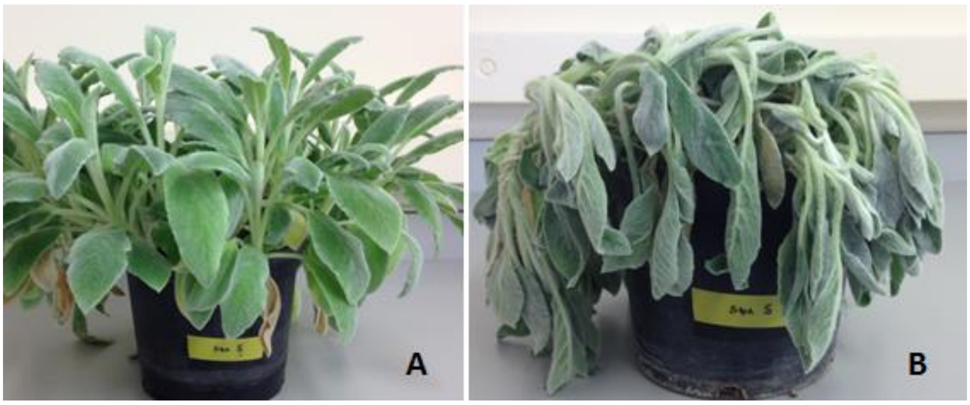


Figure 4.6: Example of a *Stachys* plant under well-watered conditions (A) and the same plant after 4 days with no irrigation in the 'dry' treatment (B), showing extreme turgor loss.

In contrast, with *Sedum* and the control, the relationship between antecedent SMC and daily ET in all trials was extremely weak, with adjusted R^2 values of 0.01 and 0.02 respectively. Moreover, in contrast to other studies (e.g. Voyde *et al.*, 2010b), ET rates did not decline over the course of the trials, probably because of the short duration of the trials and the consistently low daily ET rates limiting the depletion of substrate moisture. A rapid decline in stomatal conductance (and thus transpiration) of *Sedum* species when they switch to CAM photosynthesis in response to low SMC has previously been observed (D'Arco *et al.*, 2017). Additionally, *Sedum spurium* is considered to have relatively low leaf succulence compared to other *Sedum* and succulent species, likely reducing its ability to survive in severe drought conditions (Farrell *et al.*, 2012). However, substrate moisture did not appear to become restricted with *Sedum* in the presented experiment due to the short duration of the trials and its low ET rate, and so these effects were not observed.

4.5 Key Conclusions

- ET rates differed significantly between species under all T/RH treatments: *Stachys* and *Salvia* had the highest rate of water loss and therefore potential to quickly restore the substrate's retention capacity, and thus the capacity to provide the greatest overall rainfall retention. *Sedum* had the lowest ET rate in all treatments but this was significantly greater than the control, confirming that the use of *Sedum* on a green roof would result in better rainfall retention than bare substrate alone.
- There were significant differences in the rate of water use in different T/RH simulated summertime scenarios for all species; the highest ET rates were observed in high VPD treatments ('hot' and 'dry'). With *Sedum* and *Salvia*, ET rates were significantly higher during some or all of the 'dry' trial compared to the 'hot' trial, indicating that provision of stormwater management can be maximised by selecting the plants best suited to a the environment in a particular location. For example, the best stormwater management provision with *Sedum* is likely to be achieved in 'dry' conditions.
- The contribution of plant transpiration to total ET, and thus to restoration of substrate retention capacity between storms, was greater in 'cool' and 'humid' conditions, when evaporation from the bare substrate was very low. Transpiration by broadleaf species contributed to total ET more than *Sedum*.
- *Stachys* and *Salvia* removed water from the substrate at a high rate, even as SMC decreased, suggesting that these species could provide a good rainfall retention service (and additional ESs such as cooling) if supplementary irrigation is provided in periods of drought (approximately every 3 – 4 days) to maintain plant health and these high ET rates.

Chapter 5

An ET-based model for sustainable irrigation management of green roofs to ensure maintenance of ecosystem services provision

5.1 Introduction

Plants require water for their health and growth as well as for the maintenance of ecosystem services (ESs) provision, particularly those which depend on evapotranspiration (ET) such as cooling (Vaz Monteiro *et al.*, 2017) and stormwater management (through restoration of substrate retention capacity between storms; Chapters 3 and 4). Ensuring that adequate soil moisture is maintained is therefore essential (Bean and Pitt, 2012). Green roof planting choices have generally been dominated by succulent species, such as *Sedum*, due to their ability to survive without irrigation (Butler and Orians, 2011) since their water requirements should typically be fulfilled by rainfall alone in the UK (GRO, 2014). However, research has shown that provision of some ESs (e.g. cooling and stormwater management) could be maximised by selecting alternative species with high transpiration rates (Blanuša *et al.*, 2013; Vaz Monteiro *et al.*, 2017; Chapter 3). These species typically have higher water requirements, and supplementary irrigation of a green roof planted with these species is therefore likely to be required, particularly during prolonged dry periods in the summer, in order to maintain high ET rates and provision of ESs (Blanuša *et al.*, 2013). Indeed, experimental results presented in Chapter 4 indicated that species with high ET rates (*Stachys* and *Salvia*) are likely to require irrigation every 3 – 4 days during dry periods. Furthermore, climate change projections indicate changing precipitation patterns and longer periods of drought in the UK (IPCC, 2013), which is likely to increase the requirement for supplementary irrigation of all green roofs in the summer to maintain plant health (Van Mechelen *et al.*, 2015).

As well as the potential to use greywater as a sustainable water source (see Chapter 6), supplementary irrigation should be efficiently managed to optimise the timing and amount of water used, thus minimising green roof maintenance costs and avoiding excess runoff and potential leaching issues due to over-irrigation (Kashyap and Panda, 2001; Snyder *et al.*, 2015). In agriculture, estimating crop ET has proven to be an effective method of determining the irrigation requirements of specific crops (Droogers and Allen, 2002), thus allowing irrigation timing, frequency and volume to be scheduled and ensuring optimal efficiency of time and water resources without compromising yield. Employing irrigation management similar to these agricultural methods for the efficient irrigation of green infrastructure, including green roofs, has the potential to reduce water demand for irrigation in urban areas whilst also maintaining plant health and aesthetic quality and provision of ESs.

5.1.1 FAO-56 Penman-Monteith model for estimating evapotranspiration

Crop ET can be estimated by direct measurement (e.g. using weighing lysimeters or the soil water or energy balance methods) or by modelling (see Section 1.3.5). Disparity in ET estimates obtained with different models led to the creation of a standardised model based on the Penman-Monteith equation, developed in FAO Drainage and Irrigation Paper No. 56 (Allen *et al.*, 1998). This model was recommended for all ET calculations and provides methods for obtaining or estimating all of the necessary meteorological parameters.

The Penman-Monteith equation was developed from the original Penman equation (1948), which combined mass transfer with the energy balance to calculate evaporation from open water surfaces, by adding resistance factors in order to apply the equation to cropped surfaces. The equation takes the form (Allen *et al.*, 2006):

$$ET = \frac{\Delta\,(R_n - G) + \rho_a\, c_p\, \frac{(e_s - e_a)}{r_a}}{\left(\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)\right)\rho_w \lambda} \qquad \text{(Eq. 5.1)}$$

where ET is the evapotranspiration in mm day^{-1}, λ is the latent heat of vaporisation (MJ kg^{-1}), R_n is the net radiation reaching the surface (MJ m^{-2} day^{-1}), G is the soil heat flux (MJ m^{-2} day^{-1}), ρ_a is the air density at constant pressure (kg m^{-3}), c_p is specific heat of the air (J kg^{-1} K^{-1}), ρ_w is the density of liquid water (kg m^{-3}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), r_a is the aerodynamic resistance (s m^{-1}), Δ is the slope of the saturation vapour pressure temperature curve (kPa °C^{-1}), ϒ is the psychrometric constant (which is a function of atmospheric pressure and thus elevation; kPa °C^{-1}) and r_s is the bulk surface resistance (s m^{-1}). Equation 5.1 includes all of the meteorological parameters that influence ET: radiation is described by the (R_n - G) term, wind speed is a parameter of the r_a term (see Eq. 5.2), and air temperature and humidity are accounted for in the (e_s-e_a) term, which is effectively vapour pressure deficit (VPD).

Additionally, the characteristics of the specific crop are incorporated into the equation by the two resistance terms, r_a and r_s, thus allowing the ET of the crop to be calculated directly.

The aerodynamic resistance, r_a, describes the resistance to the transfer of water vapour from the evaporating surface into the atmosphere (i.e. the boundary layer resistance), and is given by (Allen *et al.*, 1998):

$$r_a = \frac{ln\left(\frac{z_m - d}{z_{om}}\right)\, ln\left(\frac{z_h - d}{z_{oh}}\right)}{k^2\, u_z} \quad \text{(Eq. 5.2)}$$

where z_m is the height at which wind measurements were recorded (m), z_h is the height of humidity measurements (m), d is the zero plane displacement height (m), z_{om} is the roughness length governing momentum transfer (m), z_{oh} is the roughness length governing transfer of heat and vapour (m), k is Von Karman's constant (0.41), and u_z is the wind speed at height z (m s^{-1}). Values of d, z_{om} and z_{oh} vary depending on crop architecture and can be calculated from Equations 5.3 – 5.5 where h is the crop height (m):

$$d = \frac{2}{3}\, h \quad \text{(Eq. 5.3)}$$

$$z_{om} = 0.123\, h \quad \text{(Eq. 5.4)}$$

$$z_{oh} = 0.1\, z_{om} \quad \text{(Eq. 5.5)}$$

The r_a term assumes neutral atmospheric stability with no heat exchange, and may require stability correction factors when calculation timesteps are very short (i.e. less than hourly).

The surface resistance, r_s, describes the total resistance to flow of the water vapour through the leaves (Allen *et al.*, 1998):

$$r_s = \frac{r_l}{LAI_{active}} \quad \text{(Eq. 5.6)}$$

where r_l is the bulk stomatal resistance of the well-illuminated leaf (s m^{-1}) and LAI_{active} is the active (sunlit) leaf area index (LAI), which is approximately 0.5 LAI. Although bulk stomatal resistance, r_l, describes the average resistance of a single leaf and is therefore crop specific, r_l may also vary depending on crop management, the age of the crop, water availability and climate (Allen *et al.*, 1998; Schneider, 2011). Additionally, LAI_{active} for a crop may vary through its growth stages, and also depends on crop type and density.

Both resistance terms show variability even within a specific crop type, since crop characteristics may vary with climate, soil water status, growth stage and so on, and it may be difficult and time consuming to calibrate ET for every crop condition. Thus, in order to simplify ET calculations, the FAO created a standardised version of the Penman-Monteith equation (hereafter referred to as the FAO-56 PM equation) in Drainage and Irrigation Paper No. 56 (Allen *et al.*, 1998), in which ET is calculated for a standard 'reference' surface, as in Equation 5.7:

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{T + 273}\,u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)} \qquad \text{(Eq. 5.7)}$$

where ET_o is the ET of the reference crop, known as the reference ET (mm day^{-1}), T is the mean daily air temperature at a height of 2 m (°C), u_2 is the wind speed at a height of 2 m (m s^{-1}) and all other terms are as previously described.

The reference surface is defined as a hypothetical crop with a uniform height of 0.12 m, an albedo of 0.23 and a fixed surface resistance of 70 s m^{-1}, which is designed to represent a well-watered, actively growing grass surface with 100% ground coverage (Allen *et al.*, 1998). The reference surface is also assumed to be extensive (at least 50 m in all directions) and homogenous so that only vertical fluxes are included and any horizontal fluxes (e.g. advection) can be ignored (Allen *et al.*, 2005; see Section 5.4.1 for further discussion). Since all crop-specific parameters are incorporated into the reference surface, calculation of ET_o only requires input of easily obtained weather parameters (which can be estimated where data are missing), and as such it expresses the evaporative demand of the atmosphere irrespective of specific crop characteristics. Thus, the purpose of ET_o is to give a reference ET that the ET of other crops can be related to and that ET at different locations and different times of the year can also be compared to.

The actual ET of a specific crop (ET_c) can be estimated from ET_o by using a crop coefficient (K_c), so that:

$$ET_c = ET_o \times K_c \qquad \text{(Eq. 5.8)}$$

The crop coefficient incorporates all of the characteristics of the particular crop that differ from those of the reference crop and may affect ET (e.g. crop size and architecture, crop albedo, stomatal resistance) without the need to measure them directly (as in Eq. 5.1), and a standard K_c for a crop may theoretically be applied to ET_o calculated in any location and at any time of the year (Allen *et al.*, 1998; Nouri *et al.*, 2013). K_c can be determined using Eq. 5.8 by measuring the actual ET_c of a crop (with a direct method, such as weighing lysimeters; see Section 1.3.5) and comparing it with the ET_o calculated from meteorological parameters for the same time period and location to give K_c. ET_c for that crop could then be estimated in any environmental conditions using Equations 5.7 and 5.8, by calculating ET_o with the specified weather conditions and then applying the pre-determined K_c.

5.1.2 Application of FAO-56 PM for estimating evapotranspiration on green roofs

The vast majority of currently available ET data and crop coefficients are for agricultural crop species, and many studies have demonstrated that the FAO-56 PM model can provide accurate estimates of daily crop ET (e.g. Liu *et al.*, 2002). However, studies using FAO-56 PM for estimation of ET from species other than agricultural crops (e.g. wetland species) have demonstrated the importance of calculating an accurate K_c value for each individual species, location and environmental conditions (Borin *et al.*, 2011). Indeed, the characteristics of urban environments and the vegetation used on green roofs may differ vastly from those of agricultural crops (Nouri *et al.*, 2013), and a separate database of values and coefficients specific to those species therefore needs to be established. Some studies have attempted to model ET or identify K_c values for green roof species using the FAO-56 PM method (e.g. Schneider *et al.*, 2011; Locatelli *et al.*, 2014; Poë *et al.*, 2015), but these primarily use *Sedum*, and there has been no attempt to identify crop coefficients for alternative species with high ET rates that may be able to maximise the provision of ESs on a green roof. Identifying crop coefficients for these species would provide green roof managers with information regarding the water requirements of each specific species based on their ET, which would enable efficient scheduling of green roof irrigation (i.e. timing and quantity of irrigation). This could therefore ensure efficient use of limited water resources whilst also maintaining plant health, high ET rates and thus continued provision of ESs such as cooling and stormwater management.

Some of the underlying assumptions in the FAO-56 PM equation may compromise the validity or accuracy of using this model for calculation of ET on green roofs, in particular the assumption that the crop is an extensive surface of at least 50 m in all directions, thus allowing horizontal fluxes to be ignored (Allen *et al.*, 2005). Green roofs are generally rather smaller than the agricultural fields for which FAO-56 PM was designed, and horizontal fluxes may be more significant than is accounted for by the equation. Additionally, green roofs often have mixed plant types, do not always maintain 100% ground coverage, and are often subject to soil water deficits (Nagase and Dunnett, 2010; Heim and Lundholm, 2016). Moreover, there may be additional energy fluxes from the building below the green roof that are not accounted for in the FAO-56 PM equation (Locatelli *et al.*, 2014).

5.1.3 Study aims

Once crop coefficients for individual green roof plant species have been identified, the FAO-56 PM model could potentially be used to estimate and predict daily ET in any weather conditions, allowing green roof managers to determine when irrigation is necessary in order to maintain plant health and provision of ESs. Crop coefficients have been calculated for a wide range of agricultural crops, but there has been little research to identify the K_c values of landscape plants (e.g. Lazzarin *et al.*, 2005), though there is a clear use for them in irrigation scheduling by allowing easy calculation of green roof ET from measurement of simple meteorological data.

The aim of this chapter was therefore to use the FAO-56 PM model to estimate K_c values for the four tested potential green roof species (*Heuchera*, *Salvia*, *Stachys* and *Sedum*) to contribute towards a database of crop coefficients for species suitable for use in green infrastructure. These K_c values were then used to create an example of a basic irrigation management reference table, with estimated daily ET_c of each species in a range of UK summertime weather conditions. The purpose of this table is to provide a quick and simple reference table from which a green roof manager could easily identify estimated daily ET_c from a green roof vegetated with one of these species, based on simple observations of the weather (i.e. cloud cover and wind conditions) without the need for any equipment or direct measurements. This would then inform the scheduling of supplementary irrigation (with mains water or greywater), based on cumulative estimated ET for a particular species during dry periods, in order to maintain plant health and provision of ESs. By scheduling irrigation according to specific plant water requirements (based on ET), it could also help to manage water resources in a sustainable way, especially if greywater is used for irrigation, thus lowering green roof maintenance costs. Furthermore, cost and time efficiencies would be increased by using a reference table to look up estimated daily ET_c instead of measuring ET each day, as it requires no equipment and very little input from a green roof manager.

For the purpose of creating an example irrigation management reference table, three simple hypothetical weather scenarios for a UK summertime, based on cloud cover, were chosen: 'blue sky' (i.e. clear skies and bright sunshine all day); 'sunny spells' (i.e. mixed sunshine and cloud throughout the day); and 'overcast' (i.e. full cloud cover). Since irrigation is only intended to supplement rainfall, all scenarios are dry days. Since wind speed also affects ET and is independent of the other parameters that may be inferred from cloudiness (i.e. solar radiation, temperature and RH), two easily observable wind conditions were used for each scenario – 'calm' and 'windy'. Basic observations of the weather should thus enable classification of each day into one of the 6 hypothetical weather scenarios, without overcomplicating the input required from the green roof manager.

Specific objectives of this study were therefore:

- To use the FAO-56 PM model to estimate K_c values for each species (*Heuchera*, *Salvia*, *Stachys* and *Sedum*) based on actual ET (ET_a) measured in Experiment 3 and the corresponding calculated reference ET (ET_o) to contribute towards a database of K_c values of potential green roof species;
- To use the estimated K_c values of each species and calculated ET_o for 6 weather conditions to estimate daily ET_c in these hypothetical UK summertime weather scenarios, classified by the simple daily weather observations described above;
- To create an example of an irrigation management reference table with estimated daily ET_c for each species under each of these weather scenarios to enable a green roof manager to schedule irrigation (ideally with greywater) based on simple daily weather observations in order to maintain ESs provision whilst also managing water sustainably.

5.2 Materials and Methods

Actual ET (ET_a) data from Experiment 3 (rainfall retention experiment), in conjunction with measured meteorological parameters for the same period (13th – 16th April 2016), were used to calculate K_c values for each species. The plant material and substrate used in Experiment 3 are described in Sections 2.3 and 2.4, and the experimental procedure is outlined in Sections 2.6.3 – 2.6.5. Daily ET from trays of each species (*Heuchera*, *Salvia*, *Stachys* and *Sedum*) following rainfall application under 'saturated' conditions (see Section 3.2.1) was measured as described in Section 2.5.2. Since all trays were generally weighed between 11:30 and 15:30 each day following rainfall application in Experiment 3, the 'days' referred to in these calculations correspond to the period 13:31 on one day to 13:30 on the following day rather than calendar days. All calculation procedures for ET_o and K_c outlined below follow the guidelines and equations described by Allen *et al.* (1998).

5.2.1 Experiment 3 actual evapotranspiration, ET_a

ET_a in mm day^{-1} for each individual tray was calculated using Equation 1.1 (see Section 1.3.5). In order to account for differences in the sizes of each plant canopy, plot area was taken to be the surface area covered by the canopy and was calculated from diameter measurements of each replicate made during Experiment 3. The plants used in Experiment 3 were large and fully grown, with good coverage of the substrate (typically 100% for all species except *Heuchera*, which had approximately 90% coverage on average), and were therefore considered to be representative of mature plants during the summer on a green roof. ET data for the period 24 – 48 hours after rainfall in the 'saturated' run (see Section 3.2.1) were used in the calculations to ensure that, whilst substrate moisture was not limiting, the substrate had fully drained to field capacity following the rainfall application. Average substrate moisture content (SMC) was high in this period (0.533, 0.530, 0.548 and 0.549 m^3 m^{-3} on average for *Heuchera*, *Salvia*, *Stachys* and *Sedum* respectively; data not shown) and plants could therefore be considered 'well-watered' but not waterlogged, thus satisfying underlying assumptions of the FAO-56 PM equation. Since two replicate trays of each species were tested each day over 3 consecutive days in Experiment 3, the period of 24 – 48 hours after rainfall fell on different dates for different replicates, as summarised in Table 5.1; these are hereafter referred to as Days 1, 2 and 3 for the purposes of this chapter. Values of ET_a, ET_o and K_c were therefore calculated for each species for each of the three days individually, and then average values per species were determined.

Table 5.1: Summary of the dates of rainfall application to each replicate tray in Experiment 3 and the dates that therefore correspond to the period 24 – 48 hours after rainfall.

Experimental 'day'	Date of rainfall application (13:30 on average)	Dates covered by 24-48 h period (13:31 – 13:30)	Tray replicates (of all species)
Day 1	12th April 2016	13th – 14th April 2016	1 and 2
Day 2	13th April 2016	14th – 15th April 2016	3 and 4
Day 3	14th April 2016	15th – 16th April 2016	5 and 6

5.2.2 Experiment 3 reference evapotranspiration, ET_o

ET_o for each of the 24-hour time periods (i.e. Days 1, 2 and 3) was calculated using Equation 5.7. Since ET_o only takes into account meteorological parameters (as all crop characteristics are set by the reference crop), one ET_o value was obtained per 'day'. Daily maximum and minimum air temperature (T_{max} and T_{min}) and relative humidity (RH_{max} and RH_{min}) for each 24-hour period were obtained from Tinytag data recorded inside the glasshouse every 30 minutes during Experiment 3. These were then used to calculate mean daily air temperature (T; °C), the slope of the saturation vapour pressure curve (Δ; kPa $°C^{-1}$), saturation vapour pressure (e_s; kPa) and actual vapour pressure (e_a; kPa) using Equations 5.9 – 5.13:

$$T = \frac{T_{max} + T_{min}}{2} \quad \text{(Eq. 5.9)}$$

$$e^o(T) = 0.6108\, exp\left(\frac{17.27\, T}{T + 237.3}\right) \quad \text{(Eq. 5.10)}$$

$$\Delta = \frac{4098\ e^o(T)}{(T + 237.3)^2} \quad \text{(Eq. 5.11)}$$

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \quad \text{(Eq. 5.12)}$$

$$e_a = \frac{e^o(T_{min})\ \frac{RH_{max}}{100} + e^o(T_{max})\ \frac{RH_{min}}{100}}{2} \quad \text{(Eq. 5.13)}$$

where $e^o(T)$, $e^o(T_{max})$ and $e^o(T_{min})$ are the saturation vapour pressures at temperature T, T_{max} and T_{min} respectively (kPa).

The psychrometric constant (ϒ; kPa $°C^{-1}$) was calculated with Equation 5.14, where P is the atmospheric pressure (kPa) calculated from the elevation above sea level (z; m) of the experimental site (taken as 60 m for Reading; Google Maps, 2016) as in Equation 5.15.

$$\gamma = 0.665 \times 10^{-3}\, P \quad \text{(Eq. 5.14)}$$

$$P = 101.3\left(\frac{293 - 0.0065\, z}{293}\right)^{5.26} \quad \text{(Eq. 5.15)}$$

Wind speed inside the glasshouse was not measured directly but was assumed to be very low due to the sheltering effect of the glasshouse. Using estimated wind speed in the FAO-56 PM equation has proven to have a relatively low impact on the calculated ET_o (Cai *et al.*, 2007), and so a daily average wind speed (u_2) of 0.5 m s^{-1} was used in all calculations; this is the minimum value recommended by Allen *et al.* (1998) in order to improve the accuracy of ET_o calculations at very low wind speeds. As ET_o was calculated at daily timesteps, daily soil heat flux (G) was assumed to be zero (Allen *et al.*, 1998).

R_n was calculated using Equation 5.16, where R_{ns} and R_{nl} are the net shortwave and net longwave radiation respectively.

$$R_n = R_{ns} - R_{nl} \qquad \text{(Eq. 5.16)}$$

5.2.2.1 Net shortwave radiation, R_{ns}

Net shortwave radiation, R_{ns}, was calculated using Equation 5.17, where α is the albedo of the crop surface (0.23 for the reference crop) and R_s is the incoming shortwave/solar radiation at the surface (MJ m^{-2} day^{-1}).

$$R_{ns} = (1 - \alpha)R_s \qquad \text{(Eq. 5.17)}$$

For the whole experimental period, five minute averages of incoming shortwave radiation (R_s) data were obtained from the University of Reading Atmospheric Observatory (UoR AO), located approximately 600 m away from the glasshouses on the Whiteknights campus. Radiation data were converted from W m^{-2} to MJ m^{-2} day^{-1} by multiplying by a conversion factor of 0.0864 (Allen *et al.*, 1998) and averages were calculated for each 'day'.

As Experiment 3 took place inside a glasshouse, it was necessary to adjust R_S values obtained from the UoR AO to reflect the fact that some fraction of incoming solar radiation is reflected from and absorbed by the glass, thus decreasing the actual R_s reaching the plant surfaces. The transmissivity of a glasshouse can be described by a transmissivity coefficient (τ), which varies depending on the angle of the sun (affected by time of day, time of year and latitude), glasshouse type, orientation and cleanliness, and daily atmospheric conditions including cloud cover and the resultant effect on the proportion of radiation reaching the glasshouse as direct beam or diffuse radiation (Oke, 1987). There are further spatial variations of R_s within a glasshouse due to shading of some areas by construction materials and the varying aperture of glasshouse vents, which may allow radiation to enter directly when vents are open wide.

Estimating the reduction in R_s inside a glasshouse by modifying outdoors R_s measurements with a glasshouse transmissivity coefficient has previously yielded good results (Valdés-Gómez *et al.*, 2009). Therefore, an attempt was made to estimate the transmissivity (τ) of the glasshouse compartment used in Experiment 3, which was in a multi-span glasshouse with an approximately east-west orientation. Light levels (photosynthetically active radiation; PAR) inside and outside the glasshouse were measured using an SKP 215 PAR Quantum Sensor attached to a SpectroSense 2+ 8-channel meter (Skye Instruments, Powys, UK) held approximately 1 m above the ground (the average height of the plant canopies on benches in Experiment 3). The transmissivity of glass to PAR is reported to be marginally higher (0.03 – 0.06) than to the entire solar spectrum (Kittas *et al.*, 1999; Papadakis *et al.*, 2000), and so the calculated τ should be considered an upper estimate.

Measurements were repeated on three separate occasions throughout the day (approximately 08:50 – 09:00, 13:00 – 13:10 and 16:50 – 17:00) on a bright, sunny day (3rd October 2016). At each measuring time, 10 light measurements were made inside the glasshouse and 10 were made outside, with measurements made alternately inside and outside and as close together as possible so that results were not affected by any changes in environmental conditions. Measurements inside were made in the centre of the glasshouse compartment and measurements outside were made as close to the glasshouse as possible without being in its shadow. A summary of the results of the light measurements and τ calculations are presented in Table 5.2. A daily average τ value of 0.62 was obtained, which was similar to glasshouse τ values reported in other studies (e.g. 0.51 - 0.73; Heuvelinka *et al.*, 1995); this value was then used to calculate R_{ns}, using a modified version of Equation 5.17:

$$R_{ns} = (1 - \alpha) \times (R_s \, \tau) \qquad \text{(Eq. 5.18)}$$

Table 5.2: Average light (photosynthetically active radiation; PAR) measured inside and outside the glasshouse compartment used in Experiment 3 on three occasions on a clear, sunny day (3rd October 2016).

Measurement time	**PAR (µmol m^{-2} s^{-1})**		**Transmissivity (τ)**
	Inside glasshouse	**Outside glasshouse**	
08:50 - 09:00	179.0	390.8	0.46
13:00 - 13:10	935.0	1231.3	0.76
16:50 - 17:00	59.8	95.2	0.63
Average τ	-	-	**0.62**

5.2.2.2 Net longwave radiation, R_{nl}

Net longwave radiation, R_{nl}, was calculated from Equation 5.19, a modified form of the Stefan-Boltzmann law, which states that the emission of longwave radiation from a surface is proportional to its temperature (in K) raised to the fourth power. However, the net flux at the Earth's surface is also influenced by absorption and emittance of longwave radiation from the atmosphere due to the presence of clouds, water vapour and gases (Allen *et al.*, 1998), and consequently Equation 5.19 also contains correction factors for the humidity and cloudiness of the atmosphere.

$$R_{nl} = \sigma \left(\frac{{T_{max}}^4 + {T_{min}}^4}{2} \right) \left(0.34 - 0.14 \sqrt{e_a} \right) \left(1.35 \frac{R_s}{R_{so}} - 0.35 \right) \qquad \text{(Eq. 5.19)}$$

where σ is the Stefan-Boltzmann constant (4.903 x 10^{-9} MJ K^{-4} m^{-2} day^{-1}), T_{max} and T_{min} are the maximum and minimum absolute temperatures during the day respectively (K), R_{so} is the clear-sky radiation (MJ m^{-2} day^{-1}) and R_s and e_a are as previously described. R_{so}, calculated from Equation 5.20, gives the potential maximum amount of solar radiation reaching the surface on any given day assuming zero cloud cover, and as such is a function of latitude and time of year, both of which are incorporated into the calculation of extraterrestrial radiation, R_a (Equation 5.21). R_s/R_{so} in Equation 5.19 thus describes the relative solar radiation reaching the surface at a particular location compared to the maximum amount possible on any given day and must therefore have a value ≤ 1. Since the calculations here relate to a glasshouse experiment, calculated R_{so} values were also adjusted with the glasshouse transmissivity coefficient of 0.62 to be in line with R_s values.

$$R_{so} = (0.75 + 2 \times 10^{-5}\, z)\, R_a \qquad \text{(Eq. 5.20)}$$

$$R_a = \frac{24(60)}{\pi} G_{sc}\, d_r \left[\omega_s \, \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s \right] \qquad \text{(Eq. 5.21)}$$

where R_a is the extraterrestrial radiation (MJ m^{-2} day^{-1}), z is the elevation above sea level (m), G_{sc} is the solar constant (0.0820 MJ m^{-2} day^{-1}), d_r is the inverse relative distance between the Earth and the sun, ω_s is the sunset hour angle (radians), φ is the latitude (radians) and δ is the solar declination (radians). The latitude of Reading was taken as 51°21' (Google Maps, 2016) which converted to 0.898 radians. d_r, δ and ω_s were calculated from Equations 5.22 – 5.24, where J is the Julian day (between 1 and 365/366). Since the 'days' used in the ET_o calculations covered the period 13:31 on one day to 13:30 on the following day and were therefore not exact Julian days,

R_a was calculated for both Julian days covered in each 24-hour period, and the average R_a for each experimental 'day' was then used in further calculations.

$$d_r = 1 + 0.033 \cos\left(\frac{2\,\pi}{365}\,J\right) \quad \text{(Eq. 5.22)}$$

$$\delta = 0.409 \sin\left(\frac{2\,\pi}{365}\,J - 1.39\right) \quad \text{(Eq. 5.23)}$$

$$\omega_s = arccos\,[-\tan\varphi\tan\delta] \quad \text{(Eq. 5.24)}$$

5.2.2.3 Summary of Experiment 3 ET_o input parameters

Summaries of all of the constants and calculated parameters for each 'day' of Experiment 3 that were used in the calculation of ET_o are given in Table 5.3 and Table 5.4 respectively. Using these input values, ET_o for each experimental day was calculated using Equation 5.7.

Table 5.3: Constants used in the calculation of ET_o and their sources.

Constant	Units	Value used	Source
z	m	60	Google Maps (2016)
σ	MJ K^{-4} m^{-2} day^{-1}	4.903×10^{-9}	(Allen *et al.*, 1998)
φ	radians	0.898	Google Maps (2016)
G_{sc}	(MJ m^{-2} day^{-1})	0.0820	(Allen *et al.*, 1998)
α	-	0.23	(Allen *et al.*, 1998)
ϒ	(kPa °C^{-1})	0.067	Eq. 5.14
τ	-	0.62	Measured
G	(MJ m^{-2} day^{-1})	0	(Allen *et al.*, 1998)

Table 5.4: Summary of input parameters for the calculation of ET_o for each of the experimental 'days' in Experiment 3.

Parameter	Units	Values used			Source
		Day 1	Day 2	Day 3	
u_2	(m s^{-1})	0.5	0.5	0.5	(Allen *et al.*, 1998)
T_{mean}	(°C)	22.40	22.67	20.93	Eq. 5.9
Δ	(kPa °C^{-1})	0.165	0.167	0.152	Eq. 5.11
e_s	kPa	2.772	2.815	2.504	Eq. 5.12
e_a	kPa	1.444	1.566	1.468	Eq. 5.13
R_n	(MJ m^{-2} day^{-1})	3.574	3.277	3.097	Eqs. 5.16 – 5.24

5.2.3 Calculation of crop coefficients, K_c

Using ET_a calculated in Section 5.2.1 and ET_o calculated in Section 5.2.2.3, K_c for each species was calculated using Equation 5.8. K_c was initially determined for each of the experimental days individually and then averaged to give one K_c value for each species.

5.2.4 Calculation of ET_o in hypothetical UK summertime weather scenarios

To identify values of air temperature, relative humidity and solar radiation to input into the ET_o calculations for each hypothetical weather scenario (as described in Section 5.1.3), representative values of each parameter under similar weather conditions in Reading were obtained from meteorological data measured at the UoR AO. Since supplementary irrigation on a green roof is only likely to be required during periods of hot and dry weather, the data were obtained for the summer months (June, July and August) of 2015 and 2016, which were the only two years of data available from UoR AO. Parameters obtained included 5-minute averages of sunshine duration, incoming shortwave radiation (R_s), air temperature, relative humidity and wind speed at 2 m, as well as hourly rainfall totals. Unfortunately sunshine duration data were unavailable for all of June 2016, and incoming shortwave radiation data were missing for 1st – 23rd June 2015; for this latter period, global solar radiation data were used instead as the two parameters are comparable. The data were examined for accuracy, and all data from 27th July 2015 and 29th - 31st August 2015 were discarded due to missing or incorrect data. Additionally, since irrigation would not be required on rainy days, all days with a rainfall total greater than 0.2 mm (defined by the UoR AO as 'days with rain') were discarded from the dataset.

To calculate ET_o, R_n must be calculated for a particular day of the year (as Julian day is a required parameter for calculating R_a; Equations 5.21 – 5.24). Since day length and solar radiation (i.e. R_a) in Reading vary quite considerably between the beginning of June and the end of August, it was decided to calculate ET_o for each month individually, using the 15th day of each month as the Julian day required. The data were therefore separated into three datasets – June, July and August – with data from both 2015 and 2016 combined for each month.

5.2.4.1 Classification of days into hypothetical weather scenarios

For each day in the datasets, daily average values of air temperature, RH, R_s and wind speed were calculated, as well as total daily sunshine duration. Daily values of T_{max}, T_{min}, RH_{max} and RH_{min} were also identified for each day in the datasets. The weather observations required for a green roof manager to classify a particular day into the correct hypothetical scenario are based mainly on cloud conditions; days in each month's dataset were therefore classified based on total daily sunshine duration as follows:

- 'Blue sky' scenario: more than 800 minutes total sunshine duration per day
- 'Sunny spells' scenario: 500 – 600 minutes total sunshine duration per day
- 'Overcast' scenario: less than 300 minutes total sunshine duration per day

This classification system loosely followed that used by Cai *et al.* (2007) to classify weather conditions based on cloudiness, in which sunshine duration was assumed to increase linearly between various cloudiness conditions. The values of sunshine duration used here were arbitrarily chosen based partly on the requirement of categorising at least 3 days per month in each scenario to be able to calculate average meteorological data for each scenario and thus obtain a more representative ET_o estimate. Since no sunshine duration data were available for June 2016, R_s data from 2015 for each scenario were examined and compared to R_s data from 2016 in order to identify days in 2016 likely to have similar sunshine durations, thus enabling inclusion of 12 days from June 2016 in the analysis.

5.2.4.2 Average meteorological data for each hypothetical weather scenario

Once days had been classified, average values of R_s, T_{max}, T_{min}, RH_{max} and RH_{min} were calculated for each scenario in each month (Table 5.5). Since these hypothetical calculations relate to green roofs, R_s was not adjusted with the glasshouse transmissivity coefficient. Average values for some of the weather parameters for the overcast scenario in June were rather high (RH_{min}) or low (R_s, T_{max}) compared to those calculated for July and August. This was probably a result of the way the days were classified and the specific weather experienced in the years of available data.

Table 5.5: Daily average meteorological parameters for each of the hypothetical UK summertime weather scenarios in June (A), July (B) and August (C), calculated from 2015 and 2016 data obtained from the University of Reading Atmospheric Observatory (UoR AO).

Hypothetical UK summertime scenario	Daily average meteorological parameters					
A June	**Total sunshine duration (mins)**	**T_{max} (°C)**	**T_{min} (°C)**	**RH_{max} (%)**	**RH_{min} (%)**	**R_s (MJ m^{-2} s^{-1})**
'Blue sky'	850	23.28	8.96	94.8	37.3	27.88
'Sunny spells'	577	19.53	9.70	88.7	41.3	23.01
'Overcast'	242	17.11	10.96	94.1	74.3	9.31
B July	**Total sunshine duration (mins)**	**T_{max} (°C)**	**T_{min} (°C)**	**RH_{max} (%)**	**RH_{min} (%)**	**R_s (MJ m^{-2} s^{-1})**
'Blue sky'	842	27.02	13.11	95.9	37.1	27.66
'Sunny spells'	544	21.76	10.49	94.6	45.8	21.22
'Overcast'	209	21.81	12.99	92.3	53.9	13.60
C August	**Total sunshine duration (mins)**	**T_{max} (°C)**	**T_{min} (°C)**	**RH_{max} (%)**	**RH_{min} (%)**	**R_s (MJ m^{-2} s^{-1})**
'Blue sky'	820	24.24	9.98	97.9	41.6	23.15
'Sunny spells'	543	23.43	11.74	94.8	42.9	19.42
'Overcast'	145	22.16	12.08	90.0	51.1	10.36

Daily average wind speed from all days in the datasets ranged from 0.49 to 4.14 m s^{-1}, with the vast majority (nearly 60%) of daily wind speeds in the range 1 – 2 m s^{-1} (data not shown). To keep the weather observations and classifications simple, only two wind conditions were used for the irrigation management reference table: 'calm' and 'windy'. Wind speed (u_2) values chosen for use in the ET_o calculations were based on the upper and lower wind speeds actually recorded so that they were representative of a UK summer, whilst also accounting for the fact that wind speeds are typically higher on a green roof (Nagase and Dunnett, 2010). Values of 0.75 m s^{-1} and 4.0 m s^{-1} were therefore used for the 'calm' and 'windy' scenarios respectively. Both of these values were within the range recorded at UoR AO but were close to the lowest and highest daily average wind speeds, and they therefore represent the extremes. Although a daily average wind speed greater than 4.0 m s^{-1} was recorded only once during the summers of 2015 and 2016, higher wind speeds are expected on a green roof and so it is likely that values of 4.0 m s^{-1} would be recorded more frequently.

5.2.4.3 *Summary of ET_o input parameters for each hypothetical weather scenario*

Input parameters for the ET_o calculation (e_s, e_a, Δ, R_n and T) were calculated from the average meteorological values identified for each weather scenario (Table 5.5) and are summarised in Table 5.6; values used for constants were the same as those presented in Table 5.3. Within each month, all parameters apart from wind speed were the same in the 'calm' and 'windy' scenarios. R_s on 'blue sky' days was noticeably lower in August than in June and July as expected due to shorter day length, whilst there was less difference between months on 'overcast' days. T was very similar in all of the hypothetical scenarios in August, partly due to the higher value of T_{min} observed with 'overcast' conditions whereas 'blue sky' days experienced a lower T_{min}. As discussed in Section 5.2.4.2, average values of some weather parameters in June differed from those calculated for July and August; correspondingly, some of the input parameters (T_{mean} and $e_s - e_a$) for the ET_o calculation were low for 'overcast' days in June.

Using these parameters, ET_o in June, July and August for each of the hypothetical weather scenarios was then calculated using Equation 5.7.

5.2.5 Creation of irrigation management reference table

Daily ET_c for each species in each hypothetical weather scenario was estimated using Equation 5.8 by applying the average K_c value calculated for each species (Section 5.2.3) to the ET_o calculated for each scenario in each month (Section 5.2.4.3), thus creating the irrigation management reference table.

Table 5.6: Summary of input parameters for each hypothetical UK summertime weather scenario in June (A), July (B) and August (C) for the calculation of ET_o.

Hypothetical UK summertime scenario		ETo input parameters				
A	**June**	u_2 (m s^{-1})	T_{mean} (°C)	Δ (kPa °C^{-1})	$e_s - e_a$ (kPa)	R_n (MJ m^{-2} day^{-1})
'Blue sky'	'Calm'	0.75	16.12	0.117	0.926	15.742
	'Windy'	4				
'Sunny spells'	'Calm'	0.75	14.62	0.107	0.735	13.391
	'Windy'	4				
'Overcast'	'Calm'	0.75	14.04	0.104	0.289	6.859
	'Windy'	4				
B	**July**	u_2 (m s^{-1})	T_{mean} (°C)	Δ (kPa °C^{-1})	$e_s - e_a$ (kPa)	R_n (MJ m^{-2} day^{-1})
'Blue sky'	'Calm'	0.75	20.06	0.145	1.154	15.621
	'Windy'	4				
'Sunny spells'	'Calm'	0.75	16.13	0.117	0.740	12.471
	'Windy'	4				
'Overcast '	'Calm'	0.75	17.40	0.126	0.659	8.884
	'Windy'	4				
C	**August**	u_2 (m s^{-1})	T_{mean} (°C)	Δ (kPa °C^{-1})	$e_s - e_a$ (kPa)	R_n (MJ m^{-2} day^{-1})
'Blue sky'	'Calm'	0.75	17.11	0.124	0.896	12.174
	'Windy'	4				
'Sunny spells'	'Calm'	0.75	17.59	0.127	0.859	10.615
	'Windy'	4				
'Overcast'	'Calm'	0.75	17.12	0.124	0.723	6.734
	'Windy'	4				

5.3 Results

5.3.1 Crop coefficients for each species

Crop coefficients (K_c) calculated for each species, based on actual ET (ET_a) and reference ET (ET_o) for each 'day' of the Experiment 3 data, are presented in Table 5.7. ET_a was calculated as an average of the two replicates of each species that were tested on each day (see Section 5.2.1). ET_o for each 'day' was identical for all species on each day since it was calculated with only meteorological data. ET_a of *Salvia* and *Stachys* were around 50% and 25% lower respectively on Day 3 compared to Days 1 and 2, resulting in somewhat lower K_c values on Day 3 (see Section 5.4.1). However, the average K_c values calculated for *Salvia* and *Stachys* were substantially higher than those calculated for *Heuchera* and *Sedum*. The average K_c value for each species was used in subsequent ET_c calculations for each of the hypothetical weather scenarios.

Table 5.7: Calculated crop coefficients (K_c) for each of the species, based on actual ET (ET_a) and reference ET (ET_o) calculated for each 'day' of Experiment 3.

Species	Experimental 'day'	Actual ET, ET_a (mm day^{-1})	Reference ET, ET_o (mm day^{-1})	K_c	Average K_c for each species
Heuchera	Day 1	1.87	1.25	1.50	**1.47**
	Day 2	1.71	1.15	1.49	
	Day 3	1.50	1.05	1.43	
Salvia	Day 1	4.25	1.25	3.41	**2.98**
	Day 2	4.02	1.15	3.50	
	Day 3	2.12	1.05	2.02	
Stachys	Day 1	3.67	1.25	2.95	**2.94**
	Day 2	3.66	1.15	3.18	
	Day 3	2.82	1.05	2.69	
Sedum	Day 1	2.19	1.25	1.76	**1.66**
	Day 2	1.97	1.15	1.71	
	Day 3	1.58	1.05	1.51	

5.3.2 Irrigation management reference table

The completed irrigation management reference table for all species, based on the calculated ET_o and K_c values, is presented in Table 5.8. For all species in all months, estimated ET_c was highest under 'blue sky' conditions and lowest under 'overcast' conditions, and higher in 'windy' conditions compared to 'calm' condition. ET_c in 'blue sky windy' conditions was 2 - 3 times greater than ET_c in 'overcast calm' conditions for all species in all months. Within each scenario, ET_c was generally an average of 20 - 30% higher in windy conditions compared to calm conditions for all species. ET_c was lower in August than in June and July in 'blue sky' and 'sunny spells' conditions, as a consequence of the lower R_s values obtained for August in Section 5.2.4.3 due to shorter day length. In 'overcast' conditions, ET_c was lowest in June, corresponding to the unusually low meteorological values for this scenario in June discussed in Section 5.2.4.3. ET_c in the different scenarios varied less in August compared to June and July, with a maximum difference in ET_c (between 'blue sky windy' and 'overcast calm') of 7.89 mm day^{-1} in August compared to 11.17 and 10.49 mm day^{-1} in June and July respectively, all with *Salvia*.

Corresponding to their higher K_c values, *Salvia* and *Stachys* had higher daily ET_c than *Sedum* and *Heuchera* in all scenarios and all months; indeed, *Salvia* and *Stachys* ET_c was double that of *Heuchera* (as were their K_c values; Section 5.3.1). Additionally, the range of ET_c values estimated for the different scenarios was much greater with *Salvia* and *Stachys* compared to *Heuchera* and *Sedum*. The greatest variations in ET_c were 13.09 mm day^{-1} with *Salvia* compared to 6.46 mm day^{-1} with *Heuchera*, both between 'blue sky windy' conditions in July and 'overcast calm' conditions in June. ET_c variations between months in each scenario were also more pronounced with *Salvia* and *Stachys*; for example, ET_c in 'blue sky windy' conditions was 4.04 mm day^{-1} higher in July than in August with *Salvia*, compared to a 2.00 mm day^{-1} difference with *Heuchera*.

Table 5.8: Completed irrigation management reference table, with estimated daily ET_c (mm) from a green roof vegetated with *Heuchera* (A), *Salvia* (B), *Stachys* (C) or *Sedum* (D) in 6 hypothetical UK summertime weather scenarios in June, July and August.

Irrigation management reference table

	Estimated daily ET_c (mm)					
A	'Blue sky'		'Sunny spells'		'Overcast'	
Heuchera	'Calm'	'Windy'	'Calm'	'Windy'	'Calm'	'Windy'
June	6.55	8.14	5.39	6.66	2.63	3.00
July	7.07	9.09	5.20	6.48	3.91	5.20
August	5.33	7.09	4.76	6.51	3.20	4.91
B	'Blue sky'		'Sunny spells'		'Overcast'	
Salvia	'Calm'	'Windy'	'Calm'	'Windy'	'Calm'	'Windy'
June	13.28	16.50	10.93	13.50	5.33	6.07
July	14.34	18.42	10.54	13.14	7.93	10.53
August	10.81	14.38	9.65	13.20	6.49	9.95
C	'Blue sky'		'Sunny spells'		'Overcast'	
Stachys	'Calm'	'Windy'	'Calm'	'Windy'	'Calm'	'Windy'
June	13.10	16.28	10.78	13.32	5.26	5.99
July	14.15	18.17	10.40	12.96	7.82	10.39
August	10.67	14.18	9.52	13.02	6.40	9.82
D	'Blue sky'		'Sunny spells'		'Overcast'	
Sedum	'Calm'	'Windy'	'Calm'	'Windy'	'Calm'	'Windy'
June	7.40	9.19	6.09	7.52	2.97	3.38
July	7.99	10.26	5.87	7.32	4.42	5.87
August	6.02	8.01	5.38	7.35	3.62	5.54

5.4 Discussion

In this chapter, crops coefficients (K_c) for four potential green roof species (*Heuchera*, *Salvia*, *Stachys* and *Sedum*) were estimated, which could contribute to a wider database of K_c values for landscape plants. These were then used to create a table of estimated daily ET_c from a green roof vegetated with each of the four species under different weather conditions, as an example of a simple irrigation management reference table that could be created using simple weather observations. The purpose of the table is to allow a green roof manager to make simple observations of the weather each day and look up the corresponding estimated ET_c from the green roof in order to inform irrigation scheduling so that plant health and provision of ESs is maintained, whilst also managing limited water resources in a sustainable way. As such, the use of greywater for this supplementary irrigation is encouraged.

5.4.1 Estimated crop coefficients for each species

The FAO-56 PM model has proven to be a robust and reliable method for calculating crop coefficients for a wide range of agricultural crops (e.g. Tyagi *et al.*, 2000; Liu *et al.*, 2002), but few attempts have been made to calculate K_c values for landscape plants that may be used on green roofs (e.g. Poë *et al.*, 2015). Previous studies highlighted the importance of calculating K_c values for individual species, locations and environmental conditions to ensure accurate calculation of ET (Borin *et al.*, 2011), and these are likely to differ vastly on a green roof compared to agricultural environments (Nouri *et al.*, 2013). In this chapter, one K_c value was calculated for each species, using mature, fully grown plants with 100% coverage (or 90% for *Heuchera*) in well-watered conditions, considered to be representative of green roof conditions in the summertime in the UK. Since landscape plants are likely to show greater variation in vegetation characteristics (e.g. height and density) than agricultural crops, even within growth stages (Allen and Pereira, 2009), K_c values for green roof plants would ideally need to be obtained under a range of conditions to achieve a representative average value for use in further ET_c calculations. This was also evident in the ET_a results from Experiment 3, in which ET_a (and consequently K_c) of *Stachys* and especially *Salvia* were substantially lower on Day 3 than on Days 1 and 2 (50% lower for *Salvia*). This could have been a result of differences in environmental conditions on Day 3, particularly higher humidity and lower solar radiation compared to Days 1 and 2 (data not shown), which is likely to have restricted ET, as discussed in Section 4.4.2. However, although environmental conditions on each experimental day are accounted for in the ET_o calculation, K_c values were still up to 40% lower on Day 3 for *Salvia*. This is therefore likely to indicate a difference between the plants themselves, with the plant replicates used on Day 3 likely having a lower ET rate than those used on Days 1 and 2 since all plants were of comparable size. This highlights the variation that can be found in landscape plants and thus the need for calculating K_c values in a wide range of conditions in order to obtain a robust and representative species average.

Whilst good initial estimates, the K_c values calculated in this chapter would need to be validated outdoors and in a green roof context to ensure applicability of the K_c values to further ET estimations for these species. Calculated K_c values were somewhat higher than published values for agricultural crops, which typically should not exceed 1.3 (Allen and Pereira, 2009). Values were particularly high for *Salvia* and *Stachys* (2.98 and 2.94 respectively), whereas for *Heuchera* and *Sedum* they were only slightly higher than the indicated range (1.47 and 1.66 respectively). These values reflect the higher ET_a of *Salvia* and *Stachys* compared to *Heuchera* and *Sedum* (discussed in Chapters 3 and 4), highlighting the different irrigation needs of the different species and therefore the importance of calculating K_c values for each species individually. Accurate estimation of ET_c of specific species is particularly important for the purposes of scheduling irrigation based on plant water requirements in order to maintain provision of ESs.

K_c values have rarely been calculated for landscape plants, so comparison of the results of this study is limited, particularly for the broadleaf species as the majority of studies have typically focussed on *Sedum* mixes. Additionally, results that are available for landscape plants show a lot of variation. For example, K_c values of 0.4 – 0.5 and 0.53 were calculated for well-watered *Sedum* on green roofs in August and September in Italy and New Hampshire, USA respectively (Lazzarin *et al.*, 2005; Sherrard and Jacobs, 2012), whilst on a different *Sedum*-vegetated green roof in Pennsylvania, USA, monthly average K_c values of 1.0 – 1.4 were obtained under low-stress summertime conditions (Schneider, 2011). Compton and Whitlow (2006) attempted to identify K_c values for alternative species that may be suited to green roofs due to their tolerance of both drought and salt (*Solidago canadensis* and *Spartina alterniflora*), obtaining average values of 3.9 and 3.4 respectively. However, the ET_o used in their calculations was measured by evaporation pan, and therefore did not take into account transpiration and crop factors, hence resulting in such large K_c results.

The FAO-56 PM equation has a number of underlying assumptions built into the calculations, including the requirement for a large (> 50 m in all directions), homogenous crop due to the exclusion of lateral energy fluxes in the calculations. The size of the plots tested in Experiment 3 were much smaller than this, and horizontal energy exchanges therefore probably played a larger role than accounted for by the calculations, probably resulting in overestimation of K_c values and consequently ET_c (Allen and Pereira, 2009). K_c values obtained for small, isolated stands of vegetation are frequently higher than expected (Allen *et al.*, 1998), often between 1.9 and 2.3 (Schneider, 2011). The high K_c values calculated for *Salvia* and *Stachys* in this study were likely to be a result of the small plot size and would therefore need further validation in a green roof context to ensure accuracy. However, it is also unlikely that a green roof would be as large as required for the FAO-56 PM model, which was designed for large agricultural crops, and therefore lateral energy exchanges may always play a larger role in ET_c than is accounted for with FAO-56 PM.

5.4.2 ET_c under hypothetical UK summertime weather scenarios

ET_c of each species in six simple hypothetical UK summertime weather scenarios was estimated to create an example of an irrigation management reference table for a UK summer, the aim of which was to allow a green roof manager to easily observe the weather each day, without the need for equipment, and simply classify the day into one of the six scenarios. Estimated daily ET_c of a particular species in that weather scenario could then easily be looked up in the irrigation management reference table and irrigation scheduled appropriately. The hypothetical weather scenarios were based mainly on cloud cover and wind conditions, covering all likely summer weather conditions in the southern UK, with typical meteorological values on similar days obtained from weather data of previous summers (2015 and 2016) in Reading.

Estimated ET_c for all species was high compared to the ET_a calculated from Experiment 3 data and compared to published ET values in experiments with green roof species, which typically averaged 1 – 3 mm day^{-1} in summer conditions on green roofs vegetated with *Sedum* in New York City (DiGiovanni *et al.*, 2012) and New Hampshire (Sherrard and Jacobs, 2012). This was probably due to overestimation of ET_c in the irrigation management reference table resulting from the high K_c values calculated for these species as some of the underlying assumptions in the ET_o calculation were not met (Section 5.4.1). Additionally, ET_a may be low compared to ET_c estimates due to the different environmental conditions inside a glasshouse; for example, it was noted that R_n values used in all hypothetical weather scenarios in all months were substantially higher than the R_n values used for the Experiment 3 ET_o calculations (3.10 – 3.57 MJ m^{-2} day^{-1}).

This example of an irrigation management table clearly highlights the differences in irrigation requirements between the species, and under different weather conditions. ET_c differences between species corresponded directly to differences in their K_c values; for example, the mean K_c of *Heuchera* was half that of *Salvia* and *Stachys* (1.47 compared to 2.98 and 2.94 respectively), resulting from the lower ET_a with *Heuchera*, which was likely due to the slightly older and smaller plants (with approximately 90% surface coverage) with *Heuchera* compared to all other species. This meant that ET_c with *Heuchera* was half that of *Salvia* and *Stachys* in all hypothetical weather scenarios and all months, resulting in a wider range of ET_c values between the different weather scenarios and between months for *Salvia* and *Stachys* compared to *Heuchera* and *Sedum*. This highlights the importance of basing irrigation scheduling on plant water use (i.e. ET) of individual species in particular weather conditions in order to maintain plant health and provision of ESs whilst also using limited water resources in an efficient way.

Differences in estimated ET_c between species were most pronounced in the 'blue sky windy' scenario in all months (e.g. ET_c in July ranged from 18.42 mm day^{-1} for *Salvia* to 9.09 mm day^{-1} for *Heuchera*) and the least variation in 'overcast calm' conditions (e.g. ET_c was 7.93 mm day^{-1} for *Salvia* in July and 3.91 mm day^{-1} for *Heuchera*). This pattern was also evident for differences in ET_c between months, with the greatest variation in the 'blue sky windy' scenario for all species (e.g. a difference of 4.04 mm day^{-1} for *Salvia* in July compared to August), whilst ET_c values for each month were the most similar in the 'overcast calm' scenario (e.g. a difference of 2.60 mm day^{-1} in July compared to June with *Salvia*). ET_c values within each weather scenario were generally similar in June and July and lower in August for all species, with the exception of the 'overcast' scenario, in which ET_c was lowest in June. Low ET_c in the 'overcast' scenario in June likely resulted from the low meteorological parameters noted previously (Sections 5.2.4.2 - 5.2.4.3); the accuracy of ET_c estimates in all scenarios could be improved by using a larger historical dataset of summertime meteorological data to ensure that values used in ET_o calculations are representative of the long-term summer averages.

Additionally, estimated ET_c in all months and with all species was around 20 – 30% greater in 'windy' compared to 'calm' conditions in each weather scenario. However, species with different aerodynamic resistances may respond differently (to the grass reference crop and to other species) to changing wind speed in terms of their actual ET, resulting in disparity between ET_a and ET_o estimates (Allen *et al.*, 2005). Indeed, Allen and Pereira (2009) suggest that K_c values may increase with increasing wind speed as a result of the higher surface roughness of crops compared to the grass reference crop, and Allen *et al.* (1998) note that K_c values tend to be larger under dry and windy conditions. The K_c values calculated in this study would therefore need to be validated for the higher wind speeds typically experienced on green roofs (Nagase and Dunnett, 2010) to ensure accurate estimation of green roof ET_c with these species.

Based on estimated ET_c, it is therefore likely that irrigation of a green roof planted with any of these species would be required most often or with the greatest volumes during June and July compared to August (in similar weather conditions), and in 'windy' and 'blue sky' conditions. These are also the conditions in which species differ the most in their irrigation requirements, and so understanding the particular requirements of the specific species used on a green roof is vital for managing irrigation sustainably whilst also ensuring that the provision of ESs does not become compromised.

5.4.3 Application of the irrigation management reference table

Little experimental data has previously been available regarding ET from different types of green roof vegetation in different climatic conditions, thus making it difficult to accurately quantify or model green roof ET (Voyde *et al.*, 2010a), or to schedule irrigation appropriately. Although they need further validation in green roof conditions, the results of this study provide a good initial estimation of how daily ET_c varies with *Heuchera*, *Salvia*, *Stachys* or *Sedum* in different hypothetical UK summertime weather scenarios. The results also highlight the ease with which ET_c can be estimated under any climatic conditions by using the FAO-56 PM model once a K_c has been calculated for the relevant species. This method therefore has the potential to be a straightforward and convenient approach to modelling green roof ET, and creation of a database of K_c values for landscape species would be beneficial in future ET modelling for green roofs.

Differences in estimated daily ET_c between the different species were clearly highlighted in the irrigation management reference table, as well as between different weather conditions and different months. This emphasises the need for careful scheduling of supplementary irrigation based on the specific type of vegetation used in order to maintain provision of ESs, such as cooling and stormwater management, whilst also preserving limited water resources. An irrigation management reference table would provide a simple way for a green roof manager to estimate daily ET_c from the roof by simply observing the weather, enabling a record to be kept of cumulative water loss in the days following rainfall. Once the total water lost from the roof reaches a pre-determined value, at which plant health and provision of ESs may become compromised, supplementary irrigation (with greywater or other water sources) is scheduled. For a green roof manager to know at what point to irrigate, the water requirements for uncompromised provision of ESs for each species need to be accurately determined through further experimental work. As an example, based on the experimental results presented in Chapter 4, it was proposed that irrigation would be required after 3 – 4 dry days in hot and dry conditions (i.e. high T and low RH) with *Salvia* and *Stachys* in order to maintain plant health and aesthetic quality (i.e. to prevent wilting) and to maintain high ET rates, which equated to a cumulative ET loss of 25 – 30 mm for both species (see Sections 4.3.2 and 4.4.3). Using the example irrigation management reference table to estimate ET_c for *Salvia* and *Stachys*, this water loss threshold would be reached after 2 consecutive 'blue sky windy' days, compared to 4 – 5 consecutive 'overcast calm' days, depending on month.

The example irrigation management reference table created in this chapter indicates that ET-based irrigation scheduling could be used in a very simple way to schedule irrigation of a green roof in order to maintain the provision of ESs by particular species. Using greywater for the supplementary irrigation will further improve the sustainability of this approach, helping to preserve high quality tap water without compromising the needs of the plants. To further improve the accuracy of ET_c estimates for each species in various summertime weather scenarios, the K_c values calculated from Experiment 3 data could be validated in the green roof context, taking into account differences in plot size, wind speed and atmospheric conditions outdoors rather than inside a glasshouse. Furthermore, this initial table is valid only for well-watered conditions as no stress factor (K_s) was applied in these calculations as ET_a was measured under well-watered conditions in Experiment 3 (i.e. K_s = 1). Since ET decreases over time as the substrate dries following rainfall or saturation (Castiglia Feitosa and Wilkinson, 2016), in practice, K_s would become increasingly large over consecutive dry days. K_s is typically calculated each day from the soil water balance (Allen and Pereira, 2009) and is therefore difficult to account for in an irrigation management reference table such as the example created in this study, whilst maintaining simplicity. However, as the purpose of such a table would be to allow a green roof manager to schedule irrigation based on cumulative ET during dry periods between rainfall, further work is needed to attempt to identify K_s for each species on each consecutive dry day in order to modify ET_c estimates appropriately.

5.5 Key conclusions

- The FAO-56 PM model provided a simple method for estimating daily ET_c from a green roof under a variety of hypothetical UK summertime weather scenarios. Irrigation management reference tables may have potential for enabling green roof managers to schedule irrigation according to plant water requirements whilst also conserving limited water resources and keeping green roof maintenance costs low.

- K_c values for each species under standard growing conditions in the summertime were identified and could contribute to a database of K_c values for landscape species. However, further validation of K_c and ET_c results is required to account for the small plot size and the validity of extrapolating results from inside a greenhouse to outdoors on a green roof, as well as to identify K_s for each species on each consecutive dry day to account for decreasing ET due to drying substrate.
- *Salvia* and *Stachys* had higher K_c values than *Sedum* and *Heuchera*; consequently, they always had the highest daily ET_c and therefore would require irrigation with greater volume or frequency in order to preserve the provision of ESs.
- ET_c for all species was greatest under 'blue sky windy' conditions in June and July, and irrigation is thus likely to be required more frequently under these conditions.

Chapter 6

Potential of greywater for sustainable irrigation of green roofs: impacts on plants, continued provision of ecosystem services and runoff quality

6.1 Introduction

Green roofs have the potential to provide multiple ecosystem services (ESs), including surface and aerial cooling and stormwater management. Recent studies at the University of Reading have shown that a variety of species with different morphological and physiological characteristics than traditionally used succulent species (e.g. *Sedum*) may be able to provide ESs to a higher degree (Blanuša *et al.*, 2013; Vaz Monteiro *et al.*, 2016a). However, it is also apparent that supplementary irrigation of these species is required during times of drought to ensure plant survival and continued provision of ESs, particularly cooling (Butler and Orians, 2011; Blanuša *et al.*, 2013). Indeed, the extent of cooling provided by some species, including *Sedum*, has been shown to be significantly higher when supplementary irrigation is provided (MacIvor *et al.*, 2016). Furthermore, experimental results presented in Chapters 3 and 4 indicate that irrigation of species with high transpiration rates (e.g. *Stachys* and *Salvia*) would be required approximately every 3 days during a dry summer period in the UK in order to maintain plant health and high evapotranspiration (ET) rates. Transpiration has previously been identified as the primary mechanism providing cooling with these species (Blanusa *et al*, 2013; Vaz Monteiro *et al*, 2016a; 2017), and preservation of high ET rates are thus crucial for continued cooling provision, as well as stormwater management through restoration of substrate retention capacity.

Increasing demand for water in urban areas and changing rainfall patterns in the UK due to climate change (including longer and more frequent droughts; IPCC, 2013) means that the possibility of water shortages and competition for limited water resources may become more likely (Jones and Hunt, 2010; Pinto *et al.*, 2010). Using greywater (GW) instead of tap water (TW) may provide a sustainable alternative for green roof irrigation and could result in fresh water savings of up to 50% (Jeppesen, 1996). Additionally, GW is a consistent and reliable source of water all year, regardless of rainfall (Mohamed *et al.*, 2013) and is available in large quantities, accounting for up to 75% of total household wastewater (Ghaitidak and Yadav, 2013).

It is as yet unclear whether vegetation can continue to grow and function efficiently when irrigated with GW, as previous studies have yielded a range of both positive and negative impacts in terms of plant growth and health (Ali *et al.*, 2013). It is also clear that different species respond differently to GW irrigation, possibly because the toxic threshold for various elements is likely to vary between plant species (Sharvelle *et al.*, 2012). Moreover, the majority of studies examining the impacts of GW on plant health have focused on vegetable crops (Finley *et al.*, 2009; Al-Hamaiedeh and Bino, 2010) or wetland species e.g. willow (Eriksson *et al.*, 2006), with very few studying potential green roof species, particularly species with high ET rates. As well as the tolerance of a particular species, the effect of GW on plants and soils also depends on the soil type, the irrigation regime (if GW is used solely or the plants also receive freshwater e.g. rain), the quality of the GW itself (i.e. its chemical and physical properties) and the length of exposure to GW (Kaboosi, 2016). Impacts of GW irrigation on soils and plants were discussed fully in Sections 1.5.1 - 1.5.2. Rodda *et al.* (2011a) suggest that changes to soil properties are slow and will therefore only become apparent when GW has been used for irrigation long-term, whereas impacts on plants may occur in the short-term.

The effect of GW on plant functioning (such as leaf stomatal conductance) has not yet received much attention, but is important to understand in order to determine whether GW-irrigated plants continue to provide ESs such as cooling and stormwater management, which depend on high ET rates (Vaz Monteiro *et al.*, 2017), to the same extent as those irrigated with TW. The few studies that have examined the impact of GW on plant transpiration and water uptake have yielded differing results, with some indicating reduced transpiration with GW irrigation (Eriksson *et al.*, 2006; Ouldboukhitine *et al.*, 2014), whilst others found no difference in water uptake with GW or TW treatments (Misra *et al.*, 2010; Pinto *et al.*, 2010). Eriksson *et al.* (2006) also identified a clear difference in plant response to GW of different qualities and synthetic greywater is therefore often recommended for use in laboratory studies to ensure consistency and repeatability of results (Diaper *et al.*, 2008).

Green roofs also provide the service of improving the quality of runoff compared to runoff from conventional roofs, through plant uptake and substrate storage of chemical constituents, thus reducing the pollutant load in urban runoff (Berndtsson *et al.*, 2009). Similarly, the quality of irrigation GW may be improved by this filtering effect and plant uptake of nutrients on a green roof, thus resulting in runoff that is of better quality than the original irrigation GW. As well as factors such as roof type and age, maintenance practices (e.g. application of fertilisers; Emilsson *et al.*, 2007), and environmental factors including temperature and size of rainfall event (Teemusk and Mander, 2007; Buffam *et al.*, 2016), the magnitude of this service is strongly dependent on substrate type, plant species and quality of the original irrigation water (Berndtsson *et al.*, 2006; Sharvelle *et al.*, 2012; Fowdar *et al.*, 2017). However, green roofs may sometimes act as a source of some nutrients rather than a sink, particularly phosphorus which is thought to leach from the substrate (Van Seters *et al.*, 2009). Irrigation with GW may impact the capacity of a green roof to improve runoff quality, due to the additional input of salts and generally lower quality of GW compared to TW, so that runoff from GW-irrigated roofs may be of lower quality than runoff from TW-irrigated roofs (Alfiya *et al.*, 2012). Runoff quality is also likely to vary with plant type used as different species have different capacities for taking up and storing nutrients in plant tissues.

6.1.1 Study aims

It is clear that GW has the potential to be used for supplementary irrigation of green roofs but it is not yet fully understood how potential green roof species with high transpiration rates will respond to it and how it will impact their ability to continue providing ESs, especially cooling and stormwater management. The principal aims of this study, therefore, were to investigate the impacts of short-term GW irrigation on the health, growth and functioning of potential green roof species with high ET rates. Since plant transpiration has previously been identified as the main mechanism by which these species provide both cooling (Blanuša *et al.*, 2013; Vaz Monteiro *et al.*, 2016a; 2017) and stormwater management (through restoring the substrate retention capacity between storms; Chapters 3 and 4), the impact of GW on continued provision of ESs though stomatal modification and associated ET was also investigated.

It is not clear how irrigation with GW will impact the quality of the runoff from a green roof and whether plant presence or type may influence runoff quality. This study therefore also aimed to evaluate whether the quality of runoff was improved above that from bare substrate alone by any of the potential green roof species, and whether runoff quality was impacted by using GW for irrigation instead of TW.

The specific objectives of the study were therefore:

- To evaluate the impact of short-term (6 – 8 weeks) irrigation with greywater on the health and growth of potential green roof species, compared to plants of the same species irrigated with tap water;

- To investigate whether irrigation with greywater affects plant processes such as transpiration, which are necessary for the continued provision of ecosystem services such as cooling and stormwater management;
- To investigate species differences in nutrient uptake (focusing on P, B and Na) and any resultant improvement in runoff quality, and whether plant presence offers an advantage compared to bare substrate.

6.1.2 Synthetic greywater formulation and nutrient tracer selection

Sodium (Na), phosphorus (P) and boron (B) were chosen as 'tracer elements' in this study (P and B in Experiment 5; P, B and Na in Experiment 6). The primary concern relating to elevated B and Na concentrations in GW is their impact on soil and plant health, whilst the main environmental concerns relating to elevated P concentrations in GW are leaching and reduced runoff quality resulting in contamination of water bodies (e.g. Misra *et al.*, 2010; Mohamed *et al.*, 2013; discussed fully in Section 1.5.2.1). The accumulation of these elements in the soil depends on their concentrations in irrigation waters, which for GW varies with the types of product used in the household and the source within the house as well as the quality of the original TW. Additionally, different plant species are likely to respond differently to GW due to varying plant requirements and tolerances to the various elements.

Therefore, in order to standardise the water quality and element content received by all species throughout this study and to be able to easily replicate results, a synthetic GW was used. The recipe selected was developed by Diaper *et al.* (2008), and is designed to simulate combined bathroom and laundry GW (see Section 2.7.1). This recipe was selected due to the thorough and robust research and development techniques used in its formulation, and the similarity in chemical and physical properties to real GW achieved with the final recipe. Using synthetic GW also allowed some control over the chemical formulation of the GW used: for example, B concentrations were low in the original GW formulation used in Experiment 5, so ingredient amounts were adjusted in Experiment 6 to increase GW B content and enable easier tracing through the study. Although a disadvantage of using synthetic GW is that it lacks the variability in chemical and physical parameters of real GW, for the purposes of this study a controlled application with water of consistent quality was considered to be of greater advantage.

6.2 Materials and Methods

Two experiments were carried out to examine the impact of greywater (GW) on plant health, growth, functioning and ability to continue providing ecosystem services, as well assessing how runoff quality is affected by GW irrigation. The experimental setup of both experiments is summarised in Table 6.1. Experiment 5, using an industry standard green roof substrate, was carried out for 8 weeks in summer 2014, during which half of each plant treatment were irrigated with mains tap water (TW) and half with GW. Experiment 6 was set up as a 'model' situation, using a nutrient-poor substrate mix (see Section 2.4), and was carried out over a 7 week period in summer 2015; for the first 6 weeks, half the containers in each plant treatment were irrigated with TW and half with GW. After 6 weeks, plants in 'runoff quality' containers (5 replicates of each treatment; see Section 2.7) were harvested for chemical analysis, whilst the experiment with the remaining 'ET assessment' containers continued into the 7th week, in which water uptake from each container was measured (6 replicates of each treatment).

Table 6.1: Summary of Experiments 5 and 6.

	Experiment 5	**Experiment 6**
Dates	22nd May – 18th July 2014	22nd May – 13th July 2015
Set-up	Individual plants in 2 L containers with 11 cm of Meadow Roof Medium	Individual plants in 2 L containers with 11 cm of vermiculite: peat-based compost 50:50 mix
Treatments	16x *Heuchera*, *Salvia*, *Stachys*, *Sedum*, control	22x *Heuchera*, *Salvia*, *Stachys*, *Sedum*, control
Irrigation regime	TW, GW; identical volumes for all replicates of all treatments	TW, GW; different volumes for each species/control based on water use
Measurements	SMC; substrate EC; plant growth and health; g_s; canopy temperature; leaf area; root and shoot dry weights; runoff EC; nutrient concentrations in roots, shoots, substrate and runoff.	SMC; substrate EC; plant growth and health; g_s; canopy temperature; ET; leaf area; root and shoot dry weights; runoff EC; nutrient concentrations in roots, shoots, substrate and runoff.

Plant materials and substrates used in the experiments are described in Sections 2.3 and 2.4, and the basic setup of each experiment, including formulation of synthetic GW and irrigation regimes, is detailed in Section 2.7. Average chemical and physical properties of the tap water and synthetic GW mixed for both experiments are presented in Table 6.2.

General principles of all measurements made over the course of Experiments 5 and 6 are described in Section 2.5. However, specific details of the measurements made in each experiment are described in Sections 6.2.1 - 6.2.4.

Table 6.2: Average chemical and physical properties of the tap water and synthetic greywater used in Experiments 5 and 6, sampled each time a new GW batch was mixed.

Parameter	Experiment 5		Experiment 6	
	Tap water	Greywater	Tap water	Greywater
EC * (µS cm^{-1})	386.0	530.7	373.1	521.0
pH	7.7	7.8	8.5	7.7
Total P (mg L^{-1})	< 0.1	5.2	< 0.2	4.9
Total B (mg L^{-1})	< 0.04	0.48	0.01	0.75
Total Na (mg L^{-1})	-	-	16.3	107.1

*** Electrical conductivity (EC) values are reported at 25°C**

6.2.1 Baseline plant measurements

Four additional plants of each species were destructively harvested at the start of both experiments to obtain baseline values. Baseline plant biomass for each experiment was obtained by harvesting the roots and shoots of the baseline plants to obtain dry weights. In addition, in Experiment 5, leaf stomatal conductance to water vapour (g_s) of the baseline plants was measured prior to harvesting on Day 0 of the experiment. Containers had been watered daily to container capacity with TW before g_s was measured, so that values were an indicator of normal plant functioning with optimal substrate moisture content (SMC). In Experiment 6, baseline values of g_s and canopy temperature of all the experimental plants (22 replicates per treatment) were measured on Day 1 of the experiment.

6.2.2 Impact of greywater on the substrate and plant health, growth and functioning

Starting from Day 1, SMC and substrate electrical conductivity (EC) of all containers were measured three times per week throughout both experiments. Plant growth was measured and visual health was assessed at the start of both experiments and then fortnightly throughout the experiments. The health of each plant was scored between 0 and 5 based on the visual plant health assessment system used by Sharvelle *et al.* (2012), including assessment of factors such as crown size and density, foliage colour, leaf senescence and overall quality. Following baseline measurements, stomatal conductance (g_s) was measured throughout both experiments (fortnightly in Experiment 5 and weekly for the first 6 weeks of Experiment 6), as described in Section 2.5.5, as an indicator of the plants' functioning.

6.2.2.1 Substrate sodium adsorption ratio

Sodium adsorption ratio (SAR) describes the concentration of Na^+ in the substrate relative to the concentrations of Ca^{2+} and Mg^{2+}, which counteract the negative effects of Na^+. As such, it is a dimensionless ratio that expresses the sodium content of the substrate.

In Experiment 6, the SAR of the VC mix substrate after 6 weeks of TW or GW irrigation was calculated. At the end of Week 6, substrate was harvested from 'runoff quality' containers (5 replicates per treatment) and dried, and the concentrations of sodium (Na), calcium (Ca) and magnesium (Mg) were measured using ICP-OES at NRM Laboratories (Bracknell, UK), as described in Section 2.7.4. SAR of the substrate was then calculated using Equation 6.1 (Travis *et al*, 2010):

$$SAR = \frac{Na^+}{\sqrt{\frac{[Ca^{2+}] + [Mg^{2+}]}{2}}} \qquad \text{(Eq. 6.1)}$$

6.2.3 Impact of greywater on provision of ecosystem services

Canopy temperatures were measured as an indicator of the extent of cooling provision. In Experiment 5, thermal images were taken once, as described in Section 2.5.6, at the end of the experiment (Day 58) when SMC had been brought up to an optimal range (> 0.300 m^3 m^{-3}) following flushing (see Section 6.2.4). In Experiment 6, images of all plants were taken fortnightly throughout the 6 week experiment.

To further examine the impact of GW on plant transpiration and water use, in Experiment 6 daily water uptake (i.e. ET) from the 'ET assessment' containers (12 replicates of each plant treatment - 6 each from the TW and GW irrigation treatments) was measured in Week 7. This directly followed on from the first 6 weeks of controlled irrigation, so containers had already been exposed to GW for 6 weeks. Each container was saturated to container capacity by submerging in either TW or synthetic GW as appropriate for 15 minutes and then draining for 1 hour. Containers were weighed and SMC and substrate EC were measured after draining and then every 24 hours for 6 days. At the end of this period, leaf areas of 4 randomly selected plants from every treatment were measured, and shoots and roots were harvested and weighed.

6.2.4 Impact of greywater on runoff quality

To assess how different species may influence runoff quality and the impact of GW on this service, containers were flushed with either TW or GW (depending on their irrigation treatment) at the end of both experiments and the runoff was collected for chemical analysis. All containers were flushed at the end of 8 weeks in Experiment 5, whilst in Experiment 6, 'runoff quality' containers only (i.e. 10 replicates of each species/control – 5 each from the TW and GW treatments) were flushed at the end of 6 weeks.

To ensure that the whole depth of substrate was saturated whilst generating runoff, a total of 600 mL of water (TW or GW) was applied directly to the substrate of each container in three separate applications 5 minutes apart in Experiment 5, and a total of 800 mL in four separate applications in Experiment 6. Containers were stood in clean trays to collect the runoff, which was then poured into sample bottles. The EC of each runoff sample was measured using the WET sensor, and samples were stored below 4°C until analysis.

After flushing, roots and shoots from 4 replicates per treatment in Experiment 5 and all 'runoff quality' containers in Experiment 6 were harvested. Additionally, substrate from each of the containers (350 g of Meadow Roof Medium (MRM) and 1 L of the vermiculite: peat-based compost mixed substrate (VC mix) in Experiments 5 and 6 respectively) was collected and air dried. Concentrations of boron and phosphorus (plus sodium in Experiment 6) in all runoff, root, shoot and substrate samples were determined by chemical analysis, as described in Section 2.7.4.

6.2.5 Data analysis

All statistical analyses were performed as described in Section 2.8. Daily ET measured in week 7 of Experiment 6 was calculated as the weight loss per container in each 24-hour period and converted to depth (mm). To account for any differences in plant sizes between TW and GW treatments, daily ET relative to leaf area for each plant was also calculated.

6.3 Results

Experiments 5 and 6 were conducted with different substrates to explore the impact of plant choice on runoff quality in realistic green roof (GR) conditions as well as in an idealised, modelled setting. For simplicity, Experiments 5 and 6 are hereafter referred to as being conducted under 'industry standard GR conditions' (i.e. with the Meadow Roof Medium; MRM) or 'model GR conditions' (i.e. with the vermiculite: peat-based compost mixed substrate; VC mix) respectively.

6.3.1 Impact of greywater irrigation on the substrate

6.3.1.1 Sodium Adsorption Ratio of the substrate

The average substrate Sodium Adsorption Ratio (SAR) of each treatment after 6 weeks of TW or GW irrigation in Experiment 6 is presented in Table 6.3. SAR was significantly higher in GW-irrigated substrates compared to those irrigated with TW for all species and the control ($P < 0.001$), with SARs of all species irrigated with GW greater than 6. The SAR of the bare substrate control was somewhat lower than for all planted treatments (31% lower on average); this is likely to have resulted from the lower total input of nutrients to control containers due to the irrigation regime employed in Experiment 6 based on the ET losses of each treatment (see Sections 2.7.2 - 2.7.3).

Table 6.3: Mean Sodium Adsorption Ratio (SAR) of the substrate after 6 weeks of tap water (TW) or greywater (GW) irrigation for all treatments in Experiment 6. Data are means of 5 replicates per treatments with associated LSDs (5%); red colour indicates statistical differences between TW and GW irrigation treatments within each species/control.

Expt. 6	Mean SAR of substrate		
Treatment	**TW**	**GW**	**LSD** (d.f. = 9)
Heuchera	1.7	6.3	**0.56**
Salvia	1.9	6.7	**0.95**
Stachys	2.2	7.0	**0.77**
Sedum	1.9	6.3	**0.74**
Control	1.3	4.5	**0.65**

6.3.1.2 Substrate electrical conductivity

Average weekly substrate electrical conductivity (EC) for each treatment throughout Experiments 5 and 6 are presented in Figure 6.1 and Figure 6.2 respectively; all EC values are reported at 25°C (see Section 2.5.1). Substrate ECs with 'industry standard GR conditions' in Experiment 5 were typically greater than 3000 µS cm^{-1} for all treatments at the start of the experiment. ECs of all species/control (both TW- and GW-irrigated) decreased significantly over the 8 weeks of the experiment ($P < 0.001$) and were only 40 – 60% of their week 1 values in week 8. Substrate ECs of TW and GW treatments were statistically similar for the majority of Experiment 5 for all species apart from *Stachys*, where the substrate EC of GW-irrigated containers was significantly higher than for TW-irrigated containers for most of the experiment Figure 6.1 C; $P = 0.005$ in week 1 and $P = 0.028$, 0.011, 0.043, 0.001 and < 0.001 in weeks 4 – 8 respectively). Additionally, the difference in substrate EC between TW- and GW-irrigated *Stachys* became progressively greater over the 8 weeks, with substrate EC of the GW treatment 10% higher than the TW treatment in week 1 increasing to 30% higher in week 8.

Substrate ECs were typically lower with 'model GR conditions' in Experiment 6 (700 – 1700 µS cm^{-1}), and increased significantly over the course of the 6 weeks for all planted treatments (both TW- and GW-irrigated treatments; $P < 0.001$), except for GW-irrigated *Sedum* and TW-irrigated *Heuchera*. Conversely, substrate EC of the control treatment decreased significantly over the course of the experiment with both TW and GW irrigation ($P < 0.001$), similar to Experiment 5. Substrate EC was frequently significantly higher with GW irrigation compared to TW for all species/control, and differences between TW and GW irrigated containers became increasingly large over the 6 weeks of the experiment, particularly for *Heuchera*, *Sedum* and the control Figure 6.2 A, D and E); for example, substrate EC of GW-irrigated *Heuchera* was 4% lower than the TW-irrigated treatment in week 1 but was 38% higher by week 6.

6.3.1.3 Accumulation of nutrients in the substrate

The average concentration of nutrients accumulated in the substrate at the end of Experiments 5 and 6 are presented in Table 6.4 and Table 6.5 respectively. In Experiment 6, species/control received different irrigation volumes, and thus different quantities of nutrients, due to the ET-based irrigation regime employed. However, identical volumes of TW and GW were used for irrigation within species, enabling comparison of nutrient accumulation in the substrate of TW and GW treatments for each species.

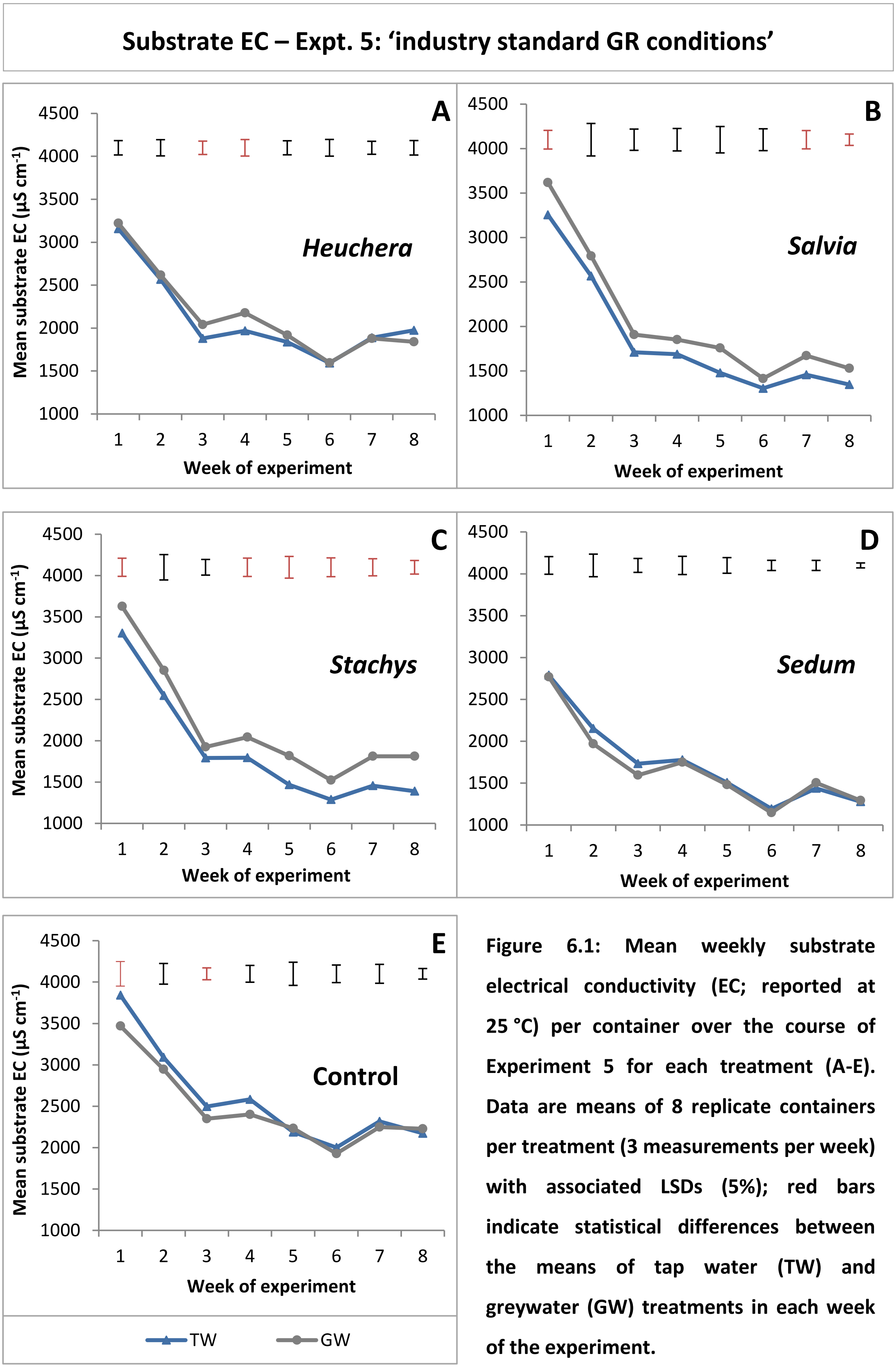


Figure 6.1: Mean weekly substrate electrical conductivity (EC; reported at 25 °C) per container over the course of Experiment 5 for each treatment (A-E). Data are means of 8 replicate containers per treatment (3 measurements per week) with associated LSDs (5%); red bars indicate statistical differences between the means of tap water (TW) and greywater (GW) treatments in each week of the experiment.

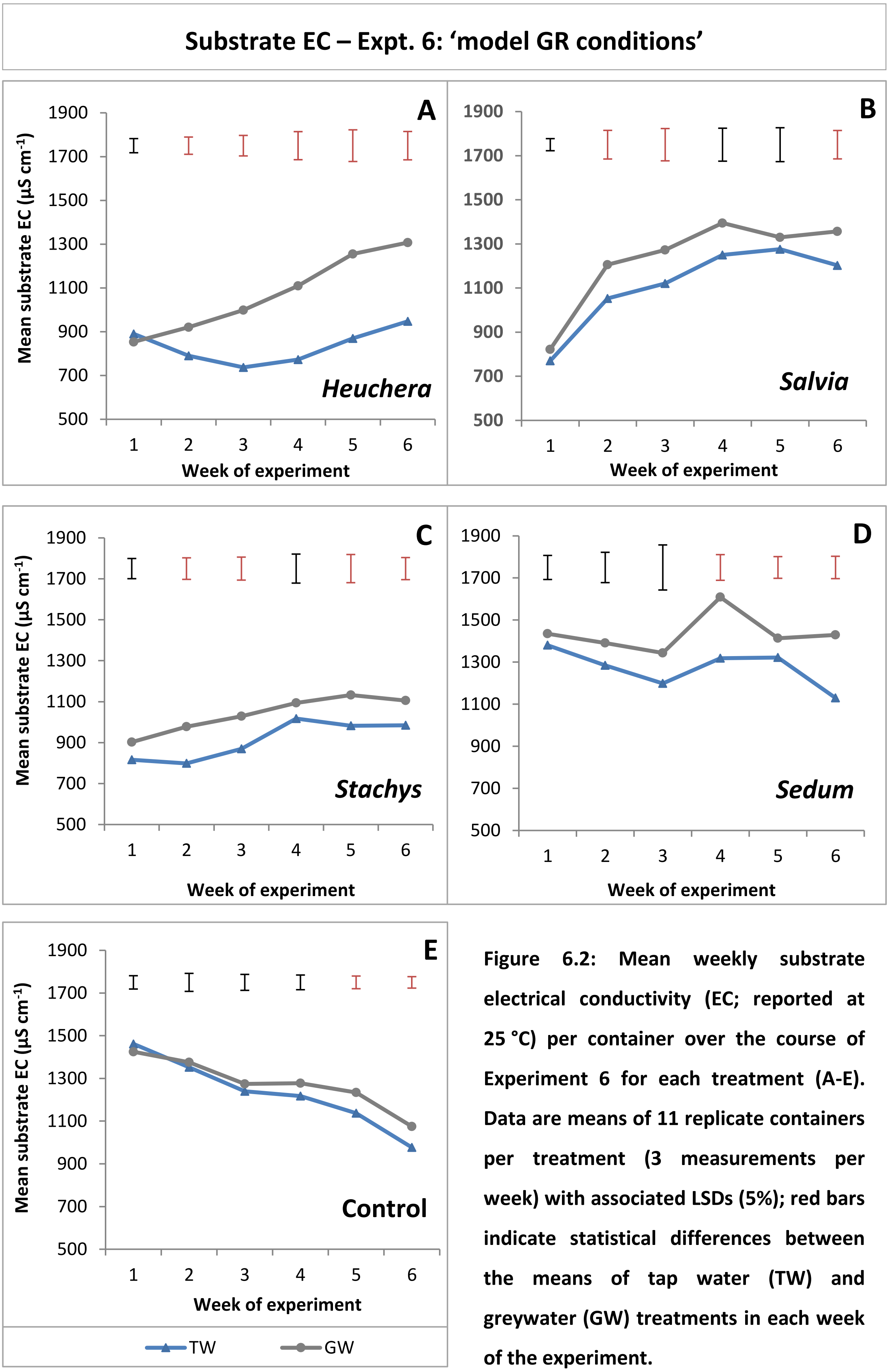


Figure 6.2: Mean weekly substrate electrical conductivity (EC; reported at 25 °C) per container over the course of Experiment 6 for each treatment (A-E). Data are means of 11 replicate containers per treatment (3 measurements per week) with associated LSDs (5%); red bars indicate statistical differences between the means of tap water (TW) and greywater (GW) treatments in each week of the experiment.

Table 6.4: Mean concentrations of phosphorus (P) and boron (B) accumulated in the MRM substrate per container after 8 weeks in Experiment 5. Data are means of 4 replicates per treatment with associated LSDs (5%); red colour indicates statistical differences between tap water (TW) and greywater (GW) irrigation treatments within each species/control.

Expt. 5	Mean concentration of nutrients in the substrate (mg L^{-1})					
Treatment	Phosphorus			Boron		
	TW	GW	LSD (d.f. = 7)	TW	GW	LSD (d.f. = 7)
Heuchera	121	143	**13.6**	6.5	7.1	**0.94**
Salvia	160	170	**16.7**	9.0	9.5	**0.82**
Stachys	153	137	**24.9**	8.8	7.1	**0.89**
Sedum	125	128	**30.7**	6.7	8.1	**0.78**
Control	128	148	**15.1**	7.5	7.4	**2.27**

Table 6.5: Mean concentrations of phosphorus (P), boron (B) and sodium (Na) accumulated in the VC mix substrate per container after 6 weeks in Experiment 6. Data are means of 5 replicates per treatment with associated LSDs (5%); red colour indicates statistical differences between tap water (TW) and greywater (GW) irrigation treatments within each species/control.

Expt. 6	Mean concentration of nutrients in the substrate (mg L^{-1})								
Treatment	Phosphorus			Boron			Sodium		
	TW	GW	LSD (d.f. = 9)	TW	GW	LSD (d.f. = 9)	TW	GW	LSD (d.f. = 9)
Heuchera	3.7	12.0	**1.77**	0.05	0.59	**0.113**	43	157	**16.2**
Salvia	3.9	18.2	**4.21**	0.05	0.74	**0.027**	61	197	**34.6**
Stachys	4.0	15.8	**5.25**	0.05	0.65	**0.126**	69	202	**17.1**
Sedum	4.9	12.6	**1.60**	0.08	0.86	**0.088**	72	220	**18.1**
Control	11.4	23.7	**5.65**	0.05	0.43	**0.061**	55	171	**37.8**

Phosphorus and boron concentrations in the substrate were substantially higher in the MRM used in Experiment 5 compared to the VC mix substrate used in Experiment 6, even with TW irrigation and despite doubling the concentration of B in the irrigation GW in Experiment 6 (Table 6.4 and Table 6.5). For example, the average P concentration in the substrate of TW-irrigated control containers was 128 mg L^{-1} for the MRM (Experiment 5) compared to 11.4 mg L^{-1} for the VC mix (Experiment 6), highlighting the inherently high nutrient content in the MRM and the inherently low nutrient content in the VC mix. With 'model GR conditions' in Experiment 6, concentrations of all nutrients in the substrate were significantly higher after 6 weeks of GW irrigation compared to TW irrigation for all species/control ($P < 0.001$; Table 6.5): P content was at least double in GW-irrigated containers, Na concentrations were around three times higher, and B content was at least 10 times higher compared to TW-irrigated containers. Nutrient concentrations in the substrate were more similar in TW- and GW-irrigated containers with 'industry standard GR conditions' in Experiment 5 (Table 6.4).

6.3.2 Impact of greywater on plant health and growth

6.3.2.1 Plant uptake of nutrients

Concentrations of nutrients taken up into the roots and shoots of TW- and GW-irrigated plants in Experiment 6 are presented in Table 6.6. As with accumulation in the substrate, although species received different quantities of nutrients through irrigation over the 6-week experiment as a result of the irrigation regime, identical volumes of TW and GW were used within species, enabling comparison of TW and GW treatments. It should also be noted that *Salvia* and *Stachys* were propagated from cuttings approximately 5 months before the start of the experiment, whereas *Heuchera* and *Sedum* were 2-year-old plants; this may account for the higher concentrations of some nutrients (such as Na) in *Heuchera* and *Sedum* shoots and roots.

With 'industry standard GR conditions' in Experiment 5, there was very little difference in the nutrient concentrations in the roots or shoots between TW and GW treatments for any species (data not shown), similar to the comparable nutrient accumulations in the substrate and probably resulting from the inherently high nutrient content in the MRM. In contrast, concentrations of nutrients in the roots and shoots with 'model GR conditions' in Experiment 6 were frequently significantly higher with GW irrigation compared to TW (Table 6.6). This was always the case with *Stachys*, with significantly higher concentrations of P, B and Na in both shoots and roots ($P < 0.001$), whilst concentrations of all nutrients in *Heuchera* roots and in *Salvia* shoots were statistically similar in TW and GW treatments.

Table 6.6: Mean concentrations of phosphorus (P), boron (B) and sodium (Na) in the roots and shoots of plants from all treatments harvested after 6 weeks in Experiment 6. Data are means of 5 replicates per treatment with associated LSDs (5%); red colour indicates statistical differences between tap water (TW) and greywater (GW) treatments within each species.

Expt. 6		Mean concentration in roots and shoots per plant (mg kg^{-1})					
		Roots			Shoots		
Nutrient	Species	TW	GW	LSD (d.f. = 9)	TW	GW	LSD (d.f. = 9)
P	*Heuchera*	2918	3351	**976.1**	2785	3549	**668.3**
	Salvia	1962	3134	**631.5**	2319	2291	**685.8**
	Stachys	1590	2646	**479.4**	2792	3769	**706.6**
	Sedum	2597	2803	**478.4**	2170	2483	**255.7**
B	*Heuchera*	15.6	19.4	**5.01**	21.2	25.0	**1.43**
	Salvia	13.2	14.8	**1.18**	31.2	34.3	**10.22**
	Stachys	13.5	17.1	**1.40**	17.3	30.3	**3.29**
	Sedum	17.3	21.8	**2.12**	22.2	30.0	**3.52**
Na	*Heuchera*	2592	4228	**2134.2**	332	384	**425.7**
	Salvia	862	1998	**618.9**	91	102	**26.0**
	Stachys	653	2293	**640.2**	76	302	**77.7**
	Sedum	1812	2434	**902.7**	392	564	**126.7**

6.3.2.2 Plant health

There were no significant differences in the visually assessed health of plants irrigated with TW or GW for any species for the duration of both Experiments 5 and 6 (Figure 6.6 and Figure 6.7). All plants appeared to grow well in both experiments with both TW and GW irrigation (e.g. Figure 6.3), with consistently high visual scores over the course of the experiments (typically above 4); the exceptions were *Heuchera* in Experiment 5 and *Salvia* in Experiment 6.

With the 'industry standard GR conditions' in Experiment 5 (i.e. the MRM substrate), the visual health of *Heuchera* declined substantially in week 4 (Figure 6.6 A) following foliar scorching in week 3 of the experiment, which resulted in high levels of leaf dieback and a reduction in plant height, diameter and overall quality (Figure 6.4). This appeared to affect plants irrigated with both TW and GW to a similar extent, with reductions in visual scores from 4.5 in week 0 to 2.9 in week 4 for TW-irrigated plants and 4.4 to 2.3 for GW-irrigated plants, and was likely to be a result of the hot, sunny weather experienced at the start of the experiment or transplant shock from transplanting *Heuchera* into the MRM approximately 1 month prior to the start of Experiment 5. Indeed, *Heuchera* plants also exhibited a decline in health following transplanting into the VC mix prior to the start of Experiment 6, resulting in relatively low visual health at the start of the experiment (visual scores around 3.5; Figure 6.7 A) and subsequent improvement over the 6 weeks to visual scores of around 5.

With the 'model GR conditions' in Experiment 6 (i.e. the low-nutrient VC mix substrate), *Salvia* visual health declined after week 2 for both TW- and GW-irrigated plants (Figure 6.5), from average visual scores of 5 in week 0 to 4 by week 6 (Figure 6.7 B). This possibly could have been due to a nutrient deficiency since the VC mix substrate had inherently low nutrient concentrations and both TW and GW treatments were similarly affected.

Figure 6.3: Examples of typical *Stachys* (A) and *Sedum* (B) plants at the end of Experiment 5; similarly, both species grew well throughout Experiment 6.

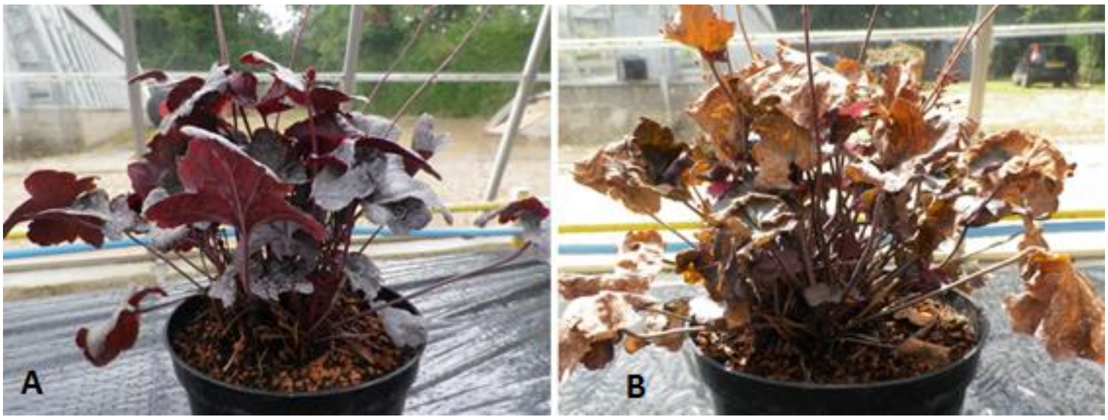


Figure 6.4: Example of a *Heuchera* plant at the start of Experiment 5 (A) and in week 4 (B), showing the decline in visual health due to high levels of foliar scorching and leaf dieback.

Figure 6.5: Example of a *Salvia* plant at the start of Experiment 6 (A) and in week 6 (B), showing foliar chlorosis and necrosis and a consequent decline in visual health.

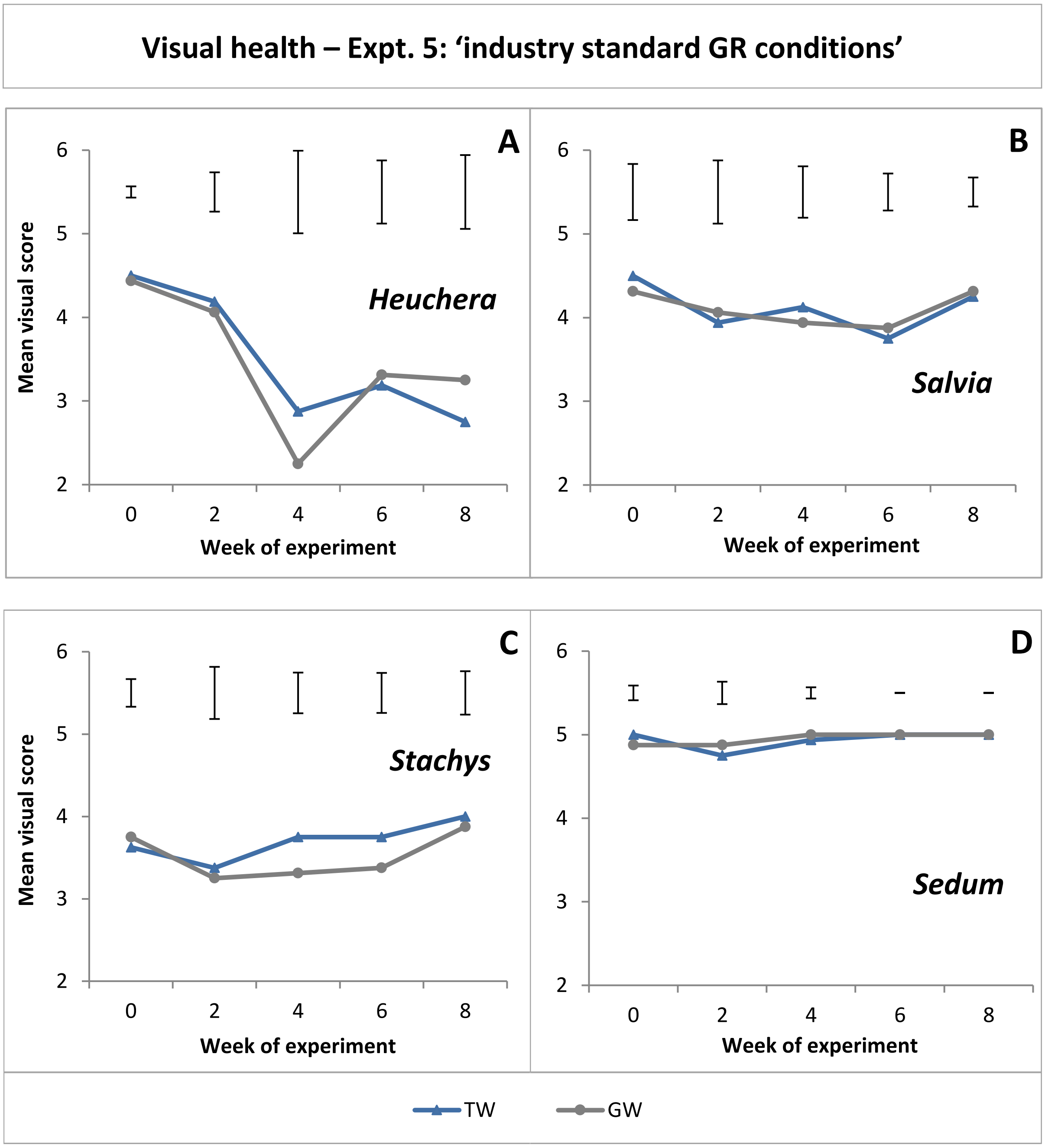


Figure 6.6: Mean visual health score of plants of each species (A – D) in tap water (TW) and greywater (GW) irrigation treatments over the course of Experiment 5. Data are means of 8 replicates per treatment with associated LSDs (5%).

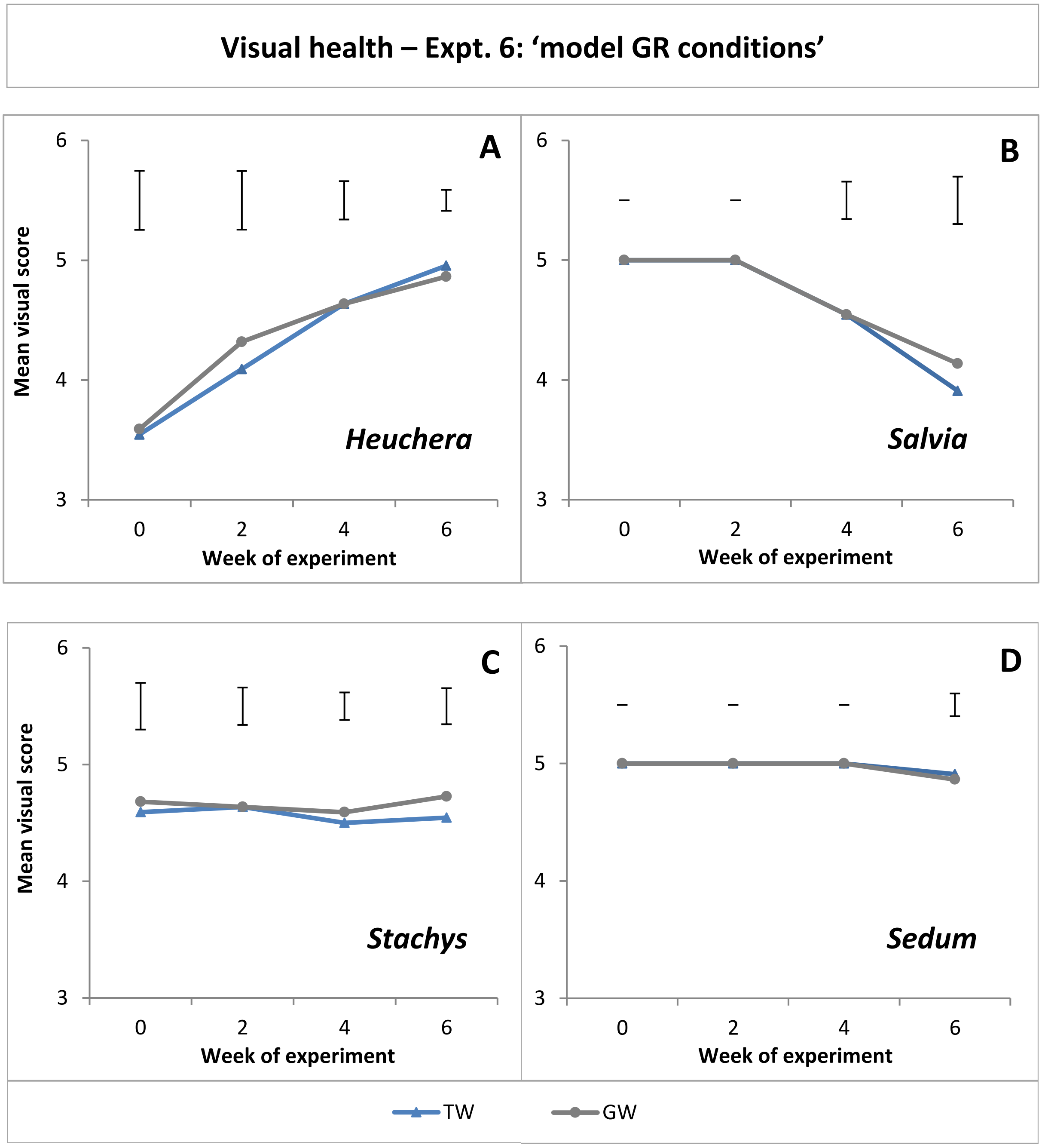


Figure 6.7: Mean visual health score of plants of each species (A – D) in tap water (TW) and greywater (GW) irrigation treatments over the course of Experiment 6. Data are means of 11 replicates per treatment with associated LSDs (5%).

6.3.2.3 Plant growth

There were no significant differences in plant height (Figure 6.8 and Figure 6.9) or diameter (data not shown) between TW or GW treatments for any of the species throughout both Experiments 5 and 6. The only exception was significantly greater plant height of *Heuchera* irrigated with TW compared to GW in week 4 of Experiment 5 ($P = 0.016$; Figure 6.8 A), which occurred when both height and diameter of all plants (both TW- and GW-irrigated) decreased concurrently with the decline in visual health and quality (Section 6.3.2.2). Plant height and diameter of all other species (and *Heuchera* in Experiment 6) generally increased over the course of both experiments. Indeed, shoot and root dry weights of most species increased significantly over the course of both experiments (Table 6.7 and Table 6.8); the only exception was *Heuchera* shoot dry weight in Experiment 5 which was significantly lower after the 8 weeks of the experiment than the baseline ($P < 0.001$; Table 6.7), corresponding to the decrease in plant height and diameter and visual health around week 4. However, there were no significant differences in root or shoot dry weights measured after 8 weeks in Experiments 5 and after 6 weeks in Experiment 6 between plants irrigated with TW or GW for any species. Additionally, root and shoot dry weights (data not shown) and leaf areas (Table 6.8) of plants used in week 7 of Experiment 6 were statistically similar for all species.

Table 6.7: Mean root and shoot dry weights of baseline plants harvested on Day 0 of Experiment 5 and plants in all treatments harvested after 8 weeks. Data are means of 4 replicates per treatment/baseline with associated LSDs (5%); red colour indicates statistical differences between baseline, tap water (TW) and greywater (GW) plants within each species.

Expt. 5	Mean root dry weight per plant (g)				Mean shoot dry weight per plant (g)			
Species	Baseline	TW	GW	LSD (d.f. = 11)	Baseline	TW	GW	LSD (d.f. = 11)
Heuchera	11.2	18.6	21.5	**4.99**	22.8	13.1	9.8	**3.55**
Salvia	0.9	3.1	2.7	**1.34**	3.1	5.5	5.4	**1.83**
Stachys	1.2	2.5	2.0	**0.67**	3.3	6.8	6.1	**1.24**
Sedum	3.1	8.2	7.8	**3.04**	17.4	23.4	25.0	**12.23**

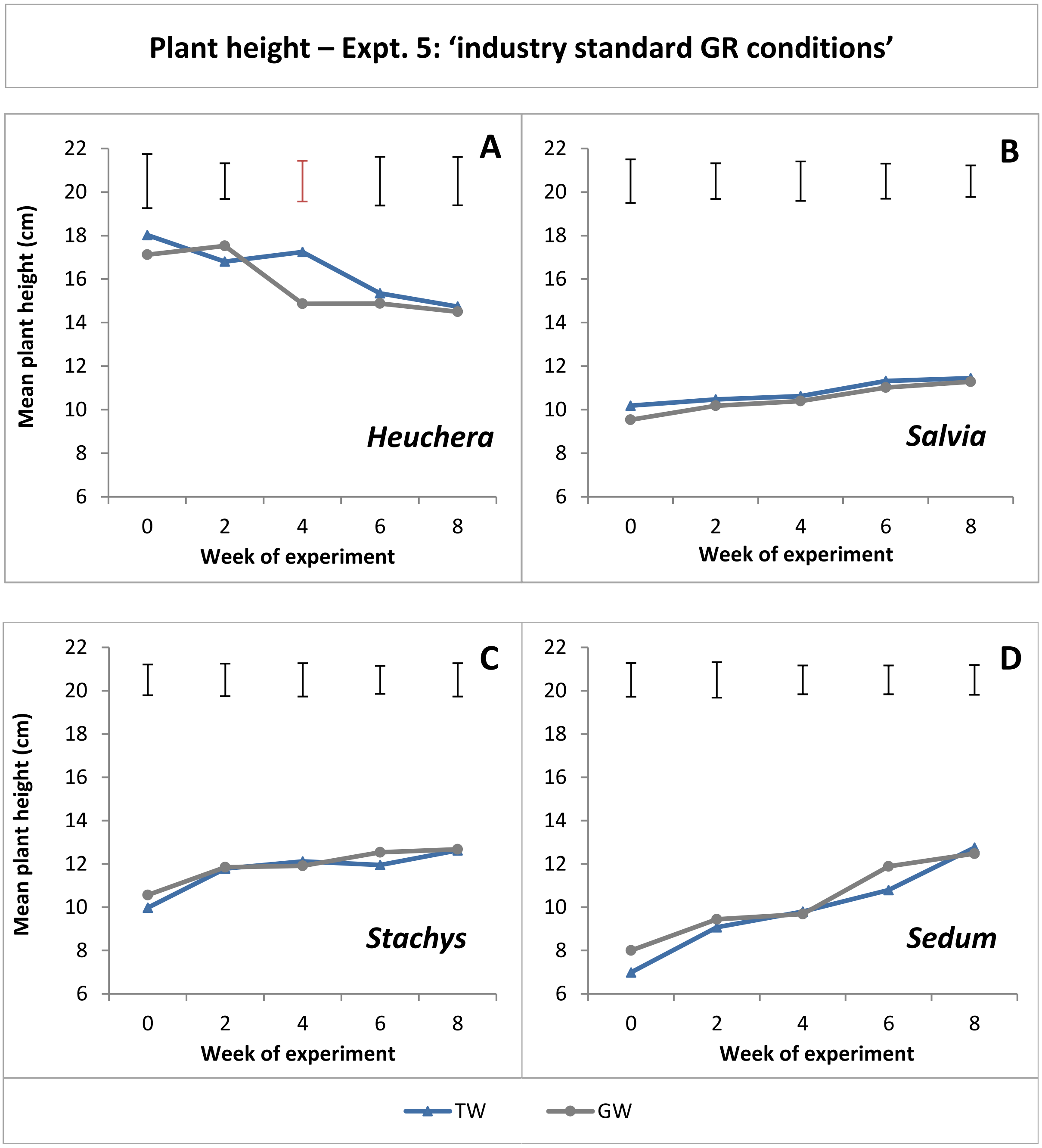


Figure 6.8: Mean height of plants of each species (A – D) in tap water (TW) and greywater (GW) treatments over the course of Experiment 5. Data are means of 8 replicates per treatment with associated LSDs (5%); red bars indicate statistical differences between the means of TW and GW treatments in each week of the experiment.

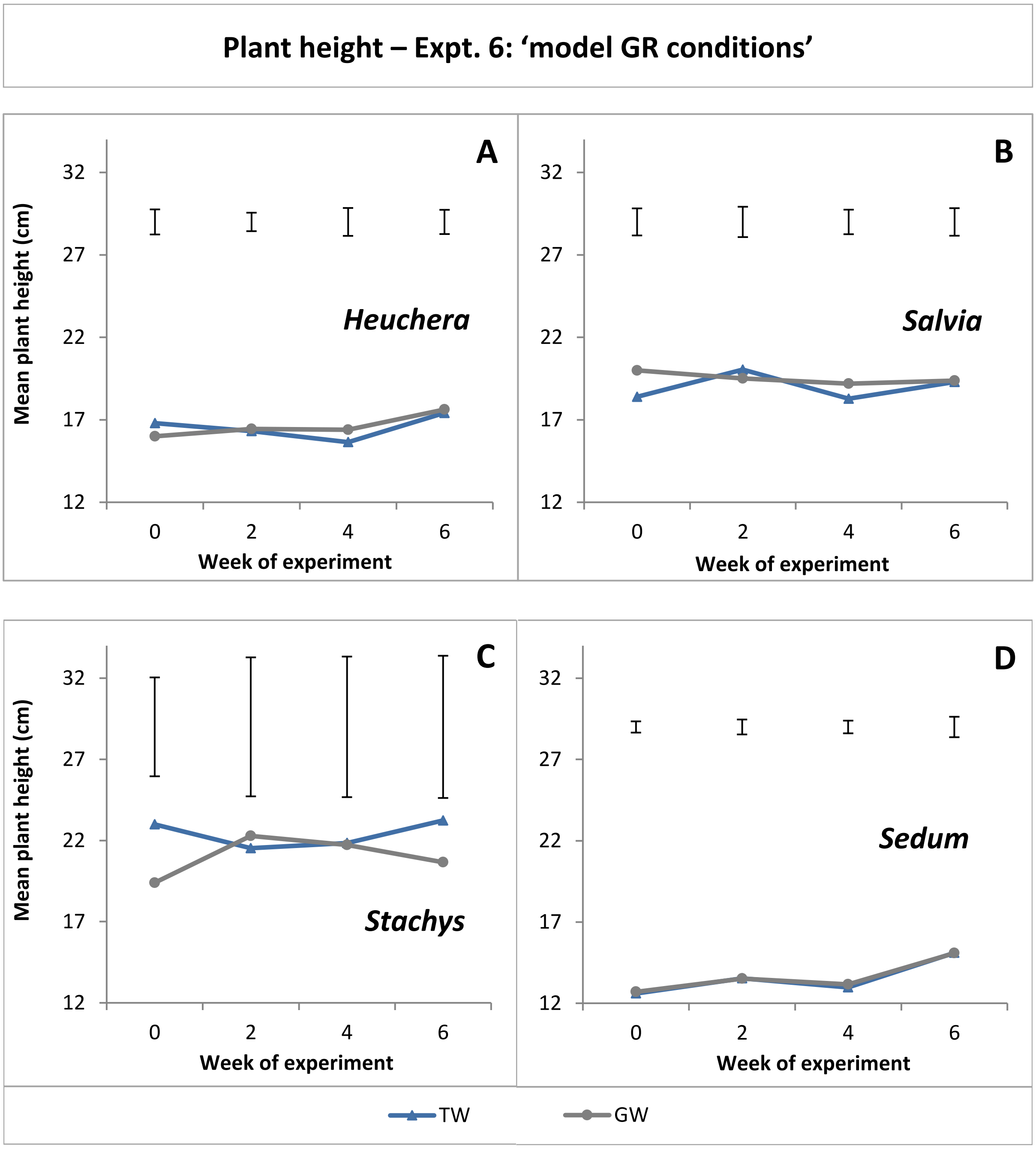


Figure 6.9: Mean height of plants of each species (A – D) in tap water (TW) and greywater (GW) treatments over the course of Experiment 6. Data are means of 11 replicates per treatment with associated LSDs (5%).

Table 6.8: Mean root and shoot dry weights of baseline plants (harvested on Day 0) and plants in tap water (TW) and greywater (GW) treatments harvested after 6 weeks in Experiment 6 ('runoff quality' containers), and mean leaf area of plants in each treatment measured at the end of week 7 ('ET assessment' containers). Shoot and root data are means of 5 replicates per treatment (or 4 replicates of baseline plants) with associated LSDs (5%); leaf area data are means of 4 replicates per treatment with associated LSDs (5%). Red colour indicates statistical differences between means within each species.

Expt. 6	**Species**	**Baseline**	**TW**	**GW**	**LSD** (d.f.)
Mean root dry weight per plant (g)	***Heuchera***	4.2	5.4	5.9	**2.37** (13)
	Salvia	1.9	5.7	5.6	**1.36** (13)
	Stachys	1.8	5.6	5.1	**2.26** (13)
	Sedum	6.5	8.1	8.3	**1.92** (13)
Mean shoot dry weight per plant (g)	***Heuchera***	7.1	16.0	16.4	**3.97** (13)
	Salvia	4.9	13.0	12.9	**1.92** (13)
	Stachys	6.4	13.7	12.7	**2.84** (13)
	Sedum	18.5	37.5	38.9	**6.54** (13)
Mean leaf area per plant (cm^2)	***Heuchera***	-	1646.7	1577.6	**407.22** (7)
	Salvia	-	626.5	526.9	**192.55** (7)
	Stachys	-	734.9	837.0	**315.84** (7)
	Sedum	-	1533.2	1815.7	**560.50** (7)

6.3.3 Impact of greywater on plant functioning and provision of ecosystem services

6.3.3.1 Leaf stomatal conductance

There were no significant differences in leaf stomatal conductance to water vapour (g_s) between TW and GW treatments of any species throughout Experiment 5 or 6 (Figure 6.10 and Figure 6.11), with the exception of *Heuchera* in week 6 of Experiment 6, when the g_s of GW-irrigated plants was significantly lower than the g_s of TW-irrigated plants (P = 0.045; Figure 6.11 A).

The g_s of *Heuchera* increased over the course of Experiment 6 concurrently with an increase in visual health (Section 6.3.2.2), particularly for the TW treatment, which was approximately 2.5 times higher in week 6 compared to week 0 (Figure 6.11 A). In contrast, *Salvia* g_s decreased over the course of Experiment 6 from week 3 onwards for both TW and GW treatments (Figure 6.11 B), in line with an observed decrease in visual health (Section 6.3.2.2); by week 6, *Salvia* g_s was only 54% or 61% of its original baseline value for TW and GW treatments respectively.

In Experiment 5, the g_s of *Heuchera*, *Stachys* and *Sedum* (both TW and GW treatments) were substantially lower for most of the experiment than the baseline g_s, with average g_s in week 2 31%, 49% and 18% of baseline g_s respectively (Figure 6.10 A, C and D). This coincided with a decline in the SMC of all treatments over the first few weeks of the experiment, from around 0.300 m^3 m^{-3} in week 1 decreasing to 0.100 – 0.200 m^3 m^{-3} by week 3 (data not shown), which resulted from the regulated deficit irrigation regime used. The g_s of all treatments was high in week 8 when the SMCs of all containers were high (> 0.350 m^3 m^{-3} for all containers; data not shown) following flushing (Section 6.2.4).

6.3.3.2 Canopy temperatures

There were no significant differences in canopy temperatures measured once after 8 weeks in Experiment 5 (Table 6.9) or at any time throughout Experiment 6 (Table 6.10) between TW and GW treatments of any species.

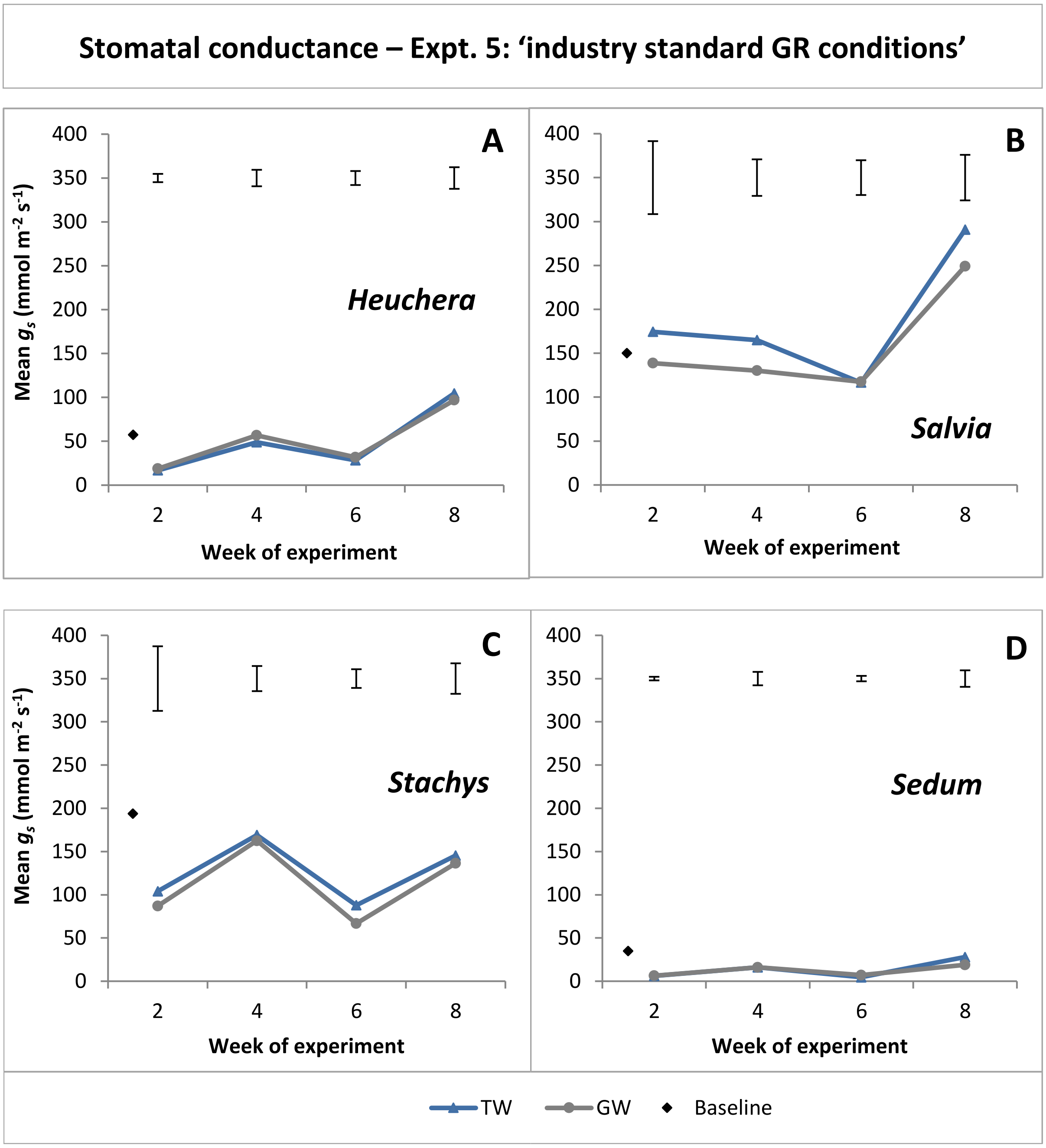


Figure 6.10: Mean stomatal conductance (g_s) of plants of each species (A – D) in tap water (TW) and greywater (GW) treatments over the course of Experiment 5. Data are means of 8 replicates per treatment with associated LSDs (5%). Baseline g_s (week 0) was measured using baseline plants (4 replicates per species).

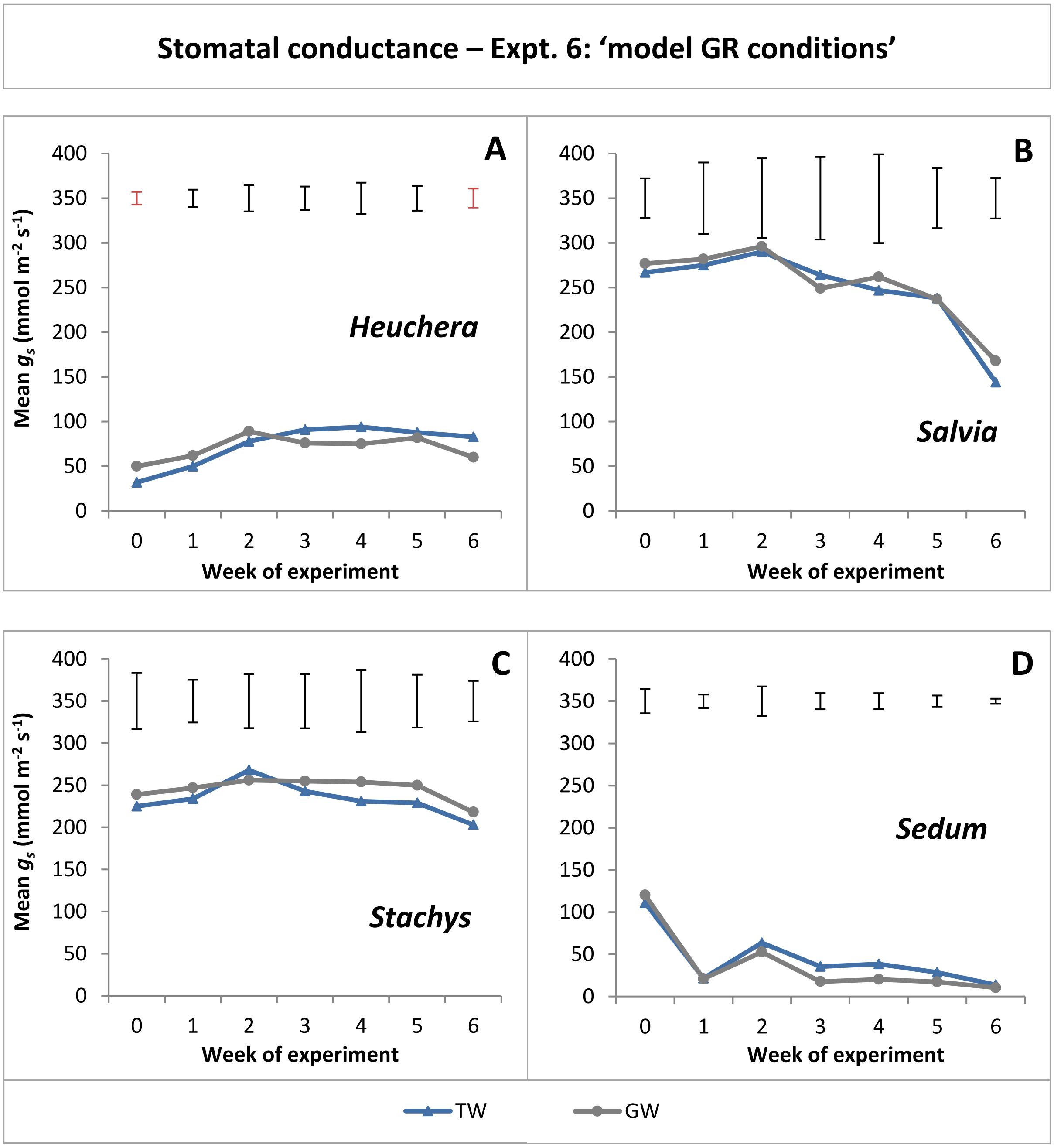


Figure 6.11: Mean stomatal conductance (g_s) of plants of each species (A – D) in tap water (TW) and greywater (GW) treatments over the course of Experiment 6. Data are means of 11 replicates per treatment with associated LSDs (5%); red bars indicate statistical differences between the means of TW and GW treatments in each week of the experiment. A significant difference (P = 0.013) in *Heuchera* baseline g_s between TW and GW treatments (A) was considered to be descriptive of plant functional 'health' as measurements were made before TW/GW irrigation commenced.

Table 6.9: Mean canopy temperature of plants in tap water (TW) and greywater (GW) treatments, measured at the end of Experiment 5 (Day 58). Data are means of 8 replicates per treatment with associated LSDs (5%).

Expt. 5	Mean canopy temperature (°C)		
Species	**TW**	**GW**	**LSD** (d.f. = 15)
Heuchera	24.3	24.8	**0.67**
Salvia	23.6	23.0	**1.12**
Stachys	24.0	23.5	**1.42**
Sedum	24.5	24.0	**1.66**

Table 6.10: Mean canopy temperature of plants in tap water (TW) and greywater (GW) treatments over the course of Experiment 6. Data are means of 11 replicates per treatment with associated LSDs (5%).

Expt. 6		Mean canopy temperature (°C)			
Treatment		**Week 0**	**Week 2**	**Week 4**	**Week 6**
Heuchera	**TW**	22.7	21.8	21.2	21.9
	GW	22.6	22.0	21.4	22.3
	LSD (d.f. = 21)	**0.64**	**0.31**	**0.25**	**0.41**
Salvia	**TW**	19.3	21.3	20.1	21.4
	GW	19.3	21.3	20.1	21.5
	LSD (d.f. = 21)	**0.26**	**0.34**	**0.21**	**0.51**
Stachys	**TW**	19.0	21.0	19.5	20.5
	GW	18.9	20.9	19.4	20.6
	LSD (d.f. = 21)	**0.48**	**0.26**	**0.29**	**0.32**
Sedum	**TW**	20.3	22.2	22.2	22.0
	GW	20.2	22.2	22.3	22.3
	LSD (d.f. = 21)	**0.43**	**0.29**	**0.22**	**0.44**

6.3.3.3 Evapotranspiration

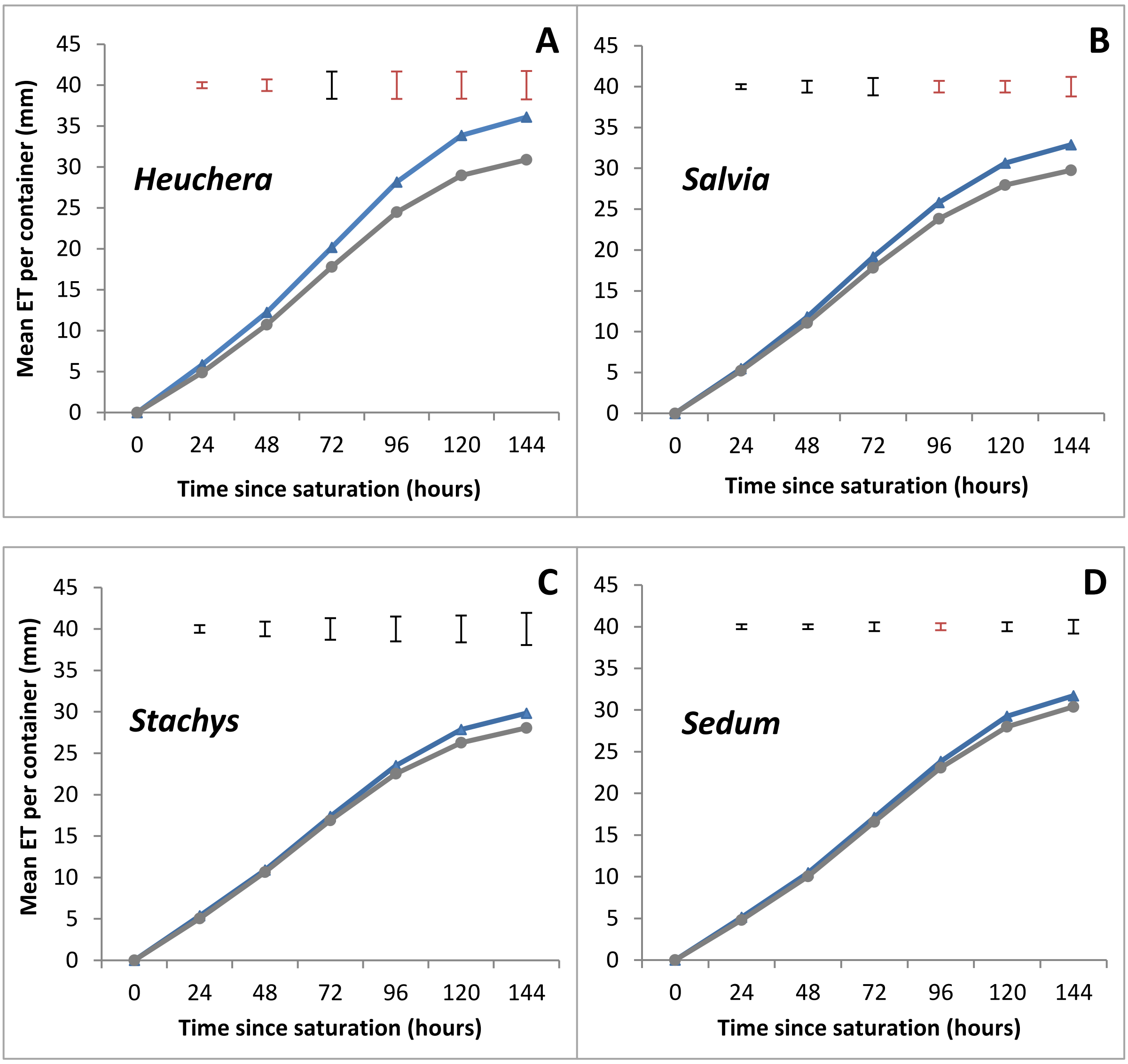
Daily evapotranspiration (ET) per container was measured following saturation in week 7 of Experiment 6, following directly on from the previous 6 weeks of irrigation with TW or GW. The saturated SMCs were lower for containers in the GW treatment compared to the TW treatment for all species/control (Table 6.11), significantly so for *Heuchera* (P = 0.007) and the control (P = 0.003).

Table 6.11: Mean SMC of each treatment following saturation at the beginning of week 7 in Experiment 6. Data are means of 6 replicates per treatment with associated LSDs (5%); red colour indicates statistical differences between tap water (TW) and greywater (GW) irrigation treatments within each species/control.

Expt. 6	**Mean SMC of saturated substrate (m^3 m^{-3})**				
Treatment	***Heuchera***	***Salvia***	***Stachys***	***Sedum***	**Control**
TW	0.600	0.563	0.617	0.591	0.621
GW	0.544	0.520	0.555	0.565	0.566
LSD (d.f. = 11)	**0.0371**	**0.0588**	**0.0783**	**0.0388**	**0.0307**

There was a general trend of slightly lower ET from GW-irrigated containers compared to TW-irrigated containers for all species throughout week 7 of Experiment 6 (Figure 6.12), which was significant for *Heuchera*, *Salvia* and the control. For *Heuchera*, ET was significantly lower in the GW treatment compared to the TW treatment for almost the whole week (P = 0.019, 0.041, 0.035, 0.008 and 0.007 at 24, 48, 96, 120 and 144 hours respectively; Figure 6.12 A), whilst for *Salvia* differences became significant after 96 hours of ET with no additional irrigation (P = 0.011, 0.002 and 0.016 at 96, 120 and 144 hours respectively; Figure 6.12 B). Although plant size and leaf area of TW and GW treatments of all species were statistically similar (Table 6.8), when ET was expressed relative to leaf area there were no significant differences in ET per cm^2 of leaf area between TW and GW treatments for any species throughout week 7 (Table 6.12).

Evapotranspiration – Expt. 6: 'model GR conditions'



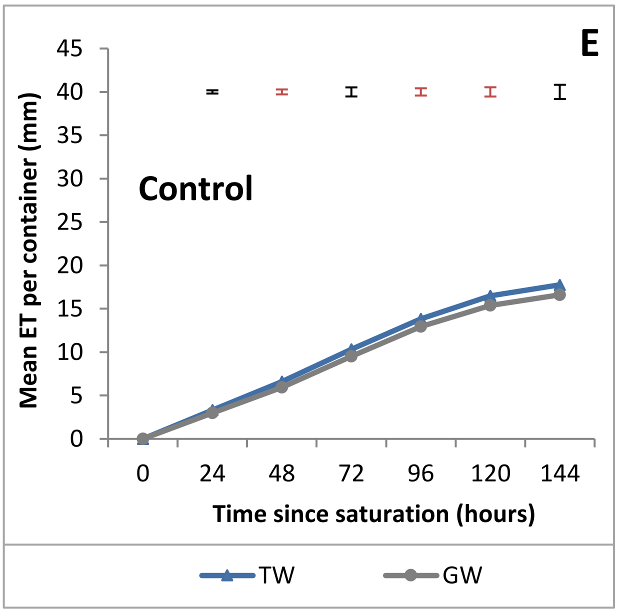


Figure 6.12: Mean cumulative evapotranspiration (ET) per container over the course of week 7 in Experiment 6 for *Heuchera* (A), *Salvia* (B), *Stachys* (C), *Sedum* (D) and the control (E). Data are means of 6 replicates per treatment with associated LSDs (5%); red bars indicate statistical differences between tap water (TW) and greywater (GW) treatments at each time point.

Table 6.12: Mean water loss per container expressed relative to leaf area for plants in tap water (TW) and greywater (GW) treatments in the week following saturation in Experiment 6. Data are means of 4 replicates per treatment with associated LSDs (5%).

Expt. 6		Mean water loss (mL) per leaf area (cm^2) following saturation					
Treatment		**24 h**	**48 h**	**72 h**	**96 h**	**120 h**	**144 h**
Heuchera	**TW**	0.076	0.168	0.276	0.378	0.459	0.491
	GW	0.070	0.164	0.269	0.365	0.432	0.458
	LSD (d.f. = 7)	**0.0155**	**0.0292**	**0.0159**	**0.0362**	**0.0889**	**0.1222**
Salvia	**TW**	0.205	0.460	0.754	0.989	1.167	1.239
	GW	0.222	0.493	0.789	1.033	1.208	1.287
	LSD (d.f. = 7)	**0.0391**	**0.1019**	**0.2704**	**0.3142**	**0.3492**	**0.3739**
Stachys	**TW**	0.161	0.345	0.550	0.733	0.866	0.918
	GW	0.137	0.310	0.500	0.654	0.760	0.806
	LSD (d.f. = 7)	**0.0246**	**0.0651**	**0.1464**	**0.1778**	**0.2137**	**0.2453**
Sedum	**TW**	0.076	0.165	0.266	0.367	0.455	0.494
	GW	0.058	0.130	0.216	0.294	0.357	0.386
	LSD (d.f. = 7)	**0.0225**	**0.0502**	**0.0831**	**0.1083**	**0.1434**	**0.1770**

6.3.4 Impact of greywater on runoff quality

Average EC and nutrient content of the runoff from all treatments, collected after 8 weeks of TW/GW irrigation in Experiment 5 and after 6 weeks in Experiment 6 are presented in Figure 6.13 and Table 6.13, respectively. In Experiment 6, species/control received different quantities of total nutrients over the course of the experiment as a result of the ET-based irrigation regime (see Section 2.7.3), with *Salvia*, *Stachys* and *Sedum* receiving approximately 1.2 times more than *Heuchera* and 1.8 times more than the control. As identical volumes of TW and GW were used within species/control, the effect of GW can still be assessed; however, species comparisons should be treated with caution.

In both experiments, runoff from GW-irrigated treatments had significantly higher concentrations of nutrients ($P < 0.001$) and significantly higher EC than runoff from TW-irrigated treatments ($P = 0.034$, 0.001 and 0.035 for *Salvia*, *Stachys* and *Sedum* respectively in Experiment 5; $P = 0.025$ for control and < 0.001 for all species in Experiment 6). The exceptions were runoff from *Heuchera* and the control in Experiment 5, both of which had similar B content and EC with both TW and GW irrigation. In Experiment 5, nutrient concentrations and ECs were typically significantly higher in the runoff from all treatments compared to the irrigation TW or GW ($P < 0.001$), except for the P content in runoff from GW-irrigated treatments, which was similar to the P content of the irrigation GW for all species/control (Figure 6.13 B). Conversely, in Experiment 6, EC and P and Na concentrations were significantly higher in the runoff from all GW-irrigated treatments compared to the irrigation GW ($P < 0.001$), whilst B concentrations were significantly lower in the runoff than in the irrigation GW (0.25 – 0.40 mg L^{-1} in the runoff compared to 0.75 mg L^{-1} in the GW, $P < 0.001$; Table 6.13 B). With TW irrigation in Experiment 6, Na content in the runoff from all treatments was significantly higher than the Na content of the irrigation TW ($P < 0.001$), but EC and P and B content of the runoff from some treatments (e.g. *Stachys*) were statistically similar to those of the irrigation TW (Table 6.13 A).

With TW irrigation in both experiments, runoff from planted treatments frequently had significantly lower EC and nutrient concentrations than runoff from the bare substrate control (Figure 6.13 A and Table 6.13 A). Indeed, despite receiving greater total quantities of nutrients over the 6 weeks of Experiment 6, runoff from *Stachys*, *Salvia* and *Sedum* had significantly lower EC and P content than runoff from the control with TW irrigation ($P < 0.001$), and also with GW irrigation for *Stachys* ($P < 0.001$). Species differences in runoff quality were also evident in both experiments, with *Heuchera* runoff having significantly higher concentrations of nutrients and EC than all other species in Experiment 5 ($P < 0.001$), and *Sedum* runoff typically having higher EC and nutrient content than runoff from *Stachys* and sometimes *Salvia* in Experiment 6.

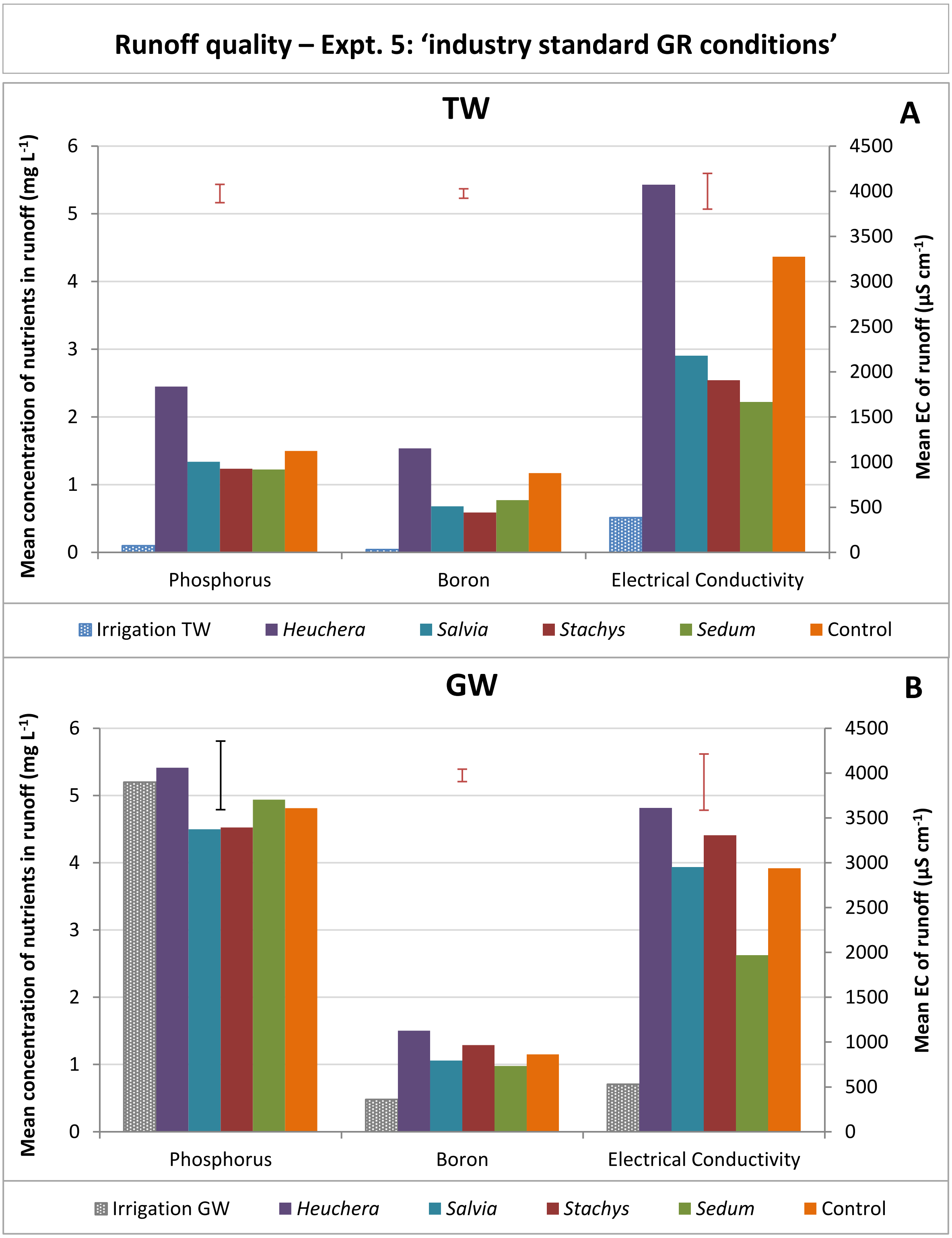


Figure 6.13: Mean concentrations of phosphorus and boron and mean electrical conductivity (EC) of runoff from containers of all species/control in the tap water (TW) and greywater (GW) treatments (A and B respectively) of Experiment 5; nutrient content and EC of the TW and GW used for irrigation are also presented. Data are means of 8 replicates per species/control (11 replicates of irrigation TW and GW) with associated LSDs (5%); red bars indicate statistical differences between treatments for each parameter respectively.

Table 6.13: Mean concentrations of phosphorus (P), boron (B) and sodium (Na) and mean electrical conductivity (EC) of runoff from containers of all species/control in the tap water (TW) and greywater (GW) treatments (A and B respectively) of Experiment 6; nutrient content and EC of the TW and GW used for irrigation are also presented. Data are means of 5 replicates per species/control (13 or 22 replicates of irrigation TW or GW respectively) with associated LSDs (5%); red colour indicates statistical differences between treatments for each parameter respectively.

Runoff quality – Expt. 6: 'model GR conditions'

A TW	**Mean concentration of nutrients in runoff and mean runoff EC**			
Treatment	**P (mg L^{-1})**	**B (mg L^{-1})**	**Na (mg L^{-1})**	**EC (µS cm^{-1})**
Irrigation TW	0.2	0.01	16.3	373
Heuchera	1.6	0.03	39.3	471
Salvia	1.2	0.02	54.9	528
Stachys	0.6	0.02	45.1	404
Sedum	0.8	0.03	57.9	501
Control	2.0	0.03	43.9	790
LSD (d.f. = 37)	**0.74**	**0.010**	**8.15**	**105.0**

B GW	**Mean concentration of nutrients in runoff and mean runoff EC**			
Treatment	**P (mg L^{-1})**	**B (mg L^{-1})**	**Na (mg L^{-1})**	**EC (µS cm^{-1})**
Irrigation GW	4.9	0.75	107.1	521
Heuchera	10.1	0.27	178.6	840
Salvia	10.2	0.25	213.2	954
Stachys	10.6	0.32	209.8	857
Sedum	12.9	0.40	228.6	1159
Control	14.0	0.27	133.0	1055
LSD (d.f. = 46)	**2.24**	**0.078**	**15.45**	**140.0**

6.4 Discussion

In this chapter, the potential suitability of greywater (GW) for use as supplemental irrigation was evaluated by assessing the impact of GW on plant health, growth, functioning and continued provision of ecosystem services (ESs) with four potential green roof species. The ability of the species to improve runoff quality (compared to bare substrate) and to improve the quality of the influent GW was also evaluated.

6.4.1 Characterisation of the synthetic greywater

The composition and properties of GW are known to vary widely depending on its source within the house and the products used (Eriksson *et al.*, 2002), and this can lead to great variation in the impacts of GW on soils and plants when used for irrigation. For example, Finley *et al.* (2009) attributed similar growth of lettuces irrigated with TW and GW to the low nutrient content of their GW not restricting growth. Indeed, P and Na concentrations in their untreated GW (0.24 - 1.02 and 20 - 27 mg L^{-1} respectively) were substantially lower than in the synthetic GW used in Experiments 5 and 6 (average of 5.1 and 107 mg L^{-1} respectively). Furthermore, another study found that the impacts of seven GW samples of differing origin on the growth and transpiration of willow varied widely depending on GW quality, from improvements in growth and functioning to suppressed transpiration (Eriksson et al, 2006).

Although concentrations of all nutrients (phosphorus (P), sodium (Na) and boron (B)) in the synthetic GW were significantly greater than in TW in both experiments, the concentration of B in the GW in Experiment 5 (0.48 mg L^{-1}) was similar to the lower toxicity threshold for sensitive plants (0.5 mg L-1; Almuktar *et al.*, 2015). Moreover, B concentration in the GW used in Experiment 6 (0.75 mg L^{-1}) was at the lower end of the range for irrigation waters classified as having slight to moderate restrictions on their usage (B content between 0.7 and 3.0 mg L^{-1}; Pescod, 1992). The concentration of B in the GW used in both experiments is therefore unlikely to have been high enough to have much negative impact on the substrate or plants.

Additionally, although the EC of the synthetic GW mixed for both experiments was slightly higher than the target range of 300 – 400 µS cm^{-1} recommended by Diaper *et al.* (2008), with an average EC of 526 µS cm^{-1} in both experiments, it was substantially lower than EC values reported in the literature for both real and synthetic GWs, which are frequently over 1500 µS cm^{-1} (Wiel-Shafran *et al.*, 2006; Al-Hamaiedeh and Bino, 2010). Moreover, the EC of the TW was only slightly (but statistically significantly) lower than that of the GW (an average of 380 µS cm^{-1} in both experiments), suggesting that plants irrigated with GW were not necessarily exposed to a much greater salinity (Gross *et al.*, 2005). High EC of irrigation GW was linked to reduced transpiration of willow plants in a study testing GWs with a range of EC and pH values (Eriksson *et al.*, 2006). However, EC values of up to 1000 µS cm^{-1} are deemed to be acceptable for irrigation waters, without affecting soil salinity or plant health (Albalawneh *et al.*, 2016). The EC, and thus salinity, of the synthetic GW used in both experiments could therefore be considered moderate, which may have limited any measurable impacts of the GW on the substrate and plants.

GW has also frequently been found to have high pH, often up to 9 or 10 (Pinto *et al.*, 2010) depending on its origin within the house and the pH of the TW, with laundry GW typically having the highest pH (Eriksson *et al.*, 2002). Irrigation with high-pH GW is likely to increase the pH of the soil (Ali *et al.*, 2013), which could result in micronutrient deficiencies, consequently limiting plant growth (Christova-Boal *et al.*, 1996). The pH of the synthetic GW used in both experiments averaged 7.8, which was within the target range of 6.5 – 8.0 specified by Diaper *et al.* (2008) and was similar to the pH of TW (8.1 on average). Consequently, substrate pH (measured in Experiment 6 with 'model GR conditions') was only marginally higher with GW compared to TW irrigation after 6 weeks (averages of 7.1 compared to 6.9 respectively; data not shown).

6.4.2 Impacts of greywater on substrate salinity

Accumulation of salts, particularly Na, in the substrate with GW irrigation can cause deterioration of the soil structure and can reduce the hydraulic conductivity of the substrate, thus making it difficult for plants to take up water (Al-Hamaiedeh and Bino, 2010; Rodda *et al.*, 2011b). Substrate Sodium Adsorption Ratio (SAR) measured at the end of 6 weeks in Experiment 6 ranged from 6.3 to 7.0 for all species irrigated with GW, compared to a range of 1.7 to 2.2 for plants irrigated with TW, indicting significantly greater substrate salinity with GW irrigation. The ability of a substrate to support plant growth is generally considered to be limited by SAR greater than 6 (Al-Hamaiedeh and Bino, 2010), indicating potential for negative impacts on plant growth and functioning (e.g. their ability to take up water for transpiration) in GW-irrigated treatments in Experiment 6. Substrate EC, which is another measure of substrate salinity, was also generally greater in GW-irrigated containers compared to those irrigated with TW in both Experiments 5 and 6 (Section 6.3.1.2), with a trend of increasingly greater substrate EC with continued GW irrigation compared to TW observed for some species (e.g. *Stachys* in Experiment 5). A similar trend has been identified in other studies (Wiel-Shafran *et al.*, 2006; Pinto *et al.*, 2010; Ali *et al.*, 2013), resulting from accumulation of salts in the substrate with continued GW application.

However, although substrate salinity was greater in containers irrigated with GW compared to TW in both Experiments 5 and 6, there was no apparent impact on the growth or health of any of the species (Section 6.4.3), although there was a suggestion that stomatal conductance may have been affected in Experiment 6 (Section 6.4.4).

Elevated substrate salinity resulting from GW irrigation could have potential implications for plant health, growth and functioning, particularly after a few weeks of continuous exposure to GW. Alternating GW with freshwater for irrigation could prevent this accumulation of salts in the substrate, thus ensuring that substrate EC and SAR do not become elevated and reducing the potential for any negative impacts on plants; indeed, Pinto *et al.* (2010) reported that substrate EC and concentrations of P in the substrate of silverbeet irrigated with freshwater and GW alternately were similar to when freshwater was used solely. Since GW is likely to be used only to supplement rainfall during extended periods of drought in the UK, substrate salinity would probably not increase and any impacts of GW would therefore be limited.

Elevated substrate EC over time with GW irrigation was particularly evident in Experiment 6 (for all treatments, especially *Heuchera*) when the inherent EC of the substrate was lower and addition of nutrients with GW irrigation had a more pronounced effect. Indeed, with these 'model GR conditions', substrate EC was relatively low with both TW and GW irrigation and was always within the range deemed acceptable for plant growth and soil microbial activities (0 - 1500 µS cm^{-1}) suggested by De Clerck *et al.* (2003). Conversely, with 'industry standard GR conditions' in Experiment 5, substrate ECs were mostly higher than this recommended range, and were particularly high at the beginning of the experiment – typically over 3000 µS cm^{-1}. Since initial substrate EC was high with all treatments and with both GW and TW irrigation, this was likely to be an inherent property of the MRM substrate, which could have masked any impacts of irrigation with GW. Substrate EC declined rapidly in the first 3 weeks of Experiment 5 but still remained relatively high (1300 – 2200 µS cm^{-1}) for the remainder of the experiment.

This decline in substrate EC over time with both TW and GW irrigation in Experiment 5 was unusual, since EC has generally been found to increase over time with GW irrigation, due to the continued addition of salts (Al-Hamaiedeh and Bino, 2010; Pinto *et al.*, 2010). The observed decline in Experiment 5 could have been a result of salts leaching down the substrate profile and accumulating at the bottom of the containers, particularly as the substrate settled in the first 3 weeks of the experiment. Indeed, substrate EC has previously been found to decrease substantially over time after original preparation, probably due to leaching or uptake of salts by plants (Noya *et al.*, 2017). However, this was unfortunately beyond the reach of the WET sensor probe, which only enabled measurement of the top 70 mm of the substrate, and actual ECs at the bottom of the containers may have been greater, especially as the irrigation regime ensured that no runoff was ever generated. However, plant roots probably reached the bottom of the 2 L containers, particularly for species with larger root systems (*Stachys* and *Salvia*); plants could therefore have been exposed to high salinity throughout the whole 8 weeks of the experiment despite an apparent decline in substrate EC at the surface. Other studies have also reported vertical leaching of salts through the soil profile, with greater EC at depth compared to the surface (Sharvelle *et al.*, 2012) and a decrease in EC over time in the top 30 cm of the soil profile (Albalawneh *et al.*, 2016).

6.4.3 Impacts of greywater irrigation on plant health and growth

Irrigation with GW could compromise plant health and growth due to accumulation and uptake of nutrients that may prove toxic (Christova-Boal *et al.*, 1996; Wiel-Shafran *et al.*, 2006) as well as its impacts on the substrate (Section 6.4.2), including elevated pH, EC and salinity (Gross *et al.*, 2005; Finley *et al.*, 2009), and decreased hydraulic conductivity as a result of salinity and the presence of surfactants (Al-Hamaiedeh and Bino, 2010; Travis *et al.*, 2010). Alternatively, the additional nutrients in GW may increase plant growth, particularly in nutrient-poor soils (Rodda *et al.*, 2011b). As such, studies have reported variable effects of irrigation with GW on plants, ranging from improvements in plant health and growth compared to plants irrigated with freshwater (Misra *et al.*, 2010; Ali *et al.*, 2013) to reduced growth and health (Travis *et al.*, 2010) or even plant death (Sawadogo *et al.*, 2014).

For all species tested in this study, there were no significant differences in height, diameter, biomass (shoot and root dry weights and leaf area) or health between plants irrigated with TW and those irrigated with GW, throughout the entire duration of both Experiments 5 and 6. All species generally grew well (with the exception of *Heuchera* in Experiment 5 and *Salvia* in Experiment 6; see Sections 6.3.2.2 - 6.3.2.3) with no visible symptoms of GW toxicity and a general increase in biomass over the course of both experiments. These results are in agreement with several other studies (Finley *et al.*, 2009; Pinto *et al.*, 2010; Alfiya *et al.*, 2012) which also reported no difference in plant health and growth with TW or GW irrigation. Short-term (6 – 8 weeks) irrigation with GW thus had no apparent detrimental effect on any of the species tested in this study, suggesting that GW may be suitable as a sustainable water source for irrigation of green roofs planted with these species. These results are only applicable for the synthetic GW used in the experiments, however, since the impacts of GW on plants and substrates has been shown to depend strongly on the quality of the GW (Eriksson *et al.*, 2006; Finley *et al.*, 2009). The composition and quality of real GW can vary greatly, depending on its source within the house, the products used in the household and the quality of the influent TW (Eriksson *et al.*, 2002; Pinto *et al.*, 2010), and so in practice the GW used to irrigate a green roof would probably vary in quality each time it is used. The synthetic GW used in this study was designed to simulate bathroom and laundry GW; further testing of these species with GW of varying qualities (e.g. kitchen GW, which is generally considered to have the highest organic load; Al-Jayyousi, 2003) is therefore required before any definitive conclusions can be made regarding the impact of GW on these plants.

Sharvelle *et al.* (2012) suggest that GW irrigation is required for several years before it is possible to confidently assess a particular species' tolerance to GW. In the UK, irrigation of green roofs planted with these species is likely to only be needed during relatively short periods of drought in the summertime, in order to maintain high ET rates and thus provision of ESs such as cooling and stormwater management (as discussed in Chapter 4). GW application would therefore be infrequent and would be interspersed with natural rainfall, which is likely to prevent accumulation of GW constituents in the substrate (Criswell and Roesner, 2007) and related consequences (such as substrate hydrophobicity induced by GW irrigation; Nadav *et al.*, 2013), thus limiting the impact of GW on the plants.

The wide variety of results obtained in different studies regarding the impact of GW on plant growth and health is probably due to differences in the plant species tested (Sharvelle *et al.*, 2012), substrate type and nutrient content (Rodda *et al.*, 2011b), the quality and composition of the GW used (Reichman and Wightwick, 2013), and the irrigation regime and length of exposure to GW (Kaboosi, 2016). Indeed, Rodda *et al.* (2011b) suggested that the growth of plants irrigated with freshwater in their study may have been restricted by the nutrient-poor substrate, whilst plants irrigated with GW exhibited greater growth due to the additional input of nutrients from the GW.

Although the VC mix substrate used in the 'model GR conditions' in Experiment 6 had inherently low nutrient content, plants of all species (except *Salvia*; see Section 6.3.2.2) grew well when irrigated with both TW and GW, and there was no indication that the growth of TW-irrigated plants was restricted. However, B, P and Na accumulated in the substrate to significantly higher concentrations with GW irrigation compared to TW, with P concentrations at least double, Na at least 3 times higher, and B 10 times greater in substrate irrigated with GW compared to TW, with all species. Accumulation of nutrients in the substrate with GW irrigation has frequently been reported in other studies (Wiel-Shafran *et al.*, 2006; Pinto *et al.*, 2010; Rodda *et al.*, 2011b) and could either offer an advantage to plants and improve growth or have detrimental impacts on the substrate and restrict plant growth and health (Kaboosi, 2016). In Experiment 6, neither effect was evident, despite the significantly greater concentrations of P, B or Na frequently taken up into the roots or shoots of plants irrigated with GW compared to TW (Section 6.3.2.1). This was similar to results of another study (Simmons *et al.*, 2010) and could have been due to the relatively short duration of the study (6 weeks); GW-irrigated plants may have exhibited greater growth and health if the nutrient content of the VC mix had been depleted over a longer period. Conversely, other studies have found that increased uptake of nutrients with GW irrigation compared to TW resulted in significantly higher plant growth and biomass (Rodda *et al.*, 2011b) or leaf area (Misra *et al.*, 2010).

In contrast, with the 'industry standard GR conditions' in Experiment 5, differences in nutrient concentrations in the substrate between TW and GW treatments were small, resulting from the inherently high nutrient content of the MRM substrate, which masked the effects of GW. In these conditions of high nutrient availability, the additional input of nutrients with GW was negligible, probably limiting any impacts on GW relating to nutrient accumulation and toxicity. This was also apparent in plant uptake of nutrients, with similar concentrations of P and B in both roots and shoots of TW and GW-irrigated plants of all species in Experiment 5 (data not shown). Al-Hamaiedeh and Bino (2010) similarly reported no difference in the nutrient content in plant tissues with either TW or GW irrigation.

6.4.4 Impacts of greywater irrigation on plant functioning and continued provision of ecosystem services

Constituents of GW that impact the substrate, and consequently plant health and growth, may also impact plant functioning (e.g. transpiration). As such, the provision of ESs which depend on high transpiration rates, such as cooling (Blanuša *et al.*, 2013; Vaz Monteiro *et al.*, 2017) and stormwater management (through restoration of substrate retention capacity between storms; Ouldboukhitine *et al.*, 2014; Chapters 3 and 4), therefore may also be compromised by irrigation with GW. However, very few studies have investigated the effects of GW on plant functioning, and any consequent impacts on ESs provision have not been fully addressed.

In this study, leaf stomatal conductance (g_s) was measured as an indicator of plant functioning over the course of both experiments. Stomatal conductance was relatively low for all species throughout Experiment 5 compared to previously published values for well-watered plants (e.g.

Stachys > 200 mmol m^{-2} s^{-1} and *Sedum* > 50 mmol m^{-2} s^{-1}; Blanuša *et al.*, 2013). This was likely to be a result of low substrate moisture content (SMC) experienced through the majority of the experiment with all treatments (data not shown) due to the regulated deficit irrigation regime employed, which probably resulted in stomatal closure and reduced transpiration with both TW and GW irrigation. Generally, there were no significant differences in g_s between TW and GW treatments for any of the species throughout both experiments, suggesting that plant functioning was not compromised by short-term irrigation with GW. Additionally, since previous research with these broadleaf species (*Heuchera*, *Salvia* and *Stachys*) has indicated that g_s is strongly linked to plant transpiration and that high g_s is a key trait for providing cooling (Vaz Monteiro *et al.*, 2017), results of both experiments suggest that the extent of the cooling service provided would also not have been compromised.

The canopy temperatures of each species were also not significantly different with TW or GW irrigation in either experiment (measured once at the end of Experiment 5 and fortnightly throughout Experiment 6). Leaf temperatures increase when stomata close and transpiration is suppressed (e.g. in response to low SMC; Blanuša *et al.*, 2013), and are therefore an important indicator of the extent of cooling provision. Leaf temperatures did not increase with GW irrigation for any species for the duration of either experiment, further indicating that transpiration was not suppressed in the 6 – 8 week period and the cooling provision probably would not have been reduced with short-term GW irrigation.

Very few studies have directly examined the effect of GW irrigation on plant transpiration, and results vary depending on GW quality and plant species. For example, Eriksson *et al.* (2006) investigated the impact of seven GW samples (of different origin within the house and thus differing quality) on the transpiration of willow. They found that transpiration was similar to controls with two of the GW samples, and was enhanced by up to 200% with four of the GW samples, although this may have been partly due to improved plant growth. However, transpiration was inhibited by up to 60% with the two GW samples originating from the kitchen and the laundry, which was attributed to the high EC and high pH of the samples (Eriksson *et al.*, 2006). Indeed, kitchen GW is frequently acknowledged to be more polluted than GW from showers and washbasins (Al-Jayyousi, 2003), for example with higher concentrations of oil and grease (Travis *et al.*, 2008), whilst laundry GW is also known to contain high concentrations of surfactants, salts, suspended solids and typically has the highest pH (Eriksson *et al.*, 2002; Misra and Sivongxay, 2009). Ouldboukhitine *et al.* (2014) also attributed a reduction in the thermal resistance of green roof modules irrigated with GW to reduced ET due to accumulation of salts and surfactants in the substrate.

In Experiments 5 and 6, however, it was noted that the SMCs of all GW-irrigated containers were higher than SMCs of TW-irrigated containers by the end of both experiments (data not shown), despite starting at similar values and receiving identical volumes for irrigation; for example, in Experiment 5 the SMC of TW-irrigated *Stachys* was 58% lower than GW-irrigated plants at the end of week 8. Since there were no significant differences in plant sizes between TW and GW treatments for any species in either experiment, this could indicate reduced water uptake (i.e.ET) from GW-irrigated containers (both planted and controls), thus depleting substrate moisture more slowly.

Significant differences were evident when daily ET from each container following saturation was measured in week 7 of Experiment 6, with significantly lower cumulative ET losses from containers irrigated with GW compared to TW for *Heuchera*, *Salvia* and the control. Since there were no significant differences in plant size (height, diameter, biomass or leaf area) between TW and GW treatments for any species, differences in ET are likely an impact of the GW irrigation. This also corresponds with the significantly lower g_s measured for *Heuchera* irrigated with GW compared to TW in Week 6 (discussed further below). As this part of the experiment followed immediately after the 6 previous weeks of irrigation with GW, some differences were already becoming evident at the start of week 7 which could have affected plant functioning, such as higher substrate EC and nutrient content in containers irrigated with GW compared to TW.

Although there is a suggestion that provision of ESs dependent on ET may begin to be reduced after 6 weeks of GW irrigation for some species, these results, coupled with the canopy temperature results over the 6-week period, suggest that impacts are initially small or may take longer to become apparent. It is possible that these impacts could be mitigated, however, by alternating GW with freshwater for irrigation (Pinto *et al*., 2010), although this would need to be fully tested for confirmation. Ouldboukhitine *et al.* (2014) also found species differences in response to GW, with a 32% reduction in thermal resistance with periwinkle compared to a 28% reduction with ryegrass; the greater impact of GW on periwinkle was also visually evident, as plants irrigated with GW showed poor visual health compared to those irrigated with TW.

Irrigation with GW has been shown to reduce the hydraulic conductivity of substrates compared to freshwater irrigation (e.g. by up to 95 %; Misra and Sivongxay, 2009), probably as a result of accumulation of surfactants and salts, and consequent deterioration of the soil structure.

Substrate salinity (EC and SAR) was significantly higher in containers irrigated with GW compared to TW by week 6 of Experiment 6 for all species/control, suggesting a likely reduction in substrate hydraulic conductivity. This could have made it difficult for plants to take up water (Rodda *et al.*, 2011b), which could thus account for the lower ET rates observed in GW-irrigated containers in Experiment 6. ET was also significantly lower from control containers irrigated with GW compared to TW, suggesting a lower hydraulic conductivity resulting from GW irrigation also decreased evaporation from the substrate as well as plant transpiration. The volumes of water lost from control containers each day were relatively small, and consequently any impacts of GW may have taken longer to become apparent.

Additionally, although g_s of *Heuchera* increased over the course of Experiment 6 for both TW and GW treatments, concurrently with an improvement in visual health as plants recovered from possible transplant shock, g_s was significantly lower in the GW treatment than in the TW treatment at the end of week 6. This suggests that GW may have been starting to have an impact on *Heuchera* plants after 6 weeks of continuous exposure to GW; lower ET from GW-irrigated containers during week 7 would also appear to support this indication. Indeed, substrate EC of GW-irrigated *Heuchera* became increasingly greater than TW-irrigated *Heuchera* over the 6 weeks of the experiment, and was 38% higher by week 6. ET from GW-irrigated *Salvia* became significantly lower than those irrigated with TW only towards the end of the week (from 96 hours after saturation onwards), when SMC was low (approaching 0.200 m^3 m^{-3} for both TW and GW treatments; data not shown). *Salvia* g_s declined from about week 4 onwards, concurrently with a decline in visual health, and particularly in week 6 when g_s was only 54 or 61% of baseline value (for TW and GW treatments respectively). However, this decline was similar for both TW and GW treatments, and g_s was still statistically similar for both treatments at the end of week 6, which may account for the similar ET in the first few days of week 7. g_s presumably decreased in the GW-irrigated plants as the substrate dried out, however, thus resulting in significantly lower ET in GW-irrigated plants compared to those irrigated with TW.

Since transpiration is the main contributor to cooling provided by *Salvia* and *Heuchera* (Vaz Monteiro *et al.*, 2016a; 2017), this suggests that cooling provision is likely to be compromised by GW irrigation – after 6 weeks of continuous exposure to GW for *Heuchera*, but only when the substrate became dry for *Salvia*. Moreover, reduced ET in these species resulting from GW irrigation would slow the rate of restoration of substrate retention capacity between storms, thus reducing their ability to provide stormwater management. These negative impacts of GW could potentially be counteracted by alternating GW with freshwater (e.g. rainfall) for irrigation by preventing accumulation of GW constituents in the substrate (Criswell and Roesner, 2007), thus limiting any negative impacts on the substrate and plants (Pinto *et al.*, 2010). In the temperate climate of the UK, GW may only need to be used to supplement rainfall during extended periods of drought, as it is likely that rainfall throughout the summer will occur regularly; indeed, in their study, Dunnett and Nolan (2004) reported a positive improvement to plant performance on a semi-extensive green roof with only 6 irrigation events over the entire summer season to supplement natural rainfall. Using GW only to supplement rainfall may enable these species to continue functioning, and thus providing ESs, to a similar extent to those irrigated exclusively with freshwater. Additionally, more frequent irrigation of *Salvia* may have ensured continuation of plant functioning, by maintaining high SMC, g_s and ET rates.

For *Stachys*, and for *Sedum* for almost the whole of week 7, ET losses from containers in both the TW and GW treatments were similar. This corresponds to the similar g_s of both TW and GW-irrigated plants and agrees with the findings of other studies (Misra *et al.*, 2010; Pinto *et al.*, 2010) which reported no differences in the water consumption of tomato or silver beet respectively over the course of their studies when irrigated with GW compared to TW. These authors attributed these results to high tolerance to GW of the studied species and the short-term nature of both experiments (9 weeks and 60 days respectively). Conversely, Sharvelle *et al.* (2012) observed greater water uptake by plants irrigated with GW than by plants irrigated with TW, although they hypothesised that greater plant growth with GW irrigation could account for this. Since transpiration has proven to be the primary mechanism through which cooling is provided by *Stachys* plants, and g_s is strongly linked to transpiration (Blanuša *et al.*, 2013; Vaz Monteiro *et al.*, 2017), results indicate that the cooling that could be provided by *Stachys* was not compromised by irrigation with GW. Furthermore, since ET was not reduced in *Stachys* or *Sedum* plants irrigated with GW compared to TW in Experiment 6, restoration of substrate retention capacity in dry periods would probably continue at the same rate when GW is used for irrigation, and provision of stormwater management would therefore not be compromised.

The saturated SMCs of all species and the control at the start of week 7 in Experiment 6 were lower in the GW treatment compared to the TW treatment, significantly so for *Heuchera* and the control. This could potentially indicate that the substrate's water retention capacity may have been reduced by the previous 6 weeks of GW irrigation, probably due to changes to the substrate structure and quality, and accumulation of GW constituents such as surfactants and oil (Kaboosi, 2016). Since the substrate is known to be the major store of water in rainfall events (VanWoert *et* *al.*, 2005), this potential reduction in available storage could negatively affect stormwater management provision and result in greater runoff production.

6.4.5 Impacts of greywater on green roof runoff quality

Runoff from green roofs has frequently been found to be of higher quality (e.g. lower nutrient concentrations, more neutral pH) than runoff from conventional rooftops (Teemusk and Mander, 2007) and some aspects of runoff quality may also be improved compared to rainfall (Speak *et al.*, 2014) resulting from the role of the green roof in filtering and storing some nutrients and constituents. However, green roofs are also known to be a source of some nutrients, such as P, resulting in leaching and consequently high concentrations in runoff (Dietz and Clausen, 2005; Van Seters *et al.*, 2009), particularly on newly established roofs (Berndtsson *et al.*, 2006); this can have negative environmental impacts for receiving water bodies, such as eutrophication (Christova-Boal *et al.*, 1996). The quality of runoff from green roofs varies depending on several factors, including the substrate type and use of fertilisers, plant species used (if any), the age of the green roof, and proximity to pollution sources (Berndtsson *et al.*, 2006; Van Seters *et al.*, 2009; Zhang *et al.*, 2015). Leaching of all nutrients (P and B) was clearly observed in Experiment 5 with both TW and GW irrigation, with significantly higher concentrations of nutrients and significantly higher EC in the runoff from all species/control compared to the original TW or GW used for irrigation (apart from P in GW treatments). This was likely to be a result of the inherently high nutrient content of the MRM substrate used for the 'industry standard GR conditions' in Experiment 5. Indeed, substrate is considered to the primary source of P leaching from green roofs, particularly when it contains compost or fertilisers are added (Berndtsson *et al.*, 2009). However, leaching was also observed from the nutrient-poor VC mix substrate used for the 'model GR conditions' in Experiment 6, possibly due to the higher organic matter content of the peat-based compost.

Studies have also found that nutrient concentrations in runoff from green roofs tend to be greater following heavier rainfall (Teemusk and Mander, 2007) and at the onset of rainfall (due to the 'first flush' effect), as the nutrients accumulate in the substrate during dry periods (Berndtsson *et al.*, 2006; Razzaghmanesh *et al.*, 2014). In Experiments 5 and 6, irrigation volumes were calculated to prevent leaching from any of the containers until they were flushed at the end of both experiments; nutrients were therefore able to accumulate in the substrate, particularly with the higher nutrient input with GW irrigation, which may have resulted in high concentrations of P, B and Na in the first flush of runoff generated. Indeed, runoff from GW-irrigated treatments generally contained significantly higher concentrations of all nutrients and had significantly higher EC than runoff from TW-irrigated treatments for all species/control in both experiments; this was similar to results of other studies (Alfiya *et al.*, 2012; Sharvelle *et al.*, 2012), and reflects the significantly different quality of the irrigation GW and TW (Section 6.4.1). Additionally, containers in the GW treatments in both experiments were flushed with GW in order to generate runoff, probably resulting in higher concentrations of nutrients in the runoff than if TW had been used for flushing. However, since GW is only likely to be used for green roof irrigation to supplement rainfall during times of drought in the UK, GW constituents are unlikely to accumulate in the substrate and would probably be frequently flushed out by rainfall, thus preventing such high concentrations in the runoff.

In terms of EC and P, B and Na concentrations, the quality of the runoff from all species/control was generally lower than the quality of the irrigation TW or GW in both experiments as containers mostly acted as a source for nutrients, probably as a result of nutrient accumulation in the substrate over the 6 – 8 weeks of the experiments and leaching from the substrate. However, B concentrations in the irrigation GW in Experiment 6 were reduced significantly in the runoff from all species/control, indicating an improvement in runoff quality compared to the irrigation GW, probably resulting from the very low B content in the VC mix and the relatively high concentration of B in the synthetic GW used in Experiment 6. In another study, B concentrations in runoff from GW-irrigated treatments (both bare substrate and vegetated) were always lower than the B content applied through the irrigation GW (Sharvelle *et al.*, 2012); however, in that study B concentrations in the runoff were observed to increase over the 13-month experiment as B accumulated in the soil. This may result from the fact that B has a high affinity for the soils, which can cause a lag in the time taken for B concentrations to increase in the soil water, since B may primarily adsorb to soil particles initially (Grattan *et al.*, 2015). In Experiment 6, runoff was collected from containers after only 6 weeks of GW irrigation; B concentrations in the runoff may therefore have increased after a longer time as soil water B increased.

6.4.5.1 Impact of plant presence and species selection on runoff quality

Although substrate alone may be able to improve the quality of runoff compared to irrigation waters (e.g. by reducing nutrient concentrations, pH, EC and SAR of runoff compared to irrigation GW; Misra and Sivongxay, 2009), plant presence on a green roof may enhance this service and further improve the quality of the runoff (Gagnon *et al.*, 2012; Whittinghill *et al.*, 2016), through additional uptake and storage of nutrients in plant tissue and additional filtration provided by the plant root system (Fowdar *et al.*, 2017). Indeed, runoff EC and concentrations of nutrients in the runoff from planted treatments in the TW treatments of Experiments 5 and 6 were frequently lower than in runoff from the bare substrate control, indicating an improvement in runoff quality with plants. This is similar to results of previous studies, which found that runoff from planted treatments had significantly lower concentrations of nutrients such as N and P than runoff from bare substrate (Sharvelle *et al.*, 2012; Vijayaraghavan *et al.*, 2012). When GW was used for irrigation, however, plant presence made very little difference to nutrient concentrations in the runoff from any species compared to the bare substrate control, suggesting that vegetated green roofs are not able to improve runoff quality any more than bare substrate when GW is used exclusively for irrigation. This probably also applies when substrates are nutrient-rich and plants are typically smaller on newly established green roofs or when fertilisers are added (Köhler, 2002; Berndtsson *et al.*, 2006; Emilsson *et al.*, 2007).

In Experiment 6, however, each species/control received different quantities of nutrients with both TW and GW irrigation as a result of the ET-based irrigation regime (see Section 2.7.2 - 2.7.3), making it difficult to compare the effect of different species on runoff quality. Over the 6 weeks of the experiment, control containers received approximately 56% of the total nutrients that *Salvia*, *Stachys* and *Sedum* received, and 68% of the total nutrients received by *Heuchera*, with both TW and GW irrigation. Despite this lower nutrient input, runoff from TW-irrigated control containers had significantly higher EC than all species and significantly higher P concentrations than *Salvia*, *Stachys* and *Sedum*, indicating that the presence of these species improved runoff quality. Furthermore, the EC and P content of runoff from *Stachys* were significantly lower than runoff from the control even with GW irrigation. This suggests that on more mature green roofs, when the substrate would tend to contain lower concentrations of nutrients, the choice of plant species could have an impact on runoff quality and appropriate selection of species could therefore maximise the ability of a green roof to improve runoff quality. Conversely, the concentration of Na in runoff from the control was significantly lower than Na concentrations in the runoff from *Salvia* and *Sedum* with TW irrigation and runoff from all species with GW irrigation, probably resulting from the higher nutrient content received by the planted treatments compared to the control. In practice, on green roofs in the UK, species with high ET rates, such as *Stachys* and *Salvia*, are likely to require more frequent irrigation or larger irrigation volumes, and so these species will receive higher quantities of nutrients when GW is used for irrigation. It is interesting, therefore, that there was some evidence that runoff from *Stachys* was of higher quality than runoff from bare substrate with both TW and GW irrigation, even though *Stachys* received almost double the total amount of nutrients than control over the 6 weeks of the experiment.

Plant species selection has proven to be important in terms of nutrient uptake efficiency (Fowdar *et al.*, 2017), and consequently, differences in the quality of runoff (e.g. P and N concentrations) from different species have also been identified in previous studies (Sharvelle *et al.*, 2012; Aloisio *et al.*, 2016). There was some evidence of species differences in runoff quality in Experiments 5 and 6, with runoff from *Sedum* having significantly higher concentrations of P and B and higher EC than *Salvia* and *Stachys*, despite receiving the same quantity of nutrients over the 6 weeks of Experiment 6 with GW irrigation. Additionally, although fewer differences between species were apparent with TW irrigation, runoff from *Stachys* had significantly lower Na content than runoff from *Salvia* and *Sedum,* and significantly lower EC than runoff from *Salvia*. Under the 'model GR conditions' of Experiment 6, runoff from *Stachys* therefore appeared to be of better quality than runoff from other species or bare substrate, in terms of nutrient concentrations and EC.

6.5 Key conclusions

- Short term (6 – 8 weeks) irrigation with greywater had no apparent impact on the health and growth of any of the plant species tested, suggesting that greywater may be a suitable alternative water source for supplemental irrigation of green roofs in the UK during periods of drought in the summer.
- GW generally did not appear to affect plant functioning (measured by leaf stomatal conductance) or canopy temperatures of any of the species over the 6 or 8-week period, suggesting that the provision of ESs such as cooling and stormwater management were not compromised. However, *Heuchera* g_s was significantly lower in week 6 of Experiment 6 with GW irrigation, which may indicate negative effects of GW after 6 weeks of continual exposure.
- There was some evidence that 6 weeks of GW irrigation in Experiment 6 may have altered substrate properties such as hydraulic conductivity and water retention capacity to the extent that there were significant differences in ET between TW and GW treatments for *Heuchera*, *Salvia* and the control after 6 weeks of GW irrigation. Provision of ESs that rely on high transpiration rates (i.e. cooling and restoration of substrate retention capacity) were likely to be compromised for these species beyond the 6-week period of continuous GW irrigation.

- *Salvia*, *Stachys* and *Sedum* appeared to improve the quality of runoff (in terms of lower nutrient concentrations and EC) compared to runoff from the bare substrate control, but only when TW was used for irrigation. Runoff quality was generally not improved by plant presence, however, when GW was used exclusively for irrigation for 8 and 6 weeks in Experiments 5 and 6, although there was some evidence that runoff from *Stachys* was of better quality than runoff from the control (in terms of EC and P concentrations only) in Experiment 6. There was evidence that appropriate species selection could maximise the ability of a green roof to improve runoff quality when the nutrient content of the substrate is low, as on an older, mature roof.
- There was little evidence of an improvement in the quality of runoff compared to the quality of the irrigation TW or GW in either experiment, with only B concentrations in GW treatments in Experiment 6 significantly lower in runoff than in the irrigation GW. Otherwise, both the MRM and VC mix substrates were a source of nutrients, resulting in leaching and higher concentrations of nutrients and higher EC in the runoff from all species/control compared to the irrigation TW or GW.

Chapter 7

General discussion and concluding remarks

7.1 Can provision of stormwater management on a green roof be maximised by appropriate plant species selection?

Previous studies have shown that urban surface flooding and combined sewer overflows could be mitigated by introducing vegetation into urban areas, including green roofs (e.g. Dunnett *et al.*, 2008; MacIvor and Lundholm, 2011; Stovin *et al.*, 2012; Heim *et al.*, 2017), as discussed in Section 1.2.1. This is due to the increased interception, infiltration and storage of rainfall in the substrate and vegetation layers of green roofs, resulting in delayed and reduced volumes of runoff, as well as the return of water back to the atmosphere through increased evapotranspiration (ET) during dry periods; factors influencing stormwater management are summarised in Figure 7.1.

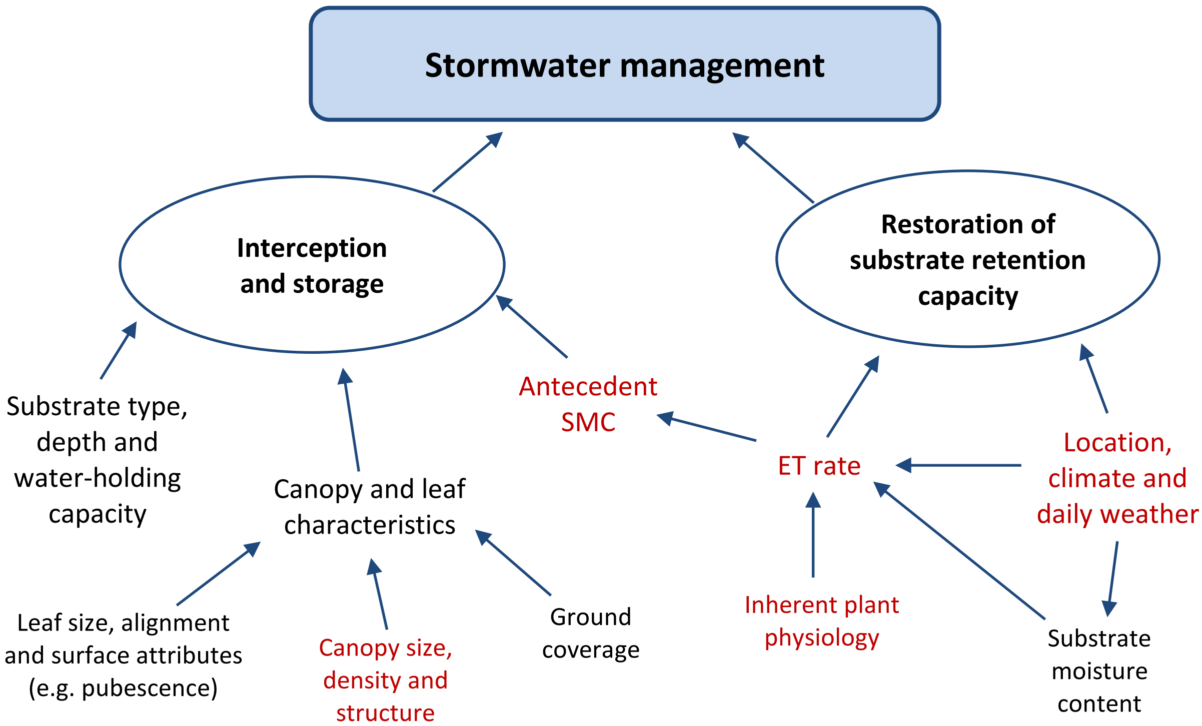


Figure 7.1: Major factors influencing the stormwater management provision of a green roof; variables highlighted in red were investigated in this study.

However, although some studies have broadly identified differences between plant types in stormwater management performance on green roofs (e.g. Lundholm *et al.*, 2010; Nagase and Dunnett, 2012; Soulis *et al.*, 2017), the majority of studies focus on grasses or *Sedum* as typical vegetation covers, even though succulents are widely acknowledged to have low ET rates that may limit their ability to provide a good stormwater management service. Furthermore, very few studies have attempted to identify the plant attributes that could allow maximum stormwater management provision on an extensive or semi-extensive green roof. The focus of this study was therefore to compare species with different underlying structure and function and identify the key plant characteristics for maximising rainfall retention on a green roof and thus reducing runoff and mitigating the risk of urban flooding. This information could allow green roof and landscape professionals to select vegetation with these desirable attributes in order to maximise the provision of ecosystem services (ESs) such as stormwater management. Results of this study therefore have important implications for green roof design and management, and, more broadly, could also be applied to help vegetation selection for a wider range of green infrastructure, such as rain gardens, parks, gardens and allotments.

7.1.1 How do the studied species compare in their ability to provide stormwater management?

In this study, significant differences in rainfall retention and runoff reduction were observed between species, resulting from differences in both canopy attributes and inherent ET rates. Overall, species with high ET rates (*Salvia* and *Stachys*) exhibited the greatest potential for stormwater management provision, due to greater restoration of the substrate's water retention capacity in dry periods. However, canopy characteristics were also an important factor, particularly when antecedent substrate moisture content (SMC) was high and canopy interception became dominant, with species with large, dense canopies (e.g. *Sedum*) performing best.

The substrate has frequently been acknowledged as the major store of water on a green roof (VanWoert *et al.*, 2005; Dunnett *et al.*, 2008), and so the ability of plants to remove water from the substrate between storms through ET, thus increasing the available storage capacity in the substrate for subsequent rainfall events, is often viewed as the most important role played by vegetation (Stovin *et al.*, 2015). Indeed, in this study, a much higher proportion of rainfall was retained by all species and the unvegetated control after a 72-hour antecedent dry period compared to when the substrate was saturated at the onset of rainfall (e.g. 73% in 'unsaturated' conditions compared to 13% in 'saturated' conditions with *Stachys* in Experiment 3);

consequently, runoff from all species/control was substantially lower from the rainfall event following a 72-hour antecedent dry period.

ET during the 72-hour antecedent dry period was strongly linked to rainfall retention, and thus runoff reduction, in the subsequent rainfall application (adjusted R^2 values of 0.94 and 0.91 respectively; $P < 0.001$), and significant species differences were also evident: species with high ET rates (i.e. broadleaf species) took up more water from the substrate than *Sedum,* resulting in lower antecedent SMCs and thus retention of a greater proportion of rainfall (e.g. 73% retention with *Stachys* compared to 49% with *Sedum* in Experiment 3). In this respect, species with inherently high ET rates clearly have an advantage over those with low ET rates, as they are able to restore the substrate's water retention capacity to a greater extent and thus retain more water in subsequent rainfall events. The low ET rate of *Sedum*, conversely, limited its ability to retain rainfall in 'unsaturated' conditions, despite having high canopy capture in 'saturated' conditions, thus limiting its overall potential to provide stormwater management on a green roof. Results of this study therefore suggest that the provision of stormwater management on a green roof could be maximised by using species with high ET rates, such as *Stachys* and *Salvia*.

Canopy traits, such as structure, density and substrate coverage, were also important for rainfall retention in 'saturated' conditions, with significant differences between species evident. Interception of rainfall by the canopy was high with *Sedum* (up to 17% of the total rainfall), and was in fact greater than all other species or bare, unvegetated substrate in Experiment 3. Further analysis of results revealed that leaf area density and shoot dry weight were significant factors in determining retention on the canopy, whereas plant height was not correlated with retention. The low-growing, dense *Sedum* canopy therefore exhibited these traits as well as having full substrate coverage, thus resulting in high retention and lower runoff volumes and indicating that *Sedum* can still offer some stormwater management on a green roof, despite its low ET rate. This is particularly the case when antecedent SMC is high at the onset of rainfall, for example when rainfall events occur close together or in cool, humid conditions when ET, and thus restoration of substrate retention capacity between storms, is restricted with all vegetation types. Furthermore, all species, including *Sedum*, retained more rainfall and reduced runoff more than bare, unvegetated substrate in both 'saturated' and 'unsaturated' conditions (up to 52% more retention in 'unsaturated' conditions in Experiment 3). This resulted from the additional canopy capture and enhanced ET in dry periods increasing available substrate storage, thus highlighting and confirming the advantage of any vegetation on a green roof over and above substrate alone (Voyde *et al.*, 2010a; Stovin *et al.*, 2015).

Additionally, plants with hairy leaves and open canopies (*Stachys* and *Salvia*) retained a greater volume of water than canopies with smooth leaves and closed canopies (*Heuchera*). Indeed, the closed structure of the *Heuchera* canopy prevented rainfall from penetrating down to the lower layers whilst the smooth leaves were unable to retain water droplets, particularly when they coalesced and became large. Consequently, these leaf and canopy characteristics resulted in an average of 18% of the total applied rainfall dripping from the *Heuchera* canopy in Experiment 1, compared to averages of just 2.2, 3.6 and 3.7% for *Salvia*, *Stachys* and *Sedum* respectively . On a green roof, runoff may not be delayed or reduced if a large volume of water slides from the canopy onto adjacent surfaces, particularly where conventional roofing materials may be present, such as around the edge of the vegetated area (Speak *et al.*, 2013). The 'edge effect' in this study, however, was likely to have been exaggerated by the small size of the plots used in Experiment 1, and so the proportion of rainfall 'lost due to dripping' from the *Heuchera* canopy would probably be lower on a full size green roof.

Although the retention performance and ET rate of *Heuchera* was comparable to *Stachys* in Experiment 1, it was the worst performing species in Experiment 3 and was in fact similar to the bare substrate control. This could have partly resulted from the incomplete canopy coverage (around 90%) or small plant size leading to overall lower ET from *Heuchera* plots, or could have been due to the age and condition of the plants used in Experiment 3. Young, actively growing *Heuchera* plants were found to be vigorous with high ET rates, consequently providing good cooling, in previous studies (Vaz Monteiro *et al.*, 2016a; 2017). This was also observed in some of the experiments in this study (e.g. Experiment 1), particularly when plants had been cut back during the winter or split before transplanting, thus encouraging new plant growth and high ET rates. However, the older plants used in Experiment 3 appeared to have slow growth and low ET rates (lower than *Sedum*), suggesting that *Heuchera* would need regular pruning in order to maintain vigorous growth, high ET rates, and continued provision of ESs such as cooling and stormwater management. *Heuchera* is therefore probably not suited for use on a green roof where maintenance costs should be kept low and provision of ESs maximised.

7.2 How do the evapotranspiration rates of these species vary with environmental conditions?

As the restoration of substrate water retention capacity through ET between storms has been identified as the most important role of vegetation in stormwater management provision, environmental conditions that control ET (e.g. meteorological variables, SMC, etc.) will also influence the extent of the stormwater management provision. Indeed, previous studies have identified differences in rainfall retention performance of green roofs in different geographical locations (i.e. with different climates; Sims *et al.*, 2016) and different seasons (Speak *et al.*, 2013; Berretta *et al.*, 2014), and a decline in daily ET as SMC decreases has been observed in laboratory studies (Voyde *et al.*, 2010b; Poë *et al.*, 2015). However, most studies have typically tested *Sedum* species, while the performance of species with high ET rates in different weather conditions and with drying substrate is not fully understood. The focus of this study was therefore to compare the ET rates of different species under various weather scenarios, as a proxy for restoration of substrate retention capacity and thus stormwater management provision, and to identify the optimal environmental conditions for each species in which stormwater management provision could be maximised.

Species 'rankings', in terms of both daily and cumulative ET, were the same in all temperature/relative humidity (T/RH) scenarios simulated in this study: *Stachys* and *Salvia* had the highest ET rates in all T/RH treatments, followed by *Heuchera*, whilst *Sedum* had the lowest ET rate of the species tested in all T/RH treatments (approximately 50% lower than *Stachys* and *Salvia* after 96 hours) but was significantly higher than the bare substrate control. These results indicate that ET took place at a high rate in all weather conditions with *Stachys* and *Salvia*, and these species would therefore be able to restore the substrate's water retention capacity faster and to a greater extent than the other species in any weather conditions. For example, daily ET on Day 1 in the 'dry' treatment was 15.2 mm for *Stachys* compared to 6.3 mm for *Sedum*, indicating that 8.9 mm of additional water storage capacity was available with *Stachys* just 24 hours after saturation (i.e. the previous rainfall event). Provision of stormwater management in any climatic region and any season could thus theoretically be maximised by using species such as *Stachys* and *Salvia* on a green roof, particularly when rainfall events occur relatively close together. However, results also suggest that even *Sedum* could significantly improve stormwater management provision compared to bare substrate alone, which is in line with results of other studies (Berghage *et al.*, 2007; Voyde *et al.*, 2010b). The ET rate of *Heuchera* was intermediate in all T/RH treatments in this experiment, being significantly lower than *Stachys* and *Salvia* but significantly higher than *Sedum*. However, as discussed in Section 7.1.1, there is evidence that the ET rate of *Heuchera* may decrease as the plants age unless they are regularly pruned, and, as such, *Heuchera* is not recommended for use on green roofs.

The daily ET rates of *Salvia* and *Stachys* declined over time after saturation in all T/RH treatments in this experiment, probably due to rapid depletion of substrate moisture, consequently restricting further ET (e.g. Denmead and Shaw, 1962; Hsiao, 1973; Stovin *et al.*, 2013). In particular, *Stachys* ET rates typically declined rapidly in the first 3 days following saturation, for example from 15.2 to 4.2 mm day^{-1} from Days 1 to 3 in the 'dry' treatment. Consequently, the daily ET rate of *Stachys* after this time became more similar to other species, even approaching that of the control by the end of the experiment (Day 4 or 5). This suggests that the greatest advantage of species with very high ET rates, such as *Stachys*, would be in the first few days after rainfall (or saturation), when the substrate's water retention capacity is restored to a significantly greater extent with these species compared to species with low ET rates, and before the substrate's finite retention capacity has been fully restored. Stormwater management provision on a green roof planted with these species would therefore be maximised when rainfall events occur relatively close together or supplementary irrigation is available, ensuring that substrate moisture does not become restricted and thus allowing ET to continue at high rates in the intervening dry periods. This would also be beneficial for the continued provision of other ESs that depend on ET, in particular cooling. If irrigation is not available during prolonged periods of drought, however, the benefits of species with high ET rates such as *Stachys* and *Salvia* may become less over time, as, in addition to slower restoration of substrate retention capacity, cooling provision would also be reduced by declining ET rates (Vaz Monteiro *et al.*, 2017), and the aesthetical appeal of *Stachys* may be limited due to wilting in response to drought conditions.

7.2.1 Are there optimal environmental conditions for each species in which restoration of the substrate's water retention capacity through ET is maximised?

In this study, there were significant differences in ET rates in different simulated T/RH conditions with all species. ET rates were always greatest in the treatments with high vapour pressure deficit (VPD; i.e. dry and hot conditions) and lowest in treatments with low VPD (i.e. cool and humid conditions) for all species and the bare substrate control; for example, cumulative ET after 96 hours was around 30% higher on average in high VPD compared to low VPD treatments. This was expected, as the vapour pressure gradient between the leaf and the air is smaller in low VPD conditions, resulting in slower removal of water vapour from the leaf and thus low ET (Allen *et al.*, 1998). These results therefore indicate that overall stormwater management performance would be greatest in dry, hot conditions (e.g. in summer or in hot, arid climatic regions) as the substrate's water retention capacity would be restored to a greater extent between storms, thus enabling retention of a greater volume of water in subsequent rainfall events. Conversely, cool, humid conditions are likely to suppress ET, thus limiting the restoration of substrate retention capacity and subsequent rainfall retention, as has been identified in previous studies (Stovin *et al.*, 2012; Volder and Dvorak, 2014; Sims *et al.*, 2016). However, results of this study indicated that the contribution of plant transpiration to total ET was greatest in cool, humid conditions for all species (e.g. 72% in the 'humid' treatment compared to 58% in the 'hot' treatment for *Salvia*), probably as a result of limited evaporation from the substrate and plentiful substrate moisture in these conditions allowing transpiration to continue at a high rate (Voyde *et al.*, 2010b). The presence of vegetation on a green roof, compared to bare substrate, therefore appears to be of greater importance in cool, humid conditions for restoring the substrate's water retention capacity and thus increasing stormwater management provision.

For most species studied in this experiment, ET rates were similar in the 'hot' and 'dry' treatments due to the almost identical VPD in these two trials. With *Sedum*, however, ET was significantly higher in the 'dry' treatment compared to the 'hot' treatment, possibly as a result of *Sedum* plants switching to Crassulacean Acid Metabolism (CAM) photosynthesis in response to the high temperatures in the 'hot' trial (Farrell *et al.*, 2012), thus reducing ET rates and conserving water, as discussed in Section 4.4.2. There was also some evidence that the ET rate of *Salvia* was greater in 'dry' conditions than in 'hot' conditions, although it is unclear if this was a result of larger plant size in the 'dry' trial or a physiological characteristic of *Salvia* that resulted in greater ET in low RH conditions. These results suggest that the stormwater management service provided by *Sedum*, and possibly *Salvia*, could be maximised in optimal climatic conditions (i.e. low RH and moderate temperatures), since significantly greater ET in these conditions will maximise restoration of the substrate's water retention capacity between storms. Moreover, further analysis of results indicated that RH was a more important control on the ET of all species than air temperature (when substrate moisture was not limiting), suggesting that low RH conditions may result in higher ET than high temperature conditions.

7.2.2 Can daily ET be used to help schedule green roof irrigation?

As a result of climate change and a greater likelihood of summertime droughts in the UK, supplementary irrigation of all green roofs is likely to become necessary in order to maintain plant health (Van Mechelen *et al.*, 2015) and provision of ESs. Furthermore, if species with high ET rates are used in order to maximise provision of ESs such as stormwater management and cooling, irrigation will be required more frequently to maintain high ET rates and plant aesthetic quality. Water resources available for irrigation of green roofs are limited, however, due to increasing water demand in urban areas and changing precipitation patterns, and irrigation must be carefully managed to avoid wasting water whilst also maintaining plant health. Since different plants have different water requirements, scheduling irrigation based on the water use (i.e. ET) of the specific species used on a green roof could offer a potential strategy for sustainable irrigation. Indeed, irrigation scheduling based on the water balance of each specific crop has traditionally been practiced in agriculture in order to maximise yield whilst minimising water use and costs (Jones, 2004). Rather than maximising yield, the aim of supplementary irrigation on green roofs would be to maintain plant health, aesthetics and ESs provision, whilst also potentially broadening the range of species that could survive on a green roof.

Few studies have quantified ET of green roof vegetation (typically *Sedum*; Voyde *et al.*, 2010b; Poë *et al.*, 2015), and there has been no attempt to use this information for the purposes of irrigation scheduling. The aim of this study was therefore to explore the potential of using the daily ET of different species in various hypothetical weather scenarios to create a simple irrigation scheduling tool for green roofs. The approach chosen was to first calculate a crop coefficient (K_c) for each species, which, as well as contributing to a database of K_c values for landscape plants, could then be used to estimate daily ET from a green roof planted with any of these species in any weather conditions using the FAO-56 PM model (described in Section 5.1.1). K_c values calculated for *Salvia* and *Stachys* (2.98 and 2.94 respectively) in this study were roughly double those of *Heuchera* and *Sedum* (1.47 and 1.66 respectively), reflecting the inherently higher ET rates of these species as discussed in Section 7.2. Consequently, estimated daily crop ET (ET_c) was twice as high with *Salvia* or *Stachys* as with *Heuchera* or *Sedum* in all weather conditions in all months, highlighting the differences in water requirements of the different species. The K_c value, and thus ET_c values, obtained for *Heuchera* in this study are considered to be low estimates applicable to older plants (as discussed in Section 7.1.1); values may be higher with younger, more active plants with 100% substrate coverage.

It is clear, therefore, that green roof irrigation frequency and quantity should be based on the specific water requirements of the particular species used, in order to avoid wasting limited water resources by overwatering species with low water requirements whilst also ensuring that species with high water requirements receive enough supplementary irrigation to maintain plant health and provision of ESs. Moreover, it is also apparent that daily ET_c varies substantially with different weather conditions, even within species; for example, with *Salvia*, ET_c ranged from 5.33 mm day^{-1} in ‘overcast calm’ conditions in June to 18.42 mm day^{-1} in ‘blue sky windy’ conditions in July. This is a result of differences in the meteorological parameters that influence ET (i.e. solar radiation, wind, and air temperature and humidity; Allen *et al.*, 1998). Irrigation requirements of a green roof are thus also dependent on daily weather conditions and time of year, and this should be accounted for when scheduling irrigation (e.g. by using meteorologically-based models such as the FAO-56 PM model), in order to optimise the timing and quantity of supplementary irrigation in order to maintain plant health and provision of ESs whilst also preserving limited water resources.

Scheduling supplementary irrigation during dry periods using the FAO-56 PM model (Allen *et al.*, 1998) to estimate daily ET could provide a strategy for sustainable irrigation of green roofs, which incorporates both the specific species and the atmospheric parameters that influence ET without the need for much time or monetary inputs from green roof managers. An example of a hypothetical record kept by a green roof manager, using the irrigation management reference table presented in Section 5.3.2 to look up estimated daily ET_c from a green roof planted with *Sedum*, is presented in Table 7.1. Following a hypothetical rainfall on 28th June which saturates the substrate to field capacity, the green roof manager is able to easily record the accumulated moisture deficit by simply observing the weather each day and looking up the associated estimated ET_c in the table. Irrigation would then be scheduled once the accumulated substrate moisture deficit reaches a pre-defined value, which would need to be determined for the green roof through further experimentation (as discussed in Section 5.4.3), based on the substrate type, depth and water-holding capacity and the deficit at which plant health or ESs are considered to become compromised.

When scheduling irrigation of green roofs, it is also important to consider the balance between supplying water so that ET can continue at a high rate, thus maintaining plant health and provision of services such as cooling, whilst also ensuring that the maximum substrate water retention capacity is available at the onset of rainfall, thus providing maximum stormwater management. It may therefore be necessary to irrigate with small quantities of water more frequently, to avoid saturating the substrate, thereby removing the majority of the rainfall retention capacity, whilst also maintaining high enough substrate moisture to allow ET, and thus cooling, to continue at a high rate. Additionally, there was some indication in this study that the transpiration of *Salvia* irrigated with greywater for 6 weeks may have become compromised when the substrate was dry (Sections 6.3.3.3 and 6.4.4). It may therefore be important to maintain relatively high substrate moisture with *Salvia*, and thus irrigate more frequently, if greywater is used for irrigation on a green roof, in order to maintain provision of ESs dependent on high ET rates, such as cooling.

Table 7.1: Example of how cumulative ET from a green roof planted with *Sedum* could be monitored using the irrigation management reference table. The green roof manager would look up estimated daily crop evapotranspiration (ET_c), based on simple weather observations and month, and schedule supplementary irrigation when the accumulated substrate moisture deficit reaches a pre-defined value, in order to maintain plant health and provision of ESs.

Date	Observed weather	Estimated ET_c (mm)	Accumulated deficit (mm)
28th June	Rain	-	Substrate saturated
29th June	Blue sky – calm	7.40	- 7.40
30th June	Overcast - calm	2.97	- 10.37
1st July	Blue sky – calm	7.99	- 18.36
2nd July	Sunny spells – windy	7.32	- 25.68
3rd July	Sunny spells - calm	5.87	- 31.55

As discussed in Section 5.4.3, since ET is known to decline with decreasing substrate moisture (Voyde *et al.*, 2010b; Stovin *et al.*, 2013), stress factors (K_s) need to be identified for each species for each subsequent day of drying (based on the daily soil moisture balance measured in further experiments) to account for this expected decline in ET. Furthermore, both K_c and ET_c values derived in this study would need to be validated for larger, outdoor plots to ensure the suitability of their application to a full size green roof, and are therefore considered initial estimates for well-watered conditions only in this study.

7.3 Does irrigation with greywater impact the health and growth of any of the chosen species or their ability to continue providing ecosystem services?

Use of greywater for irrigation of green roofs may represent an additional strategy for sustainable irrigation, helping to preserve limited water resources in urban areas whilst ensuring plant health and maintenance of ESs and broadening the range of potential species that could be incorporated on green roofs. However, previous studies have reported contradictory results with regards to the impacts of greywater irrigation on plants and soils, with either positive results (e.g. increased plant growth and yield; Misra *et al.*, 2010; Ali *et al.*, 2013) or negative results (e.g. reduction in soil hydraulic conductivity and infiltration rates; Misra and Sivongxay, 2009; Travis *et al.*, 2010).

Moreover, although differences in the impacts of greywater on plant health and growth have been identified between different plant species (Sharvelle *et al.*, 2012; Sawadogo *et al.*, 2014), the majority of studies have tested vegetable crop and wetland species, with few potential green roof species tested (e.g. Ouldboukhitine *et al.*, 2014). Furthermore, very few studies have investigated the impact of greywater irrigation on plant functioning and ability to provide ESs (Eriksson *et al.*, 2006; Ouldboukhitine *et al.*, 2014), with no definitive trends apparent. This study therefore aimed to evaluate the impact of short-term greywater irrigation on the health and growth of potential green roof species and on their ability to provide ESs, compared to plants of the same species irrigated with freshwater. This information would hopefully confirm the suitability of greywater for sustainable supplementary irrigation of green roofs in the UK and encourage its use, whilst also identifying 'tolerant' species that have demonstrated no negative impacts of irrigation with greywater and maintenance of ESs.

In this study, there were no apparent impacts, either positive or negative, on the health or growth of any of the tested species when irrigated exclusively with synthetic greywater for 6 – 8 weeks compared to plants irrigated with tap water. These results indicate that, although the extra nutrients in the greywater did not enhance plant growth, greywater may be suitable for short-term irrigation of green roofs without compromising aesthetic quality or plant size (and thus provision of ESs dependent on canopy size and structure such as rainfall retention, air pollution capture and building insulation). Furthermore, plant functioning, as measured by leaf stomatal conductance (g_s) and canopy temperature, was generally not affected by short-term irrigation with greywater. Since both g_s and leaf temperature have been linked to cooling provision in several species (Vaz Monteiro *et al.*, 2016a; 2017), including those tested in this study, these results suggest that the extent of cooling provided by these plants would not be compromised by irrigation with greywater.

With the nutrient-poor 'model' substrate used in Experiment 6, *Heuchera* g_s was significantly reduced by week 6 with greywater irrigation compared to tap water, and ET was also significantly lower in greywater-irrigated treatments of *Heuchera*, control and *Salvia* in week 7. This suggests that, although greywater had no apparent impacts on the g_s of any species for the majority of the experiment, the cumulative effect of 6 weeks of continuous irrigation with greywater may have impacted the substrate to such an extent as to begin affecting the functioning of some species. Indeed, substrate salinity (measured by Sodium Adsorption Ratio (SAR) and electrical conductivity (EC)) was typically higher in greywater treatments, particularly towards the end of the 6-week experiment, which could have altered the substrate structure and properties, such as hydraulic conductivity, thus making it difficult for plants to take up water. For *Salvia*, the reduction in ET only became apparent as the substrate dried (i.e. after 4 days with no irrigation), suggesting that this could be avoided if irrigation (or rainfall) was provided at frequent enough intervals to prevent the substrate becoming dry. Reduced g_s and ET are also likely to indicate a reduction in cooling that could be provided by *Heuchera*, and possibly *Salvia*, after 6 weeks, as well as slower restoration of the substrate's water retention capacity between storms, thus reducing overall stormwater management provision. *Stachys* and *Sedum* g_s, canopy temperature and ET were similar with both tap water and greywater irrigation throughout the study, suggesting that provision of ESs was not compromised by greywater irrigation, and these species may therefore be good choices for a green roof that will be irrigated with greywater.

In practice, however, the irrigation regime on a green roof in the UK is likely to be quite different to this study, in which containers were irrigated with greywater exclusively for the length of both experiments (6 – 8 weeks) with no runoff ever generated from the containers, allowing greywater constituents to accumulate in the substrate. Conversely, irrigation of a green roof with greywater would only be to supplement rainfall during periods of drought (in order to maintain plant health and provision of ESs, as discussed in Section 7.2.2). Additionally, runoff would likely be generated by some rainfall events, thus flushing greywater constituents out of the substrate and preventing accumulation. Although this could have potential consequences for the quality of runoff from green roofs and the pollutant load entering downstream water bodies, previous studies have found that alternating greywater irrigation with freshwater (or rainfall) can alleviate any potential impacts of greywater on the substrate (Pinto *et al.*, 2010; Siggins *et al.*, 2016), which could also minimise any impacts on plants.

7.4 Does irrigation with greywater impact the quality of runoff compared to using tap water?

Rainfall runoff from green roofs can be of higher quality than runoff from conventional rooftops (Teemusk and Mander, 2007), with lower concentrations of nutrients and more neutral pH, thus reducing impacts of urban runoff on receiving water bodies. This results from filtering and storage of constituents as water passes through the substrate, as well as plant uptake where vegetation is present; indeed, runoff quality has frequently been found to be of significantly higher quality from vegetated green roofs compared to bare substrate alone (Emilsson *et al.*, 2007; Vijayaraghavan *et al.*, 2012), especially once the plants have become mature and well-established (Köhler, 2002). However, studies have also shown that green roofs can sometimes act as a source of certain nutrients, such as phosphorus (P) and salts (Van Seters *et al.*, 2009; Alfiya *et al.*, 2012), resulting in runoff of lower quality than the original rainwater or irrigation waters and increasing the pollutant load delivered to water bodies. The substrate is considered to be major source of these nutrients (Berndtsson *et al.*, 2009), and leaching is greater when green roofs are newly established or following application of fertilisers (Berndtsson *et al.*, 2006; Emilsson *et al.*, 2007).

In this study, leaching of nutrients was evident from both the 'industry standard' green roof substrate, which had an inherently high nutrient content, and from the nutrient-poor 'model' substrate, with both tap water and greywater irrigation. Consequently, runoff from all species had significantly higher EC and nutrient concentrations than the influent tap water or greywater used for irrigation in both experiments. Only boron (B) in the runoff from greywater-irrigated treatments in Experiment 6 was significantly reduced compared to the B content of the irrigation greywater, probably as a result of the high concentration of B in the synthetic greywater (0.75 mg L^{-1}) and the inherently low B content of the nutrient-poor substrate (0.06 mg L^{-1}). Although these results may suggest that these substrates were typically a source of nutrients, nutrients would have accumulated in the substrate over the course of the experiments since no runoff was ever generated, probably resulting in particularly high concentrations in the runoff collected at the end of the experiments. In practice, rainfall is likely to flush nutrients out of the substrate of a green roof more frequently, thus preventing accumulation and high concentrations in the runoff.

The additional nutrients and chemical constituents applied through greywater irrigation may limit the ability of a green roof to improve the quality of the runoff, potentially leading to negative environmental impacts and thus limiting its suitability for green roof irrigation. Although this has rarely been studied, available results indicate that runoff from greywater-irrigated treatments is typically of lower quality than from tap water-irrigated treatments, with higher concentrations of nutrients and higher EC and SAR (Alfiya *et al.*, 2012; Sharvelle *et al.*, 2012). In this study, EC and concentrations of P, B and sodium (Na) were also significantly higher in runoff from plants/substrate irrigated with greywater compared to tap water (P and B concentrations up to 17 times higher, Na up to 5 times higher and EC twice as high), indicating that runoff quality was indeed reduced with greywater irrigation.

As previously mentioned, the irrigation regime used in this study prevented generation of any runoff throughout the duration of the experiments, probably resulting in high accumulation of nutrients in the substrate which would have been flushed out at the end of the experiments. Indeed, other studies have found that nutrient concentrations in runoff are typically high at the onset of rainfall (the 'first flush' effect) as nutrients that have accumulated through dry deposition in dry periods are flushed out (Berndtsson *et al.*, 2006; Razzaghmanesh *et al.*, 2014). Additionally, greywater-irrigated containers were flushed with greywater at the end of both experiments to generate runoff, probably resulting in higher nutrient concentrations in the runoff than if containers had been flushed with tap water. Results obtained in this study are therefore considered to be a high estimate of the nutrient concentrations in runoff from greywater-irrigated containers. Since greywater would only be used to supplement rainfall during periods of drought on green roofs in the UK, nutrients would be unlikely to accumulate in the substrate to such high concentrations as in this study. Indeed, previous studies have shown that alternating freshwater and greywater irrigation can result in similar nutrient concentrations and substrate EC as when freshwater is used exclusively (Pinto *et al.*, 2010). Furthermore, runoff is likely to be generated during some rainfall events, flushing any greywater constituents out of the substrate more frequently and thus in lower concentrations.

7.4.1 Can species selection influence the quality of the runoff from a green roof, when irrigated with either tap water or greywater?

As well as factors such as substrate type and nutrient content, maintenance practices of green roofs and the quality of influent irrigation waters, runoff quality may also vary with plant species (Sharvelle *et al.*, 2012; Aloisio *et al.*, 2016), since species differ in their nutrient uptake efficiency (Fowdar *et al.*, 2017). Although plant presence has frequently been found to improve runoff quality compared to bare substrate alone (Vijayaraghavan *et al.*, 2012; Beecham and Razzaghmanesh, 2015), the impact of different plant species on runoff quality has received very little attention to date.

In this study, runoff from vegetated treatments was frequently of higher quality (i.e. lower nutrient concentrations and EC) than runoff from bare substrate, but only when tap water was used for irrigation. Indeed, with the nutrient-poor 'model' substrate in Experiment 6, runoff from tap water-irrigated *Stachys*, *Salvia* and *Sedum* had significantly lower EC and P content than runoff from the control, despite receiving almost double the nutrients through irrigation over the 6 weeks of the experiment (see Sections 2.7.2 - 2.7.3 and 6.4.5.1). Further species differences were also apparent with tap water irrigation, with runoff from *Stachys* having significantly lower Na concentrations than runoff from *Sedum* and *Salvia* and lower EC than *Salvia* in Experiment 6, and runoff from *Heuchera* having significantly higher EC and P and B content than runoff from all other species in Experiment 5. These results suggest therefore that *Stachys* was able to offer the greatest improvement to runoff quality when tap water was used for irrigation, whilst *Heuchera* offered the least improvement, and appropriate species selection could therefore allow runoff quality improvement on a green roof to be maximised.

When irrigated with greywater, nutrient contents were generally similar in runoff from vegetated and unvegetated containers, indicating that plant presence had little effect on improving runoff quality. However, runoff EC and P content were significantly lower in runoff from *Stachys* compared to runoff from the control in Experiment 6, even though the control received only 56% of the nutrients that *Stachys* did over the course of the experiment. Furthermore, despite receiving the same quantity of nutrients through irrigation with greywater, runoff from *Stachys* and *Salvia* had significantly lower EC and P and B concentrations than runoff from *Sedum*, highlighting the impact of species selection on runoff quality improvement.

High application and accumulation of nutrients in the substrate over the course of both experiments with greywater irrigation is likely to have made any impacts of species differences in terms of runoff quality improvement negligible. These high nutrient concentrations may also be representative of substrate nutrient conditions on a newly-established green roof with young plants or after fertiliser application (Köhler, 2002; Berndtsson *et al.*, 2006; Emilsson *et al.*, 2007), suggesting that plant presence may not offer greater runoff quality improvement than bare substrate under these circumstances. Conversely, the inherently low nutrient content of the 'model' substrate used in Experiment 6 could reflect the conditions on a mature green roof, when substrate nutrient content would tend to be lower; results of this study suggest that, in these conditions, runoff quality improvement could be maximised by selecting species that show the greatest reduction of nutrient concentrations in the runoff, such as *Stachys*.

7.5 Key conclusions and knowledge application

This study contributes to the growing body of research (Nagase and Dunnett, 2012; Blanuša *et al.*, 2013; Cameron *et al.*, 2014; Lundholm *et al.*, 2014; Vaz Monteiro *et al.*, 2016a; 2017) advocating the idea that, in addition to plant survival rates, species selection for green roofs, and indeed any form of green infrastructure, should also be based on the plants' ability to maximise the provision of a range of ESs such as stormwater management, runoff quality improvement and cooling. Results of this study could change the perspective of urban planners and architects and enable them to select appropriate species for inclusion on green roofs in order to maximise the provision of stormwater management, thus helping to mitigate surface flooding and combined sewer overflows in urban areas. Furthermore, results indicated that the ET rate of a particular species could be maximised in optimal weather conditions, thus adding further importance to the concept of selecting appropriate plants for a specific location and purpose. Green roof planners should therefore also consider the regional climate and local weather conditions experienced on the green roof, and where possible, plants should be used in locations where environmental conditions are optimal for maximum ET and thus maximum restoration of the substrate's water retention capacity and cooling provision.

Green roofs are considered to be good way of incorporating Sustainable Drainage Systems (SuDS) into urban areas, as they control surface water close to its source whilst also potentially improving water quality and providing amenity value (Stovin *et al.*, 2013). Plant choice for SuDS has not been viewed as a priority, and green roofs in the UK are typically planted with succulent species such as *Sedum*, with no irrigation systems installed. However, with increasing urbanisation and climate change projections of more frequent high intensity precipitation events in the UK, highly polluted rooftop runoff and surface flooding are likely to become greater problems and the ability of green roofs to mitigate these will therefore become a more valuable and desirable service. Although plant presence, in general, improved the quality of runoff compared to bare substrate alone, differences between species in their ability to improve runoff quality were clearly identified in this study, with the highest quality runoff from *Stachys*, even when greywater was used for irrigation. These results highlight the importance of plant selection on green roofs to maximise the ESs that can be provided, and green roof planners should therefore consider species choice in order to ensure that runoff is of the highest possible quality, thus minimising environmental impacts.

This study clearly demonstrated that maximum stormwater management provision could be achieved using species with both high ET rates and large, dense canopies, and in weather conditions with low RH. Canopy interception proved to be important when antecedent SMC is high, for example when rainfall events occur close together or in cool, humid weather when ET is restricted. In these conditions, species with large, dense canopies and rough or hairy leaves are able to provide the greatest rainfall retention. Nevertheless, restoration of the substrate's water retention capacity during dry periods appears to be the most important role played by the vegetation, and species with inherently high ET rates are therefore advantageous. However, these species may not be able to maintain high ET rates when substrate moisture becomes depleted during a prolonged period of drought, and the aesthetic quality of the plants and provision of additional ESs such as cooling may also become compromised. Irrigation during periods of drought is therefore crucial for ensuring plant health and provision of ESs, but a balance must be sought between maintaining high enough substrate moisture to allow ET (and thus cooling and restoration of substrate retention capacity) to continue at a high rate and maintaining high availability of substrate retention capacity for maximum water retention in subsequent rainfall events.

Since water demand in urban areas is increasing and climate change projections indicate an increased likelihood of droughts and water shortages (IPCC, 2013), water for irrigation of green roofs may be limited, and irrigation practices must therefore be sustainable. This study highlighted the substantially different water requirements of individual species, and in different weather conditions, lending support to the suitability of green roof irrigation scheduling based on daily ET. Indeed, results indicated that species with the highest inherent ET rates (*Salvia* and *Stachys*) will require more frequent irrigation, whilst all species will require more frequent irrigation in 'blue sky' windy conditions in June and July. Crop coefficients identified for the species used in this study could contribute towards a database of K_c values for potential green roof species, thus enabling ET-based irrigation scheduling for a broader range of species, and again, emphasise species differences, with *Salvia* and *Stachys* having K_c values twice as large as *Heuchera* and *Sedum*. Using the FAO-56 PM model to estimate daily ET from a green roof could allow green roof managers to monitor water use and schedule irrigation at a pre-determined substrate moisture deficit in order to maintain plant health and the provision of ESs whilst also preserving limited water resources and minimising costs. To make irrigation scheduling in this way easier and more accessible to green roof managers, a smartphone app could be developed with the FAO-56 PM model as its basis (see Section 7.6).

Results of this study indicate that the use of greywater for supplementary irrigation of green roofs, interspersed with natural rainfall, could offer a suitable alternative to high quality potable water without having negative impacts on plant health and provision of ESs. *Stachys* and *Sedum* demonstrated the greatest tolerance to greywater irrigation, with no observed impacts on plant health, growth or functioning, and thus, presumably, no impact on provision of ESs. Although ET rates of *Salvia* and *Heuchera* appeared to be restricted after 6 weeks of greywater irrigation, in practice the intermittent use of greywater to supplement rainfall and frequent flushing of the substrate on a green roof may negate this effect and allow ET to continue at the same rate as when freshwater is used for irrigation. Urban planners should therefore consider the use of greywater for sustainable supplemental irrigation of green roofs, or other forms of green infrastructure, and engineering systems to store or transport greywater produced inside a building up to the rooftop could be incorporated into new building design.

Main numerical findings from this study are summarised in Table 7.2. This information can hopefully be used as a benchmark and for comparison when planners intend to introduce alternative potential green roof species for the purpose of increasing the roof's stormwater management provision or when planning to use greywater for irrigation. Since all experiments in this study were carried out in glasshouse or controlled environment settings, stormwater management and ET results would need to be validated outdoors on a full size green roof. Testing species performance on this large scale would require use of equipment such as weighing lysimeters, which is also likely to increase the accuracy of measurements.

Table 7.2: Summary of plant parameters and provision of ecosystem services for species tested in this study. Mean stomatal conductance (g_s) is based on baseline measurements made at the start of Experiment 6 when substrate moisture was not restricted. Mean daily ET in well-watered conditions (i.e. the first 24 hours after saturation), mean canopy density (based on leaf and stems area) and mean rainfall retention results are from the larger canopies in Experiment 3. Runoff quality improvement is compared to runoff from bare substrate.

Plant parameters and ESs performance		*Heuchera*	*Salvia*	*Stachys*	*Sedum*	Bare substrate
Mean g_s (mmol m^{-2} s^{-1})		41	272	232	116	-
Mean ET in well-watered conditions (mm day^{-1})		2.8	4.6	4.7	3.7	2.4
Mean canopy density (cm^{2} cm^{-3})		0.23	0.44	0.47	0.53	-
Crop coefficient		1.47	2.98	2.94	1.66	-
Mean rainfall retention (%)	'Saturated'	2.2	7.9	13.1	17.1	1.1
	'Unsaturated'	28.5	63.6	72.9	48.9	20.5
Evidence of negative impacts of greywater	Plant health and growth	×	×	×	×	-
	Plant functioning	✓	✓	×	×	-
Evidence of some runoff quality improvement	With TW irrigation	×	✓	✓	✓	-
	With GW irrigation	×	×	✓	×	-

Key conclusions and recommendations for maximising stormwater management provision and providing sustainable irrigation solutions that can be drawn from this study are therefore:

- Species such as *Salvia* and *Stachys*, rather than traditionally used *Sedum*, possess key attributes for maximising stormwater management provision of green roofs (high ET rates, large, dense canopies with an open structure allowing water to penetrate and rough or hairy leaves). High ET rates of these species were correlated with their ability to retain a greater volume of rainfall;
- ET rates of all plants will generally be greater in hot and dry climates and weather conditions. However, ET of some species can be maximised by placing them in locations with optimal environmental conditions, which will maximise that species' contribution to restoration of water retention capacity. For example, with *Sedum* ET is greatest in conditions with low RH and moderate temperatures, and its stormwater management provision can thus be maximised by placing it in locations with these environmental conditions. It is therefore important for planners to consider the idea of using the 'best plant in the best place' in order to achieve the greatest ET possible in the local weather conditions;
- Irrigation of green roofs planted with these alternative species is vital for maintaining plant aesthetic quality, high ET rates and provision of ESs dependent on ET including cooling and restoration of substrate water retention capacity. Irrigation can be scheduled, using the FAO-56 PM model and irrigation management reference tables proposed here, according to the individual water requirements of each species and daily weather conditions.
- Initial results suggest that intermittent use of greywater to supplement rainfall during periods of summertime drought in the UK may provide a suitable sustainable option for irrigation of green roofs without having any negative impacts on plant health and provision of ESs. Greywater irrigation systems should therefore be considered by urban planners.

7.6 Future work

The alternative plant species for green roofs tested in this study have previously demonstrated good potential to provide a cooling service, and results of this study provide further information about the ability of these plant types to provide multiple ESs (i.e. stormwater management and improvement of runoff quality). Future research should continue to build on this knowledge by comparing the ability of different species to provide additional ESs, such as air pollution mitigation, biodiversity support etc. Software packages, such as 'i-Tree species' (USDA, 2017), have recently been developed, allowing users to identify appropriate tree species that could be planted in a particular location, based on the primary objective of the tree planting (i.e. which ESs provision is considered most important). Similar software could be developed for green roof species if enough field data were available, enabling urban planners to identify species easily that are both suited to their location and could maximise the provision of the ESs deemed most important.

Similarly, if the database of available crop coefficients for potential green roof species were expanded through field data collection, a computer model or smartphone app could be developed, based on the FAO-56 PM model, to aid irrigation scheduling of green roofs planted with a wide range of species. This app could follow the principles of the irrigation management reference table (presented in Section 5.3.2), requiring minimal input from a green roof manager (i.e. a simple observation of the weather each day) to calculate daily ET, and notifications when irrigation is required in order to maintain plant health and ESs provision. Alternatively, to further minimise user time demands, the app could be connected to weather forecasting and monitoring services to automatically calculate daily ET based on local weather data. Furthermore, if more field data were collected to establish the substrate moisture deficit at which ESs provision (e.g. cooling) may become compromised for each species, this app could notify the user to irrigate before plant health or ESs provision becomes compromised. A few smartphone apps are currently available allowing users to remotely control irrigation systems, with a small number using real-time monitoring of weather or soil moisture to adjust irrigation quantities according to need (e.g. Hydrawise and CropX); these systems typically do not account for different vegetation types, however, and require installation of sophisticated, full-scale irrigation systems or sensors which may be costly.

Some recent research has begun to attempt to link ESs provision, and thus plant selection for green roofs, to plant physiological and functional traits (Farrell *et al.*, 2013; Van Mechelen *et al.*, 2014; Lundholm *et al.*, 2015). With further research, it may also be possible to link plant tolerance to greywater irrigation and provision of additional ESs (e.g. runoff quality improvement, air pollution capture) to key plant attributes, thus allowing assessment of the potential performance of new species based on their possession of these attributes without the need to test every species individually. In addition to testing a wider range of species with varying attributes in order to identify any plant traits that may be linked to tolerance to greywater irrigation, the effect of alternating freshwater and greywater irrigation on plants, substrates and runoff quality should be verified, since it has previously been suggested that this technique can prevent accumulation of greywater constituents (e.g. salts) in the substrate (Pinto *et al.*, 2010). It is important to clarify if this could negate any of the negative impacts resulting from greywater irrigation solely that were observed in this study (i.e. reduced ET and g_s in some species) to confirm the suitability of using greywater for supplemental irrigation of green roofs.

Some green roof research has focussed on the advantages of incorporating a variety of species on a green roof instead of planting monocultures, with some evidence that, as well as improving aesthetics and biodiversity, plant communities may improve survival rates, surface cooling and stormwater management provision (Dunnett *et al.*, 2008; Lundholm *et al.*, 2010; Nagase and Dunnett, 2010). Furthermore, Heim and Lundholm (2016) suggest that selecting plants with phenological complementarity can increase plant survival by reducing competitive pressures as well as increasing the provision of ESs. Since different species have differing nutrient requirements and may take up different nutrients from the substrate, planting a mixture of species could also prove beneficial for improving runoff quality. Likewise, in addition to individual species, the tolerance of plant communities to greywater irrigation should be investigated, since species may complement each other in their requirements and uptake of nutrients. This may allow species that are sensitive to certain greywater constituents when planted individually to be incorporated on green roofs, as other species may take up these constituents or be able to moderate any negative substrate conditions.

Finally, following on from the results of this study, future research could investigate how the environmental and economic benefits obtained by using alternative species on green roofs compares to the additional costs, particularly in terms of the need for an irrigation system to maintain these plants. For urban planners to consider selecting alternative species for green roofs based on their ability to maximise ESs provision, there needs to be strong evidence that the environmental and economic benefits provided (i.e. improved ESs provision, building insulation, etc.) outweigh the additional cost and practicalities of installing and maintaining an irrigation system. Furthermore, the logistics and cost of the infrastructure required to divert greywater produced in a building up to the rooftop when it is required for irrigation should be fully investigated and compared to the monetary savings and environmental benefits gained by re-using greywater rather than freshwater for irrigation.

References

Abdulla, F A & Al-Shareef, A (2009) Roof rainwater harvesting systems for household water supply in Jordan. *Desalination,* **243 (1),** 195-207.

Abed, S N & Scholz, M (2016) Chemical simulation of greywater. *Environmental Technology,* **37 (13),** 1631-1646.

Ahmed, W, Brandes, H, Gyawali, P, Sidhu, J & Toze, S (2014) Opportunistic pathogens in roof-captured rainwater samples, determined using quantitative PCR. *Water research,* **53,** 361-369.

Akbari, H, Pomerantz, M & Taha, H (2001) Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar energy,* **70 (3),** 295-310.

Al-Hamaiedeh, H & Bino, M (2010) Effect of treated grey water reuse in irrigation on soil and plants. *Desalination,* **256 (1),** 115-119.

Al-Jayyousi, O R (2003) Greywater reuse: towards sustainable water management. *Desalination,* **156 (1),** 181-192.

Albalawneh, A, Chang, T-K & Chou, C-S (2016) Impacts on soil quality from long-term irrigation with treated greywater. *Paddy and Water Environment,* **14 (2),** 289-297.

Alexandri, E & Jones, P (2008) Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment,* **43 (4),** 480-493.

Alfiya, Y, Damti, O, Stoler-Katz, A, Zoubi, A, Shaviv, A & Friedler, E (2012) Potential impacts of on-site greywater reuse in landscape irrigation. *Water Science and Technology,* **65 (4),** 757.

Ali, H M, Siddiqui, M H, Khamis, M H, Hassan, F A, Salem, M Z M & El-Mahrouk, E-S M (2013) Performance of forest tree Khaya senegalensis (Desr.) A. Juss. under sewage effluent irrigation. *Ecological Engineering,* **61, Part A,** 117-126.

Allen, R G, Pereira, L S, Raes, D & Smith, M (1998) *Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56*: FAO, Rome.

Allen, R G, Pereira, L S, Smith, M, Raes, D & Wright, J L (2005) FAO-56 dual crop coefficient method for estimating evaporation from soil and application extensions. *Journal of irrigation and drainage engineering,* **131 (1),** 2-13.

Allen, R G, Pruitt, W O, Wright, J L, Howell, T A, Ventura, F, Snyder, R, Itenfisu, D, Steduto, P, Berengena, J, Yrisarry, J B, Smith, M, Pereira, L S, Raes, D, Perrier, A, Alves, I, Walter, I & Elliott, R (2006) A recommendation on standardized surface resistance for hourly calculation of reference ETo by the FAO56 Penman-Monteith method. *Agricultural Water Management,* **81 (1–2),** 1-22.

Allen, R G & Pereira, L S (2009) Estimating crop coefficients from fraction of ground cover and height. *Irrigation Science,* **28 (1),** 17-34.

Almuktar, S A A A N, Scholz, M, Al-Isawi, R H K & Sani, A (2015) Recycling of domestic wastewater treated by vertical-flow wetlands for irrigating Chillies and Sweet Peppers. *Agricultural Water Management,* **149,** 1-22.

Aloisio, J M, Tuininga, A R & Lewis, J D (2016) Crop species selection effects on stormwater runoff and edible biomass in an agricultural green roof microcosm. *Ecological Engineering,* **88,** 20-27.

Azam-Ali, S (2013) Plant and crop science. *In: Soil Conditions and Plant Growth.* Gregory, P J & Nortcliff, S, (eds.) Blackwell Publishing Ltd: Oxford.

Bean, R & Pitt, R (2012) Advancing Stormwater Beneficial Uses: ET Mapping in Urban Areas. *In: World Environmental and Water Resources Congress 2012: Crossing Boundaries.* Loucks, E D, (ed.) ASCE.

Beck, D A, Johnson, G R & Spolek, G A (2011) Amending greenroof soil with biochar to affect runoff water quantity and quality. *Environmental Pollution,* **159 (8–9),** 2111-2118.

Bedbabis, S, Ben Rouina, B, Boukhris, M & Ferrara, G (2014) Effect of irrigation with treated wastewater on soil chemical properties and infiltration rate. *Journal of Environmental Management,* **133,** 45-50.

Beecham, S & Razzaghmanesh, M (2015) Water quality and quantity investigation of green roofs in a dry climate. *Water Research,* **70,** 370-384.

Berghage, R, Jarrett, A, Beattie, D, Kelley, K, Husain, S, Rezai, F, Long, B, Negassi, A, Cameron, R & Hunt, W (2007) Quantifying evaporation and transpirational water losses from green roofs and green roof media capacity for neutralizing acid rain. *National Decentralized Water Resources Capacity Development Project*.

Berndtsson, J C, Emilsson, T & Bengtsson, L (2006) The influence of extensive vegetated roofs on runoff water quality. *Science of the Total Environment,* **355 (1),** 48-63.

Berndtsson, J C, Bengtsson, L & Jinno, K (2009) Runoff water quality from intensive and extensive vegetated roofs. *Ecological Engineering,* **35 (3),** 369-380.

Berndtsson, J C (2010) Green roof performance towards management of runoff water quantity and quality: a review. *Ecological Engineering,* **36 (4),** 351-360.

Berretta, C, Poë, S & Stovin, V (2014) Moisture content behaviour in extensive green roofs during dry periods: The influence of vegetation and substrate characteristics. *Journal of Hydrology,* **511,** 374-386.

Bianchini, F & Hewage, K (2012) How "green" are the green roofs? Lifecycle analysis of green roof materials. *Building and Environment,* **48,** 57-65.

Blanusa, T, Vaz Monteiro, M, Kemp, S & Cameron, R (2016) Planting choices for retrofitted green roofs. *In: Green Roof Retrofit: Building Urban Resilience.* Wilkinson, S & Dixon, T, (eds.) John Wiley & Sons Ltd.: Chichester, UK.

Blanuša, T, Vaz Monteiro, M M, Fantozzi, F, Vysini, E, Li, Y & Cameron, R W F (2013) Alternatives to Sedum on green roofs: Can broad leaf perennial plants offer better 'cooling service'? *Building and Environment,* **59,** 99-106.

Bocanegra-Martínez, A, Ponce-Ortega, J M, Nápoles-Rivera, F, Serna-González, M, Castro-Montoya, A J & El-Halwagi, M M (2014) Optimal design of rainwater collecting systems for domestic use into a residential development. *Resources, Conservation and Recycling,* **84,** 44-56.

Borin, M, Milani, M, Salvato, M & Toscano, A (2011) Evaluation of Phragmites australis (Cav.) Trin. evapotranspiration in Northern and Southern Italy. *Ecological Engineering,* **37 (5),** 721-728.

Bowler, D E, Buyung-Ali, L, Knight, T M & Pullin, A S (2010) Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and urban planning,* **97 (3),** 147-155.

Brandão, C, Cameira, M d R, Valente, F, Cruz de Carvalho, R & Paço, T A (2017) Wet season hydrological performance of green roofs using native species under Mediterranean climate. *Ecological Engineering,* **102,** 596-611.

Broadbent, A M, Coutts, A M, Tapper, N J & Demuzere, M (2017) The cooling effect of irrigation on urban microclimate during heatwave conditions. *Urban Climate***,** In press.

Bubenheim, D, Wignarajah, K, Berry, W & Wydeven, T (1997) Phytotoxic Effects of Gray Water Due to Surfactants. *Journal of the American Society for Horticultural Science,* **122 (6),** 792-796.

Buffam, I, Mitchell, M E & Durtsche, R D (2016) Environmental drivers of seasonal variation in green roof runoff water quality. *Ecological Engineering,* **91,** 506-514.

Butler, C & Orians, C M (2011) Sedum cools soil and can improve neighboring plant performance during water deficit on a green roof. *Ecological Engineering,* **37 (11),** 1796-1803.

Cai, J, Liu, Y, Lei, T & Pereira, L S (2007) Estimating reference evapotranspiration with the FAO Penman–Monteith equation using daily weather forecast messages. *Agricultural and Forest Meteorology,* **145 (1–2),** 22-35.

Cameron, R, Harrison-Murray, R, Atkinson, C & Judd, H (2006) Regulated deficit irrigation–a means to control growth in woody ornamentals. *The Journal of Horticultural Science and Biotechnology,* **81 (3),** 435-443.

Cameron, R W, Blanuša, T, Taylor, J E, Salisbury, A, Halstead, A J, Henricot, B & Thompson, K (2012) The domestic garden–Its contribution to urban green infrastructure. *Urban Forestry & Urban Greening,* **11 (2),** 129-137.

Cameron, R W, Taylor, J E & Emmett, M R (2014) What's 'cool' in the world of green façades? How plant choice influences the cooling properties of green walls. *Building and Environment,* **73,** 198-207.

Cantuaria, G A C (2000) A comparative study of the thermal performance of vegetation on building surfaces. *In: Architecture, City, Environment: Proceedings of PLEA 2000, Cambridge, UK.* Steemers, K & Yannas, S, (eds.) James & James (Science Publishers) Ltd.: London.

Carpenter, C M G, Todorov, D, Driscoll, C T & Montesdeoca, M (2016) Water quantity and quality response of a green roof to storm events: Experimental and monitoring observations. *Environmental Pollution,* **218,** 664-672.

Carter, T L & Rasmussen, T C (2006) Hydrologic behavior of vegetated roofs. *Journal of the American Water Resources Association,* **42 (5),** 1261-1274.

Castiglia Feitosa, R & Wilkinson, S (2016) Modelling green roof stormwater response for different soil depths. *Landscape and Urban Planning,* **153,** 170-179.

Charoenkit, S & Yiemwattana, S (2017) Role of specific plant characteristics on thermal and carbon sequestration properties of living walls in tropical climate. *Building and Environment,* **115,** 67-79.

Cheng, C Y, Cheung, K K & Chu, L (2010) Thermal performance of a vegetated cladding system on facade walls. *Building and environment,* **45 (8),** 1779-1787.

Christova-Boal, D, Eden, R E & McFarlane, S (1996) An investigation into greywater reuse for urban residential properties. *Desalination,* **106 (1),** 391-397.

Clarke, M A & Walsh, R P D (2007) A portable rainfall simulator for field assessment of splash and slopewash in remote locations. *Earth Surface Processes and Landforms,* **32 (13),** 2052-2069.

Collatz, G J, Ball, J T, Grivet, C & Berry, J A (1991) Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: a model that includes a laminar boundary layer. *Agricultural and Forest Meteorology,* **54 (2–4),** 107-136.

Compton, J & Whitlow, T (2006) A zero discharge green roof system and species selection to optimize evapotranspiration and water retention. *In: Proceedings of the 4th Greening Rooftops for Sustainable Communities* Boston, MA.

Costa, J M, Grant, O M & Chaves, M M (2013) Thermography to explore plant–environment interactions. *Journal of experimental botany,* **64 (13),** 3937-3949.

Criswell, M & Roesner, L (2007) Long-Term Effects of Landscape Irrigation Using Household Graywater. *Small Flows, Big Consequences,* **August/September 2007,** 15-18.

Crutzen, P J (2004) New Directions: The growing urban heat and pollution “island” effect—impact on chemistry and climate. *Atmospheric Environment,* **38 (21),** 3539-3540.

D'Arco, M, Ferroni, L, Blanusa, T & Speranza, M (2017) The influence of the transpiration of C3 and CAM-facultative species on the green roof's cooling potential. Abstract submitted to International Symposium on Greener Cities for More Efficient Ecosystem Services in a Climate Changing World, Bologna, 2017.

Dalahmeh, S S, Pell, M, Hylander, L D, Lalander, C, Vinnerås, B & Jönsson, H (2014) Effects of changing hydraulic and organic loading rates on pollutant reduction in bark, charcoal and sand filters treating greywater. *Journal of Environmental Management,* **132,** 338-345.

Davies, H, Doick, K, Handley, P, O'Brien, L & Wilson, J (2017) *Delivery of ecosystem services by urban forests*: Forestry Commission, Edinburgh.

Davies, W J, Tardieu, F & Trejo, C L (1994) How Do Chemical Signals Work in Plants that Grow in Drying Soil? *Plant Physiology,* **104 (2),** 309-314.

De-Ville, S, Menon, M, Jia, X, Reed, G & Stovin, V (2017) The impact of green roof ageing on substrate characteristics and hydrological performance. *Journal of Hydrology,* **547,** 332-344.

De Clerck, F, Singer, M J & Lindert, P (2003) A 60-year history of California soil quality using paired samples. *Geoderma,* **114 (3–4),** 215-230.

Deinlein, U, Stephan, A B, Horie, T, Luo, W, Xu, G & Schroeder, J I (2014) Plant salt-tolerance mechanisms. *Trends in plant science,* **19 (6),** 371-379.

Denmead, O & Shaw, R H (1962) Availability of soil water to plants as affected by soil moisture content and meteorological conditions. *Agronomy journal,* **54 (5),** 385-390.

Diaper, C, Toifl, M & Storey, M (2008) *Greywater technology testing protocol,* CSIRO: Australia.

Dietz, M E & Clausen, J C (2005) A field evaluation of rain garden flow and pollutant treatment. *Water, Air, and Soil Pollution,* **167 (1-4),** 123-138.

DiGiovanni, K, Montalto, F, Gaffin, S & Rosenzweig, C (2012) Applicability of classical predictive equations for the estimation of evapotranspiration from urban green spaces: green roof results. *Journal of Hydrologic Engineering,* **18 (1),** 99-107.

Dimoudi, A & Nikolopoulou, M (2003) Vegetation in the urban environment: microclimatic analysis and benefits. *Energy and buildings,* **35 (1),** 69-76.

Doick, K J, Peace, A & Hutchings, T R (2014) The role of one large greenspace in mitigating London's nocturnal urban heat island. *Science of The Total Environment,* **493 (Supplement C),** 662-671.

Domènech, L, March, H, Vallès, M & Saurí, D (2015) Learning processes during regime shifts: Empirical evidence from the diffusion of greywater recycling in Spain. *Environmental Innovation and Societal Transitions,* **15,** 26-41.

Droogers, P & Allen, R G (2002) Estimating Reference Evapotranspiration Under Inaccurate Data Conditions. *Irrigation and Drainage Systems,* **16 (1),** 33-45.

Dunnett, N & Kingsbury, N (2004) *Planting Green Roofs and Living Walls*. Timber Press: Portland, Oregon.

Dunnett, N & Nolan, A (2004) The effect of substrate depth and supplementary watering on the growth of nine herbaceous perennials in a semi-extensive green roof. *Acta Horticulturae,* **643,** 305-309.

Dunnett, N, Nagase, A, Booth, R & Grime, P (2008) Influence of vegetation composition on runoff in two simulated green roof experiments. *Urban Ecosystems,* **11 (4),** 385-398.

Dvorak, B & Volder, A (2013) Rooftop temperature reduction from unirrigated modular green roofs in south-central Texas. *Urban Forestry & Urban Greening,* **12 (1),** 28-35.

Emilsson, T, Czemiel Berndtsson, J, Mattsson, J E & Rolf, K (2007) Effect of using conventional and controlled release fertiliser on nutrient runoff from various vegetated roof systems. *Ecological Engineering,* **29 (3),** 260-271.

Environment Agency (2011) *Greywater for domestic users: an information guide,* Environment Agency: Bristol, UK.

Eriksson, E, Auffarth, K, Henze, M & Ledin, A (2002) Characteristics of grey wastewater. *Urban water,* **4 (1),** 85-104.

Eriksson, E, Baun, A, Henze, M & Ledin, A (2006) Phytotoxicity of grey wastewater evaluated by toxicity tests. *Urban Water Journal,* **3 (1),** 13-20.

Eumorfopoulou, E & Kontoleon, K (2009) Experimental approach to the contribution of plant-covered walls to the thermal behaviour of building envelopes. *Building and Environment,* **44 (5),** 1024-1038.

European Commission (2015) *Report from the Commission to the European Parliament and the Council Pursuant to Article 16 of Regulation (EC) No 648/2004 of the European Parliament and the Council of 31 March 2004 on detergents, concerning the use of phosphorus in consumer automatic dishwasher detergents*: Brussels, Belgium.

Farrell, C, Mitchell, R E, Szota, C, Rayner, J P & Williams, N S G (2012) Green roofs for hot and dry climates: Interacting effects of plant water use, succulence and substrate. *Ecological Engineering,* **49,** 270-276.

Farrell, C, Szota, C, Williams, N S & Arndt, S K (2013) High water users can be drought tolerant: using physiological traits for green roof plant selection. *Plant and soil,* **372 (1-2),** 177-193.

Fassman-Beck, E, Voyde, E, Simcock, R & Hong, Y S (2013) 4 Living roofs in 3 locations: Does configuration affect runoff mitigation? *Journal of hydrology,* **490,** 11-20.

Finley, S, Barrington, S & Lyew, D (2009) Reuse of domestic greywater for the irrigation of food crops. *Water, Air, and Soil Pollution,* **199 (1-4),** 235-245.

Fister, W, Iserloh, T, Ries, J B & Schmidt, R G (2012) A portable wind and rainfall simulator for in situ soil erosion measurements. *Catena,* **91,** 72-84.

Fowdar, H S, Hatt, B E, Breen, P, Cook, P L M & Deletic, A (2017) Designing living walls for greywater treatment. *Water Research,* **110,** 218-232.

Fowler, D (2002) Pollutant deposition and uptake by vegetation. *In: Air Pollution and Plant Life.* 2nd ed. Bell, J N B & Treshow, M, (eds.) John Wiley & Sons, Ltd.: Chichester.

Gagnon, V, Chazarenc, F, Kõiv, M & Brisson, J (2012) Effect of plant species on water quality at the outlet of a sludge treatment wetland. *Water Research,* **46 (16),** 5305-5315.

Gaston, K J (2010) Urbanisation. *In: Urban Ecology.* Gaston, K J, (ed.) Cambridge University Press: Cambridge.

Gaston, K J, Davies, Z G & Edmondson, J L (2010) Urban environments and ecosystem functions. *In: Urban Ecology.* Gaston, K J, (ed.) Cambridge University Press: Cambridge.

Getter, K L & Rowe, D B (2006) The role of extensive green roofs in sustainable development. *HortScience,* **41 (5),** 1276-1285.

Getter, K L, Rowe, D B & Andresen, J A (2007) Quantifying the effect of slope on extensive green roof stormwater retention. *Ecological Engineering,* **31 (4),** 225-231.

Ghaitidak, D M & Yadav, K D (2013) Characteristics and treatment of greywater—a review. *Environmental Science and Pollution Research,* **20 (5),** 2795-2809.

Gill, S, Handley, J, Ennos, A & Pauleit, S (2007) Adapting cities for climate change: the role of the green infrastructure. *Built Environment,* **33 (1),** 115-133.

Giorio, P, Sorrentino, G & d'Andria, R (1999) Stomatal behaviour, leaf water status and photosynthetic response in field-grown olive trees under water deficit. *Environmental and Experimental Botany,* **42 (2),** 95-104.

Google Maps (2016) URL: https://www.google.co.uk/maps [Online]. [Accessed 27 October].

Grattan, S, Diaz, F, Pedrero, F & Vivaldi, G (2015) Assessing the suitability of saline wastewaters for irrigation of Citrus spp.: Emphasis on boron and specific-ion interactions. *Agricultural Water Management,* **157,** 48-58.

GRO (2014) *Green Roof Code of Best Practice for the UK 2014,* The Green Roof Organisation: Groundwork Sheffield.

Gross, A, Azulai, N, Oron, G, Ronen, Z, Arnold, M & Nejidat, A (2005) Environmental impact and health risks associated with greywater irrigation: a case study. *Water Science & Technology,* **52 (8),** 161-169.

Gurung, T R & Sharma, A (2014) Communal rainwater tank systems design and economies of scale. *Journal of Cleaner Production,* **67,** 26-36.

Heim, A & Lundholm, J (2016) Phenological complementarity in plant growth and reproduction in a green roof ecosystem. *Ecological Engineering,* **94,** 82-87.

Heim, A, Appleby-Jones, S & Lundholm, J (2017) Green Roof Thermal and Stormwater Performance Comparisons Between Native and Industry-Standard Plant Species. *Cities and the Environment (CATE),* **9 (1),** 6.

Helmreich, B & Horn, H (2009) Opportunities in rainwater harvesting. *Desalination,* **248 (1),** 118-124.

Hess, T & Knox, J (2002) Irrigation Advisory Services: experiences in UK. Workshop on Irrigation Advisory Services and Participatory Extension in Irrigation Management. FAO-ICID. Proceedings on line: www. fao. org 24th July, Montreal, Quebec, Canada.

Heuvelinka, E, Batta, L G G & Damen, T H J (1995) Transmission of solar radiation by a multispan Venlo-type glasshouse: validation of a model. *Agricultural and Forest Meteorology,* **74 (1),** 41-59.

Hsiao, T C (1973) Plant responses to water stress. *Annual review of plant physiology,* **24 (1),** 519-570.

Humphry, J B, Daniel, T C, Edwards, D R & Sharpley, A N (2002) A portable rainfall simulator for plot-scale runoff studies. *Applied Engineering in Agriculture,* **18 (2),** 199-204.

Ip, K, Lam, M & Miller, A (2010) Shading performance of a vertical deciduous climbing plant canopy. *Building and Environment,* **45 (1),** 81-88.

IPCC (2013) Summary for Policymakers. *In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Stocker, T F, Qin, D, Plattner, G-K, Tignor, M, Allen, S K, Boschung, J, Nauels, A, Xia, Y, Bex, V & Midgley, P M, (eds.) Cambridge University Press: Cambridge.

Iserloh, T, Fister, W, Seeger, M, Willger, H & Ries, J B (2012) A small portable rainfall simulator for reproducible experiments on soil erosion. *Soil and Tillage Research,* **124,** 131-137.

Jenerette, G D, Harlan, S L, Stefanov, W L & Martin, C A (2011) Ecosystem services and urban heat riskscape moderation: water, green spaces, and social inequality in Phoenix, USA. *Ecological Applications,* **21 (7),** 2637-2651.

Jeppesen, B (1996) Domestic greywater re-use: Australia's challenge for the future. *Desalination,* **106 (1),** 311-315.

Jim, C & Chen, W Y (2009) Ecosystem services and valuation of urban forests in China. *Cities,* **26 (4),** 187-194.

Jim, C & Tsang, S (2011) Biophysical properties and thermal performance of an intensive green roof. *Building and Environment,* **46 (6),** 1263-1274.

Jim, C & Peng, L L (2012) Weather effect on thermal and energy performance of an extensive tropical green roof. *Urban Forestry & Urban Greening,* **11 (1),** 73-85.

Jiménez, B (2006) Irrigation in developing countries using wastewater. *International Review for Environmental Strategies,* **6 (2),** 229-250.

Jones, H G (1998a) Stomatal control of photosynthesis and transpiration. *Journal of Experimental Botany,* **49 (Special Issue),** 387-398.

Jones, H G, Stoll, M, Santos, T, Sousa, C d, Chaves, M M & Grant, O M (2002) Use of infrared thermography for monitoring stomatal closure in the field: application to grapevine. *Journal of Experimental Botany,* **53 (378),** 2249-2260.

Jones, H G (2004) Irrigation scheduling: advantages and pitfalls of plant-based methods. *Journal of Experimental Botany,* **55 (407),** 2427-2436.

Jones, J B (1998b) *Plant Nutrition Manual*. CRC Press LLC: London.

Jones, M P & Hunt, W F (2010) Performance of rainwater harvesting systems in the southeastern United States. *Resources, Conservation and recycling,* **54 (10),** 623-629.

Kaboosi, K (2016) The assessment of treated wastewater quality and the effects of mid-term irrigation on soil physical and chemical properties (case study: Bandargaz-treated wastewater). *Applied Water Science***,** 1-12.

Kashyap, P S & Panda, R K (2001) Evaluation of evapotranspiration estimation methods and development of crop-coefficients for potato crop in a sub-humid region. *Agricultural Water Management,* **50 (1),** 9-25.

Kaufmann, M R (1990) Estimating tree canopy transpiration from measurements of leaf conductance. *In: Measurement Techniques in Plant Science.* Hashimoto, Y, Kramer, P J, Nonami, H & Strain, B R, (eds.) Academic Press, Inc.: London.

Kent, M (2000) *Advanced Biology*. Oxford University Press: Oxford.

Kittas, C, Baille, A & Giaglaras, P (1999) Influence of Covering Material and Shading on the Spectral Distribution of Light in Greenhouses. *Journal of Agricultural Engineering Research,* **73 (4),** 341-351.

Köhler, M (2002) Green roofs in temperate climates and in the hot-humid tropics – far beyond the aesthetics. *Environmental management and health,* **13 (4),** 382-391.

Kramer, P J & Boyer, J S (1995) *Water relations of plants and soils*. Academic Press Inc.: London.

Lazzarin, R M, Castellotti, F & Busato, F (2005) Experimental measurements and numerical modelling of a green roof. *Energy and Buildings,* **37 (12),** 1260-1267.

Li, F, Wichmann, K & Otterpohl, R (2009) Review of the technological approaches for grey water treatment and reuses. *Science of the Total Environment,* **407 (11),** 3439-3449.

Li, J-F, Wai, O W H, Li, Y S, Zhan, J-M, Ho, Y A, Li, J & Lam, E (2010a) Effect of green roof on ambient CO2 concentration. *Building and Environment,* **45 (12),** 2644-2651.

Li, Z, Boyle, F & Reynolds, A (2010b) Rainwater harvesting and greywater treatment systems for domestic application in Ireland. *Desalination,* **260 (1),** 1-8.

Liu, C, Zhang, X & Zhang, Y (2002) Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter. *Agricultural and Forest Meteorology,* **111 (2),** 109-120.

Liu, T-C, Shyu, G-S, Fang, W-T, Liu, S-Y & Cheng, B-Y (2012) Drought tolerance and thermal effect measurements for plants suitable for extensive green roof planting in humid subtropical climates. *Energy and Buildings,* **47,** 180-188.

Locatelli, L, Mark, O, Mikkelsen, P S, Arnbjerg-Nielsen, K, Bergen Jensen, M & Binning, P J (2014) Modelling of green roof hydrological performance for urban drainage applications. *Journal of Hydrology,* **519, Part D,** 3237-3248.

Lundholm, J, MacIvor, J S, MacDougall, Z & Ranalli, M (2010) Plant species and functional group combinations affect green roof ecosystem functions. *Plos One,* **5 (3),** e9677.

Lundholm, J, Tran, S & Gebert, L (2015) Plant Functional Traits Predict Green Roof Ecosystem Services. *Environmental Science & Technology,* **49 (4),** 2366-2374.

Lundholm, J T, Weddle, B M & MacIvor, J S (2014) Snow depth and vegetation type affect green roof thermal performance in winter. *Energy and Buildings,* **84,** 299-307.

MacIvor, J S & Lundholm, J (2011) Performance evaluation of native plants suited to extensive green roof conditions in a maritime climate. *Ecological Engineering,* **37 (3),** 407-417.

MacIvor, J S, Margolis, L, Puncher, C L & Carver Matthews, B J (2013) Decoupling factors affecting plant diversity and cover on extensive green roofs. *Journal of Environmental Management,* **130,** 297-305.

MacIvor, J S, Margolis, L, Perotto, M & Drake, J A P (2016) Air temperature cooling by extensive green roofs in Toronto Canada. *Ecological Engineering,* **95,** 36-42.

Marschner, H (1995) *Mineral Nutrition of Higher Plants*, 2nd ed. Academic Press Ltd.: London.

Martín, M, Gargallo, S, Hernández-Crespo, C & Oliver, N (2013) Phosphorus and nitrogen removal from tertiary treated urban wastewaters by a vertical flow constructed wetland. *Ecological Engineering,* **61, Part A,** 34-42.

Mendez, C B, Klenzendorf, J B, Afshar, B R, Simmons, M T, Barrett, M E, Kinney, K A & Kirisits, M J (2011) The effect of roofing material on the quality of harvested rainwater. *Water Research,* **45 (5),** 2049-2059.

Mentens, J, Raes, D & Hermy, M (2006) Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and urban planning,* **77 (3),** 217-226.

Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-Being: Synthesis,* Island Press: Washington, DC.

Misra, R, Patel, J H & Baxi, V (2010) Reuse potential of laundry greywater for irrigation based on growth, water and nutrient use of tomato. *Journal of Hydrology,* **386 (1),** 95-102.

Misra, R K & Sivongxay, A (2009) Reuse of laundry greywater as affected by its interaction with saturated soil. *Journal of Hydrology,* **366 (1),** 55-61.

Mohamed, R M S R, Kassim, A H M, Anda, M & Dallas, S (2013) A monitoring of environmental effects from household greywater reuse for garden irrigation. *Environmental Monitoring and Assessment,* **185 (10),** 8473-8488.

Moritani, S, Yamamoto, T, Andry, H, Inoue, M, Kato, K & Saito, H (2013) Effect of combined water and salinity stress factors on evapotranspiration of *Sedum kamtschaticum* Fisher in relation to green roof irrigation. *Urban Forestry & Urban Greening,* **12,** 338-343.

Nadav, I, Tarchitzky, J & Chen, Y (2013) Induction of soil water repellency following irrigation with treated wastewater: effects of irrigation water quality and soil texture. *Irrigation Science,* **31 (3),** 385-394.

Nagase, A & Dunnett, N (2010) Drought tolerance in different vegetation types for extensive green roofs: Effects of watering and diversity. *Landscape and Urban Planning,* **97 (4),** 318-327.

Nagase, A & Dunnett, N (2012) Amount of water runoff from different vegetation types on extensive green roofs: Effects of plant species, diversity and plant structure. *Landscape and Urban Planning,* **104 (3-4),** 356-363.

Nagase, A & Dunnett, N (2013) Performance of geophytes on extensive green roofs in the United Kingdom. *Urban Forestry & Urban Greening,* **12 (4),** 509-521.

Nawaz, R, McDonald, A & Postoyko, S (2015) Hydrological performance of a full-scale extensive green roof located in a temperate climate. *Ecological Engineering,* **82,** 66-80.

Netusil, N R, Levin, Z, Shandas, V & Hart, T (2014) Valuing green infrastructure in Portland, Oregon. *Landscape and Urban Planning,* **124,** 14-21.

Ng, E, Chen, L, Wang, Y & Yuan, C (2012) A study on the cooling effects of greening in a high-density city: An experience from Hong Kong. *Building and Environment,* **47,** 256-271.

Niemczynowicz, J (1999) Urban hydrology and water management–present and future challenges. *Urban water,* **1 (1),** 1-14.

Nouri, H, Beecham, S, Hassanli, A M & Kazemi, F (2013) Water requirements of urban landscape plants: A comparison of three factor-based approaches. *Ecological Engineering,* **57,** 276-284.

Nowak, D J & Crane, D E (2002) Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution,* **116 (3),** 381-389.

Noya, M G, Cuquel, F L, Schafer, G & Armindo, R A (2017) Substrates for cultivating herbaceous perennial plants in extensive green roofs. *Ecological Engineering,* **102,** 662-669.

Oberndorfer, E, Lundholm, J, Bass, B, Coffman, R R, Doshi, H, Dunnett, N, Gaffin, S, Köhler, M, Liu, K K & Rowe, B (2007) Green roofs as urban ecosystems: ecological structures, functions, and services. *BioScience,* **57 (10),** 823-833.

Oke, T R (1987) *Boundary Layer Climates*, 2nd ed. Routledge: London.

Ouldboukhitine, S-E, Belarbi, R, Jaffal, I & Trabelsi, A (2011) Assessment of green roof thermal behavior: A coupled heat and mass transfer model. *Building and Environment,* **46 (12),** 2624-2631.

Ouldboukhitine, S-E, Spolek, G & Belarbi, R (2014) Impact of plants transpiration, grey and clean water irrigation on the thermal resistance of green roofs. *Ecological Engineering,* **67,** 60-66.

Oxlade, E (2007) *Plant Physiology: The structure of Plants Explained*. Studymates Ltd.: Abergele, UK.

Papadakis, G, Briassoulis, D, Mugnozza, G S, Vox, G, Feuilloley, P & Stoffers, J (2000) Review Paper (SE—Structures and Environment): Radiometric and thermal properties of, and testing methods for, greenhouse covering materials. *Journal of Agricultural Engineering Research,* **77 (1),** 7-38.

Pataki, D E, Carreiro, M M, Cherrier, J, Grulke, N E, Jennings, V, Pincetl, S, Pouyat, R V, Whitlow, T H & Zipperer, W C (2011) Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. *Frontiers in Ecology and the Environment,* **9 (1),** 27-36.

Pérez, G, Rincón, L, Vila, A, González, J M & Cabeza, L F (2011) Green vertical systems for buildings as passive systems for energy savings. *Applied energy,* **88 (12),** 4854-4859.

Pescod, M (1992) *Wastewater treatment and use in agriculture - FAO irrigation and drainage paper 47*: FAO, Rome.

Pinto, U & Maheshwari, B (2010) Reuse of greywater for irrigation around homes in Australia: Understanding community views, issues and practices. *Urban Water Journal,* **7 (2),** 141-153.

Pinto, U, Maheshwari, B & Grewal, H (2010) Effects of greywater irrigation on plant growth, water use and soil properties. *Resources, Conservation and Recycling,* **54 (7),** 429-435.

Poë, S, Stovin, V & Berretta, C (2015) Parameters influencing the regeneration of a green roof's retention capacity via evapotranspiration. *Journal of Hydrology,* **523,** 356-367.

Prodanovic, V, Hatt, B, McCarthy, D, Zhang, K & Deletic, A (2017) Green walls for greywater reuse: Understanding the role of media on pollutant removal. *Ecological Engineering,* **102,** 625-635.

Rayner, J P, Farrell, C, Raynor, K J, Murphy, S M & Williams, N S G (2016) Plant establishment on a green roof under extreme hot and dry conditions: The importance of leaf succulence in plant selection. *Urban Forestry & Urban Greening,* **15,** 6-14.

Razzaghmanesh, M, Beecham, S & Kazemi, F (2014) Impact of green roofs on stormwater quality in a South Australian urban environment. *Science of The Total Environment,* **470–471,** 651-659.

Reichman, S M & Wightwick, A M (2013) Impacts of standard and 'low environmental impact' greywater irrigation on soil and plant nutrients and ecology. *Applied Soil Ecology,* **72,** 195-202.

Rodda, N, Carden, K, Armitage, N & Du Plessis, H (2011a) Development of guidance for sustainable irrigation use of greywater in gardens and small-scale agriculture in South Africa. *Water SA,* **37 (5),** 727-737.

Rodda, N, Salukazana, L, Jackson, S & Smith, M (2011b) Use of domestic greywater for small-scale irrigation of food crops: Effects on plants and soil. *Physics and Chemistry of the Earth, Parts A/B/C,* **36 (14),** 1051-1062.

Rodríguez-Liébana, J A, ElGouzi, S, Mingorance, M D, Castillo, A & Peña, A (2014) Irrigation of a Mediterranean soil under field conditions with urban wastewater: Effect on pesticide behaviour. *Agriculture, Ecosystems & Environment,* **185,** 176-185.

Rowe, D B, Kolp, M R, Greer, S E & Getter, K L (2014) Comparison of irrigation efficiency and plant health of overhead, drip, and sub-irrigation for extensive green roofs. *Ecological Engineering,* **64,** 306-313.

Sadler, J, Bates, A, Hale, J & James, P (2010) Bringing cities alive: the importance of urban green spaces for people and biodiversity. *In: Urban Ecology.* Gaston, K J, (ed.) Cambridge University Press: Cambridge.

Sailor, D J, Hutchinson, D & Bokovoy, L (2008) Thermal property measurements for ecoroof soils common in the western U.S. *Energy and Buildings,* **40 (7),** 1246-1251.

Savi, T, Dal Borgo, A, Love, V L, Andri, S, Tretiach, M & Nardini, A (2016) Drought versus heat: What's the major constraint on Mediterranean green roof plants? *Science of The Total Environment,* **566–567,** 753-760.

Sawadogo, B, Sou, M, Hijikata, N, Sangare, D, Maiga, A H & Funamizu, N (2014) Effect of detergents from grey water on irrigated plants: Case of Okra (Abelmoschus esculentus) and Lettuce (Lactuca sativa). *J. Arid Land,* **24 (1),** 117-120.

Schneider, D (2011) *Quantifying evapotranspiration from a green roof analytically.* Master's thesis, Villanova University.

Schneider, D, Wadzuk, B M & Traver, R G. (2011) Using a Weighing Lysimeter to Determine a Crop Coefficient for a Green Roof to Predict Evapotranspiration with the FAO Standardized Penman-Monteith Equation. World Environmental and Water Resources Congress, 2011. 3629-3638.

Seidl, M, Gromaire, M-C, Saad, M & De Gouvello, B (2013) Effect of substrate depth and rain-event history on the pollutant abatement of green roofs. *Environmental Pollution,* **183,** 195-203.

Sharvelle, S, Roesner, L A, Qian, Y, Stromberger, M & Azar, M N (2012) *Long-term Study on Landscape Irrigation Using Household Graywater - Experimental Study,* Water Environment Research Foundation: Colorado State University, USA.

Sherrard, J A & Jacobs, J M (2012) Vegetated roof water-balance model: experimental and model results. *Journal of Hydrologic Engineering,* **17 (8),** 858-868.

Siggins, A, Burton, V, Ross, C, Lowe, H & Horswell, J (2016) Effects of long-term greywater disposal on soil: A case study. *Science of The Total Environment,* **557–558,** 627-635.

Silva, M D F M, Calijuri, M L, de Sales, F J F, de Souza, M H B & Lopes, L S (2014) Integration of technologies and alternative sources of water and energy to promote the sustainability of urban landscapes. *Resources, Conservation and Recycling,* **91,** 71-81.

Simmons, R W, Ahmad, W, Noble, A D, Blummel, M, Evans, A & Weckenbrock, P (2010) Effect of long-term un-treated domestic wastewater re-use on soil quality, wheat grain and straw yields and attributes of fodder quality. *Irrigation and Drainage Systems,* **24 (1-2),** 95-112.

Sims, A W, Robinson, C E, Smart, C C, Voogt, J A, Hay, G J, Lundholm, J T, Powers, B & O'Carroll, D M (2016) Retention performance of green roofs in three different climate regions. *Journal of Hydrology,* **542,** 115-124.

Smith, A M, Coupland, G, Dolan, L, Harberd, N, Jones, J, Martin, C, Sablowski, R & Amey, A (2010) *Plant Biology*. Garland Science: Abingdon.

Snyder, R L, Pedras, C, Montazar, A, Henry, J M & Ackley, D (2015) Advances in ET-based landscape irrigation management. *Agricultural Water Management,* **147,** 187-197.

Soulis, K X, Ntoulas, N, Nektarios, P A & Kargas, G (2017) Runoff reduction from extensive green roofs having different substrate depth and plant cover. *Ecological Engineering,* **102,** 80-89.

Speak, A, Rothwell, J, Lindley, S & Smith, C (2013) Rainwater runoff retention on an aged intensive green roof. *Science of The Total Environment,* **461,** 28-38.

Speak, A F, Rothwell, J J, Lindley, S J & Smith, C L (2012) Urban particulate pollution reduction by four species of green roof vegetation in a UK city. *Atmospheric Environment,* **61,** 283-293.

Speak, A F, Rothwell, J J, Lindley, S J & Smith, C L (2014) Metal and nutrient dynamics on an aged intensive green roof. *Environmental Pollution,* **184,** 33-43.

Starry, O, Lea-Cox, J D, Kim, J & van Iersel, M W (2014) Photosynthesis and water use by two Sedum species in green roof substrate. *Environmental and Experimental Botany,* **107,** 105-112.

Sternberg, T, Viles, H & Cathersides, A (2011) Evaluating the role of ivy (*Hedera helix*) in moderating wall surface microclimates and contributing to the bioprotection of historic buildings. *Building and Environment,* **46 (2),** 293-297.

Stovin, V, Vesuviano, G & Kasmin, H (2012) The hydrological performance of a green roof test bed under UK climatic conditions. *Journal of Hydrology,* **414-415,** 148-161.

Stovin, V, Poë, S & Berretta, C (2013) A modelling study of long term green roof retention performance. *Journal of Environmental Management,* **131,** 206-215.

Stovin, V, Poë, S, De-Ville, S & Berretta, C (2015) The influence of substrate and vegetation configuration on green roof hydrological performance. *Ecological Engineering,* **85,** 159-172.

Taha, H (1997) Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat. *Energy and buildings,* **25 (2),** 99-103.

Taiz, L & Zeiger, E (2006) *Plant Physiology*, 4th ed. Sinauer Associates, Inc.: Sunderland, Massachusetts.

Tan, C L, Wong, N H, Tan, P Y, Jusuf, S K & Chiam, Z Q (2015) Impact of plant evapotranspiration rate and shrub albedo on temperature reduction in the tropical outdoor environment. *Building and Environment,* **94, Part 1,** 206-217.

Teemusk, A & Mander, Ü (2007) Rainwater runoff quantity and quality performance from a greenroof: The effects of short-term events. *Ecological Engineering,* **30 (3),** 271-277.

Travis, M J, Weisbrod, N & Gross, A (2008) Accumulation of oil and grease in soils irrigated with greywater and their potential role in soil water repellency. *Science of The Total Environment,* **394 (1),** 68-74.

Travis, M J, Wiel-Shafran, A, Weisbrod, N, Adar, E & Gross, A (2010) Greywater reuse for irrigation: Effect on soil properties. *Science of the Total Environment,* **408 (12),** 2501-2508.

Türker, O C, Vymazal, J & Türe, C (2014) Constructed wetlands for boron removal: A review. *Ecological Engineering,* **64,** 350-359.

Turner, R D R, Will, G D, Dawes, L A, Gardner, E A & Lyons, D J (2013) Phosphorus as a limiting factor on sustainable greywater irrigation. *Science of The Total Environment,* **456–457,** 287-298.

Tyagi, N K, Sharma, D K & Luthra, S K (2000) Determination of evapotranspiration and crop coefficients of rice and sunflower with lysimeter. *Agricultural Water Management,* **45 (1),** 41-54.

United Nations (2015) *World Urbanization Prospects: The 2014 Revision (ST/ESA/SER.A/366),* United Nations, Department of Economic and Social Affairs, Population Division.

UoR AO Weather data. URL: http://www.met.reading.ac.uk/weatherdata/ [Online]. [Accessed 7 October].

USDA (2017) i-Tree species. URL: https://species.itreetools.org/ [Online]. [Accessed 12 June].

Valdés-Gómez, H, Ortega-Farías, S & Argote, M (2009) Evaluation of water requirements for a greenhouse tomato crop using the Priestley-Taylor method. *Chilean Journal of Agricultural Research,* **69 (1),** 3-11.

Van Mechelen, C, Dutoit, T, Kattge, J & Hermy, M (2014) Plant trait analysis delivers an extensive list of potential green roof species for Mediterranean France. *Ecological Engineering,* **67,** 48-59.

Van Mechelen, C, Dutoit, T & Hermy, M (2015) Adapting green roof irrigation practices for a sustainable future: A review. *Sustainable Cities and Society,* **19,** 74-90.

Van Seters, T, Rocha, L, Smith, D & MacMillan, G (2009) Evaluation of green roofs for runoff retention, runoff quality, and leachability. *Water quality research journal of Canada,* **44 (1),** 33-47.

VanWoert, N D, Rowe, D B, Andresen, J A, Rugh, C L, Fernandez, R T & Xiao, L (2005) Green roof stormwater retention. *Journal of environmental quality,* **34 (3),** 1036-1044.

Vaz Monteiro, M (2014) *Plants and temperature regulation: The impact of leaf and plant structure and function on leaf temperature and the surface energy balance.* PhD thesis, University of Reading.

Vaz Monteiro, M, Blanusa, T, Verhoef, A, Hadley, P & Cameron, R (2016a) Relative importance of transpiration rate and leaf morphological traits for the regulation of leaf temperature. *Australian Journal of Botany,* **64 (1),** 32-44.

Vaz Monteiro, M, Doick, K J, Handley, P & Peace, A (2016b) The impact of greenspace size on the extent of local nocturnal air temperature cooling in London. *Urban Forestry & Urban Greening,* **16 (Supplement C),** 160-169.

Vaz Monteiro, M, Blanuša, T, Verhoef, A, Richardson, M, Hadley, P & Cameron, R W F (2017) Functional green roofs: Importance of plant choice in maximising summertime environmental cooling and substrate insulation potential. *Energy and Buildings,* **141,** 56-68.

Verhoef, A & Campbell, C L (2005) Evaporation measurement. *In: Encyclopedia of Hydrological Sciences.* Vol. 1. Anderson, M G, (ed.) John Wiley & Sons, Ltd.: Chichester, UK.

Verhoef, A & Egea, G (2013) Soil water and its management. *In: Soil Conditions and Plant Growth.* Gregory, P J & Nortcliff, S, (eds.) Blackwell Publishing Ltd: Oxford.

Vijayaraghavan, K, Joshi, U & Balasubramanian, R (2012) A field study to evaluate runoff quality from green roofs. *Water research,* **46 (4),** 1337-1345.

Villarreal, E L & Bengtsson, L (2005) Response of a *Sedum* green-roof to individual rain events. *Ecological Engineering,* **25 (1),** 1-7.

Volder, A & Dvorak, B (2014) Event size, substrate water content and vegetation affect storm water retention efficiency of an un-irrigated extensive green roof system in Central Texas. *Sustainable Cities and Society,* **10,** 59-64.

Voyde, E, Fassman, E & Simcock, R (2010a) Hydrology of an extensive living roof under sub-tropical climate conditions in Auckland, New Zealand. *Journal of Hydrology,* **394 (3–4),** 384-395.

Voyde, E, Fassman, E, Simcock, R & Wells, J (2010b) Quantifying evapotranspiration rates for New Zealand green roofs. *Journal of Hydrologic Engineering,* **15 (6),** 395-403.

Whittinghill, L J, Rowe, D B, Andresen, J A & Cregg, B M (2015) Comparison of stormwater runoff from sedum, native prairie, and vegetable producing green roofs. *Urban Ecosystems,* **18 (1),** 13-29.

Whittinghill, L J, Hsueh, D, Culligan, P & Plunz, R (2016) Stormwater performance of a full scale rooftop farm: Runoff water quality. *Ecological Engineering,* **91,** 195-206.

Wiel-Shafran, A, Ronen, Z, Weisbrod, N, Adar, E & Gross, A (2006) Potential changes in soil properties following irrigation with surfactant-rich greywater. *Ecological Engineering,* **26 (4),** 348-354.

Wigley, T M L (2005) The Climate Change Commitment. *Science,* **307 (5716),** 1766-1769.

Winward, G P, Avery, L M, Frazer-Williams, R, Pidou, M, Jeffrey, P, Stephenson, T & Jefferson, B (2008) A study of the microbial quality of grey water and an evaluation of treatment technologies for reuse. *Ecological engineering,* **32 (2),** 187-197.

Withers, B & Vipond, S (1974) *Irrigation: design and practice*. Batsford Academic and Educational Limited: London.

Wolf, D & Lundholm, J T (2008) Water uptake in green roof microcosms: Effects of plant species and water availability. *Ecological Engineering,* **33 (2),** 179-186.

Wong, N H, Chen, Y, Ong, C L & Sia, A (2003) Investigation of thermal benefits of rooftop garden in the tropical environment. *Building and environment,* **38 (2),** 261-270.

Wong, N H, Kwang Tan, A Y, Chen, Y, Sekar, K, Tan, P Y, Chan, D, Chiang, K & Wong, N C (2010) Thermal evaluation of vertical greenery systems for building walls. *Building and environment,* **45 (3),** 663-672.

Yang, J, Yu, Q & Gong, P (2008) Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment,* **42 (31),** 7266-7273.

Yu, C & Hien, W N (2006) Thermal benefits of city parks. *Energy and Buildings,* **38 (2),** 105-120.

Zhang, Q, Miao, L, Wang, X, Liu, D, Zhu, L, Zhou, B, Sun, J & Liu, J (2015) The capacity of greening roof to reduce stormwater runoff and pollution. *Landscape and Urban Planning,* **144,** 142-150.

Appendix

A.1 Manufacturer's product information sheet for meadow Roof Medium substrate used in Experiments 1, 2, 4 and 5.

MEADOW ROOF MEDIUM

VitalEarth

Product Overview

Ingredients

5-2 mm clean brick, dust-free

10-0 mm green compost, PAS100 2011

Recommended Uses

Meadow roofs: established using plant mat, seed or transplants.

Can be installed using a Blower Truck or more conventional methods.

Key Benefits

A well-researched medium made entirely from recycled sustainable materials.
Gives excellent establishment & survival even under harsh/wet conditions.
Nil slumping.

Humified woody material hosts disease-suppressive fungi e.g. Trichoderma spp.

Advice: not recommended for drought-intolerant subjects

Always check the load-bearing properties of the roof before installation, allowing for heavy rainfall.
Follow safety procedures.

Footnotes:

[1] This should not be compared with pH of peat products (the optimal pH of peat products is much lower than for soil and composted materials).
[2] 'CAT' = aqueous solution of calcium chloride + DTPA (chelating agent) - an extractant originally developed for soils and now specified in UK and
European standards for composted materials (e.g. PAS100) because it is more appropriate for most nutrients than the water-extraction method originally developed for peat products only.

For more information on all our services and products, please call 01335 300355, email info@vitalearth.tv or visit our website www.thegreenergardener.com

Purchase Options & Application Rates		
Size:	1000 L IBC's, 20 L bags, or bulk	
Application Rates:	150 L/m^2 at 150mm depth	
Properties: typical values		
Load: as received	112 kg/m^2	
Load: saturated	151 kg/m^2	
Air-Filled Porosity	10cm tension	48% v/v
Water-Holding Capacity	10cm tension	26% v/v
Solids	10cm tension	27%v/v
Saturated hydraulic conductivity		**0.24 cm/s**
Particle size range	mm	**100%m/m <10mm**
Bulk Density	g/l	**750**
Moisture Content	%m/m	**10**
Moisture Content	g/l	**75**
Dry Matter (DM)	g/l	**675**
Organic matter	% DM	**3.5**
Carbon: Nitrogen Ratio	% DM	**13:1**
pH[1]		**7.7**
Electrical Conductivity	µS/cm	**1500**
Electrical Conductivity	mS/M	**150**
Stability: $mgCO_2$/g Organic matter		**12**
Physical Contaminants	Meets PAS100 2011	
Potentially toxic elements including heavy metals	Meets PAS100 2011	
Weeds	Meets PAS100 2011	

Nutrients

As received (fresh basis)	Total mg/l	CAT[2] soluble mg/l	Water soluble mg/l	% Water/ Total
Nitrogen (N)	**1200**	**NA**	**15**	**12.5**
Phosphorus (P)	**474**	**8**	**0**	**0**
Potassium (K)	**NA**	**310**	**NA**	**NA**
Calcium (Ca)	**NA**	**NA**	**NA**	**NA**
Magnesium (Mg)	**NA**	**53**	**NA**	**NA**
Iron (Fe)	**NA**	**19**	**NA**	**NA**
Manganese (Mn)	**NA**	**8**	**NA**	**NA**

A.2 Chemical and physical properties of the peat-based compost used in Experiment 3 (analysed and reported by NRM Laboratories Ltd., Bracknell, UK).

Parameter	Units	Value	Parameter	Units	Value
pH	-	5.7	**Conductivity at 20°**	µS cm^{-1}	555
Density	kg m^{-3}	339	**Ammonia-N**	mg L^{-1}	22.8
Dry matter	%	34.2	**Nitrate-N**	mg L^{-1}	257.9
Dry density	kg m^{-3}	115.9	**Total soluble N**	mg L^{-1}	280.7
Chloride	mg L^{-1}	24.3	**Sulphate**	mg L^{-1}	370.6
Phosphorus	mg L^{-1}	84	**Boron**	mg L^{-1}	0.1
Potassium	mg L^{-1}	246.2	**Copper**	mg L^{-1}	0.13
Magnesium	mg L^{-1}	163.7	**Manganese**	mg L^{-1}	0.29
Calcium	mg L^{-1}	136.2	**Zinc**	mg L^{-1}	0.94
Sodium	mg L^{-1}	36.7	**Iron**	mg L^{-1}	1.33

A.3 Chemical and physical properties of the vermiculite: peat-based compost 50:50 mixed substrate used in Experiment 6 (as reported by NRM Laboratories Ltd., Bracknell, UK).

Parameter	Units	Value	Parameter	Units	Value
pH	-	6.1	**Conductivity at 20°**	μScm^{-1}	382
Density	kgm^{-3}	285	**Ammonia-N**	mgl^{-1}	11.9
Dry matter	%	49.7	**Nitrate-N**	mgl^{-1}	169.9
Dry density	kgm^{-3}	141.6	**Total soluble N**	mgl^{-1}	181.8
Chloride	mgl^{-1}	14.9	**Sulphate**	mgl^{-1}	256.4
Phosphorus	mgl^{-1}	34.3	**Boron**	mgl^{-1}	0.06
Potassium	mgl^{-1}	187.6	**Copper**	mgl^{-1}	0.17
Magnesium	mgl^{-1}	113.3	**Manganese**	mgl^{-1}	0.38
Calcium	mgl^{-1}	70.1	**Zinc**	mgl^{-1}	0.52
Sodium	mgl^{-1}	28.5	**Iron**	mgl^{-1}	0.9