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Parameters Influencing the Regeneration of a Green Roof's Retention Capacity via Evapotranspiration

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ABSTRACT

The extent to which the finite hydrological capacity of a green roof is available for retention of a storm event largely determines the scale of its contribution as a Sustainable Drainage System (SuDS). Evapotranspiration (ET) regenerates the retention capacity at a rate that is variably influenced by climate, vegetation treatment, soil and residual moisture content. Experimental studies have been undertaken to monitor the drying cycle behaviour of 9 different extensive green roof configurations with 80 mm substrate depth. A climate-controlled chamber at the University of Sheffield replicated typical UK spring and summer diurnal cycles. The mass of each microcosm, initially at field capacity, was continuously recorded, with changes inferred to be moisture loss/gain (or ET/dew). The ranges of cumulative ET following a 28 day dry weather period (ADWP) were 0.6-1.0 mm/day in spring and 0.7-1.25 mm/day in summer. These ranges reflect the influence of configuration on ET. Cumulative ET was highest from substrates with the greatest storage capacity. Significant differences in ET existed between vegetated and non-vegetated configurations. Initially, seasonal mean ET was affected by climate. Losses were 2.0 mm/day in spring and 3.4 mm/day in summer. However, moisture availability constrained ET, which fell to 1.4 mm/day then 1.0 mm/day (with an ADWP of 7 and 14 days) in spring; compared to 1.0 mm/day and 0.5 mm/day in summer. A modelling approach, which factors potential evapotranspiration (PET) according to stored moisture content, predicts daily ET with very good accuracy (PBIAS = 2.0% [spring]; -0.8% [summer]).

KEY WORDS: Evapotranspiration, Green Roofs, Stormwater Management, SuDS, Retention

ABBREVIATIONS

ADWP	Antecedent Dry Weather Period
CAM	Crassulacean Acid Metabolism
ET	Evapotranspiration
ET_{CUM}	Cumulative Evapotranspiration
ET_{D}	Daily Evapotranspiration
ET_{O}	Reference Evapotranspiration
ET_{Pred}	Predicted Evapotranspiration
FAO-56	FAO-56 Penman-Monteith

FLL	Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (German Landscape Research, Development and Construction Society)
HLS	Heather & Lavender Substrate
LECA	Lightweight Expanded Clay Aggregate
MWHC	Maximum Water-Holding Capacity, as defined by FLL
PBIAS	Percent Bias
PET	Potential Evapotranspiration
SCS	Sedum Carpet Substrate
S_{MAX}	Maximum moisture storage capacity
SMD_t	Soil Moisture Deficit or retention capacity at time, t
SMEF	Soil Moisture Extraction Function
S_t	Residual stored moisture content at time, t
S_{VEG}	Vegetation moisture storage capacity
SuDS	Sustainable Drainage System
TB	Test bed
θ	Volumetric water content
θ_{FC}	Volumetric water content at field capacity
θ_{PWP}	Volumetric water content at permanent wilting point

$\theta_{<PWP}$	Hygroscopic volumetric water content
ψ_m	Matric potential

1 INTRODUCTION

Green roofs reduce rainfall runoff rates due to the plant cover (by interception), the substrate (by detention and retention for evapotranspiration [ET]) and the additional storage capacity in the underlying drainage reservoir. However, the extent of the hydrological benefit that green roofs provide within the Sustainable Drainage Systems (SuDS) management train is not well-quantified. A number of green roof hydrological research programmes, typically from temperate mid-latitudes, have reported variable retention levels – with average annual retention typically between 30 and 86% (Li & Babcock, 2014) and per event retention between 0 and 100% (Berghage et al., 2007, Stovin et al., 2012). There are, however, physical factors influencing this variability.

The hydrological cycle is driven by gravitational forces and solar energy; inducing moisture vapour transfer from the earth's surface to the atmosphere via ET. The rate at which this transfer takes place is important to a green roof's response to a subsequent storm event. Voyde et al. (2010) highlighted that "green roof ET has not been well quantified or thoroughly modelled" due to the absence of experimental data to underpin the modelling of ET losses for different vegetation treatments and climatic conditions.

There are three key, but interdependent, processes involved during ET; firstly, an upward capillary flux through the soil profile towards the soil's upper horizons; secondly, evaporative losses from the surface to atmosphere; and thirdly, transpiration of soil-water by plants. Forces inducing evaporation and transpiration losses are a function of the microclimate (i.e. solar radiation, air temperature, wind, relative humidity) and of the plant's physiology. However, the rate at which these forces induce ET depends upon the soil-water characteristics of the substrate (i.e. field capacity [θ_{FC}], permanent wilting point [θ_{PWP}], permeability), any additional moisture storage capacity within the vegetation layer and the plant's physiological response at the prevailing moisture content (Koehler & Schmidt, 2008).

1.1 The importance of moisture balance to ET

The soil-water characteristics of a green roof are an important control upon ET. All drainage systems have a finite capacity to store water (or moisture). The maximum moisture storage capacity (S_{MAX}) of a green roof will seldom be fully available (Berghage et al., 2007; Stovin et al., 2012) due to the presence of residual stored moisture, S_t (Koehler & Schmidt, 2008). During dry periods between storm events ET reduces S_t and increases the retention capacity, or soil moisture deficit (SMD_t). ET rates are expected to decay exponentially with respect to time (Fassman & Simcock, 2011; Kasmin et al., 2010) as available moisture reduces. However, in isolation, the length of the drying cycle – or Antecedent Dry Weather Period (ADWP) – "fails to characterise the complex processes that account for the roof's residual moisture content" (Stovin et al., 2012). Moisture content has consistently been seen to depend upon soil-water characteristics and plant interactions (Berretta et al., 2014). The key moisture balance terms are shown in Figure 1.

[Approximate location of Figure 1]

The terms SMD_t and S_{MAX} have been used as overarching indicators of moisture balance in green roof systems. However, these terms have previously typically been thought to consist only of substrate moisture. In vegetated systems, the vegetation will provide some additional moisture storage capacity. Here, S_{MAX} includes both plant-available moisture in the substrate (i.e. θ_{FC} minus θ_{PWP}, and therefore excluding hygroscopic moisture, $\theta_{<PWP}$) and moisture held within the vegetation itself (S_{VEG}). Equally, the capacity available for retention (SMD_t) includes the moisture deficit in both the substrate and the vegetation (i.e. S_{MAX} minus S_t).

Many methods of estimating ET assume that moisture is in abundant supply (Wilson, 1990) and that, therefore, ET will not be constrained by the SMD_t. However, it is important to differentiate Potential Evapotranspiration (PET) from ET, as they will only be equal for the relatively short period of time when the green roof is at, or very near to, S_{MAX}. Thereafter, ET will be constrained by the SMD_t. Accordingly, any models that function on the premise that ET equals PET will typically over-predict ET losses (and underestimate runoff). The decay of ET as a proportion of PET (ET/PET) is a key modelling parameter that must account for moisture availability (Stovin et al., 2013); it is variably influenced by climatic conditions and plant and soil characteristics (Berretta et al., 2014).

1.2 Differences in ET due to climate

Previous research (Rezaei & Jarrett, 2006; Koehler & Schmidt, 2008; Fassman & Simcock, 2008) has identified that climatological factors (e.g. solar radiation, air temperature and relative humidity [RH]) affect ET rates; partially explaining the geographical differences in green roof retention response. Retention is typically higher in warmer conditions (Locatelli et al., 2014) and in arid or semi-arid climates, where annual average retention is typically higher (e.g. 74% in Australia according to Razzaghmanesh & Beecham, 2014) compared with temperate climates (e.g. 32-57% in Scandinavia according to Locatelli et al., 2014). Seasonal differences in ET have been identified (Rezaei & Jarrett, 2006; Koehler & Schmidt, 2008; Marasco et al., 2014), with the highest daily ET rates observed in warm summer conditions. Rezaei & Jarrett (2006) identified that ET rates from an extensive green roof (vegetated with 80% Delosperma nubigenum and 20% Sedum album) in Pennsylvania State were approximately four times greater in high summer (3.23 mm/day) compared to winter (averaging 0.79 mm/day). Koehler & Schmidt (2008) observed similar patterns in European conditions; albeit with lower winter ET of 0.1-0.5 mm/day and a greater range of summer ET (1.5-4.5 mm/day). In addition to temperature, seasonal precipitation patterns influence retention (Hakimdavar et al., 2014) with a higher incidence of intense storm events expected to result in lower retention.

1.3 The influence of vegetation upon ET

Plant transpiration is an important control on ET rates, accounting for between 20 and 48% of moisture lost to the atmosphere (Voyde et al., 2010). The plant’s root system absorbs pore water, trans-locating it through the xylem to stomatal cavities in the leaf, where it is vapourised by solar energy. The deficit in the leaf cells creates a difference in potential between the leaves and roots, such that a suction force is transmitted back to the root (van den Honert, 1948).

Transpiration rates differ according to the plant’s metabolic processes. Plants that have crassulacean acid metabolism (CAM) are typically more drought tolerant than 95% of plant species (Voyde et al., 2010). Plants consume water by opening stomata. CAM plants open their stomata to metabolise at night when temperatures are cooler. Evaporative loss is therefore lower than from plants that transpire soil-water during warm daylight conditions. As such, ET from CAM plants (e.g. Sedum) tends to be controlled to a greater extent than would be the case with C3 or C4 species, e.g. Meadow Flowers, grasses (Nagase & Dunnett, 2012). Generally, previous research has focused on Sedum or other hardy, drought tolerant CAM species and hydrological differences attributable to plants with different traits are therefore not widely known. However, Fassman & Simcock (2008) reported that configurations vegetated with Sedum mexicanum tended to result in higher ET rates than with New Zealand Ice Plants and there is evidence that Sedum-vegetated configurations reduced runoff to a significantly greater extent than equivalent configurations with a mix of ‘Meadow Flowers’ (Poë et al., 2011). This evidence contradicts the expectation that retention would be lower in CAM (Sedum) species due to reduced ET rates. This could reflect the greater capacity for interception by the dense Sedum foliage and/or the fact that certain Sedum species may have the ability to switch their metabolism to CAM only under drought conditions (Sayed, 2001).

1.4 The effect of substrate characteristics upon ET

The soil-water characteristics of a substrate are typically recognised as a key influence in the system’s capacity to store rainfall (Palla et al., 2010). The structure and texture of a substrate governs its field capacity, permanent wilting point (Beattie & Berghage, 2004) and retention and release characteristics (Manning, 1987; Miller, 2003). Adsorption of water molecules to soil particles and cohesive forces between water molecules create negative (matric) pressure in the soil-water. Matric pressure (ψ_m) is the driving force for soil-water fluxes in unsaturated flow. When ψ_m is in equilibrium with gravitational forces, the substrate is at θ_{FC}. ψ_m is lower in large pores than in small pores due to the greater distance between soil particles (Hillel, 1998). The granulometric distribution of the substrate will therefore govern the relationship between θ and ψ_m.

This paper presents data from an experimental study, under laboratory-controlled conditions, at the University of Sheffield, aimed at identifying the drying cycle behaviour of nine different green roof configurations (with combinations of three characterised substrates and three typical planting options) that were subjected to diurnal cycles representative of UK spring and summer conditions. Responses are analysed for measurable physical influences; an important step towards the development of predictive models of ET and stormwater retention. Observed results will then be compared to ET that has been predicted using a simple moisture balance model.

2 MATERIALS AND METHODS

2.1 Experimental Set-up

An experimental set-up was established to continuously monitor mass balance changes (inferred as changes in moisture, i.e. ET) from nine different green roof configurations, comprising combinations of three substrates (to a settled depth of 80 mm, in accordance with the Green Roof Code of Best Practice for the UK [GRO, 2014]) and three vegetation treatments. A filtration membrane prevented the loss of fine particles from the substrate. A drainage layer (with zero storage capacity) facilitated drainage to field capacity. Microcosms of each configuration were established in polypropylene trays with internal dimensions of 237 x 237 x 120 mm (a size that was compatible with the capacity of the load cell and platform). Tray bases were perforated for drainage of gravitational water prior to the trials. 25 x 6 mm Ø holes (providing a nominal drainage capacity of 0.1 litres per second) were set on a 60 mm grid, with a row of holes centred 5 mm from the tray's upstand. Each microcosm was placed on to load cells within a Conviron BDW40 plant growth chamber at the University of Sheffield's Department of Animal & Plant Sciences (see Figure 2a & 2b). Starting at S_{MAX}, no irrigation was applied throughout the trials. Typical diurnal cycles were replicated for UK spring and summer conditions. The former is of interest as, in spring, vegetation exits winter dormancy and starts to transpire soil-water, whereas summer conditions will have greater ET and drought stress due to the longer dry periods with higher temperatures. From a stormwater management perspective, summer conditions are of particular interest as the long dry periods may be interspersed with intense storm events.

[Approximate location of Figure 2]

Six trials were scheduled to take place between the 7th April and the 25th August 2011. First, the spring condition was replicated three times on a sequential basis; followed by three replications under summer conditions. The third test under each climatic condition trialled for 28 days; the other two ran for 14 days. A mechanical failure within the chamber during the first spring trial led to its abortion and replacement by a fourth spring trial. The three replicate summer trials followed on from the spring trials. Each microcosm was established in triplicate, avoiding its employment in more than one trial per climatic condition and ensuring the health of the vegetation at the start of the trial. The decision to employ only three replicates for each test was informed by the following factors. The tests were intended to provide a preliminary assessment of the relative importance, and interactions between, several controlling variables, i.e. substrate, vegetation and climatic conditions. As only 10 load cells were available, replicate tests had to be run consecutively in the climate chamber, such that the full series of tests for each season required a minimum of 8 weeks. Although the climate chambers provided climatic control irrespective of the absolute date or season, the experimental timings also needed to be matched to the relevant external seasons to capture any effects due to the plants' seasonal growth cycle and to avoid any risk of shocking the plants by rapidly transferring them between contrasting climatic conditions.

2.2 Trial configurations

Microcosms were established to replicate each of the nine test bed (TB) configurations that have been the subject of on-going complementary field research trials (Poë et al., 2011; Berretta et al., 2014). Microcosms for a tenth configuration were trialled but results are not reported here.

2.2.1 Vegetation treatments

Vegetation options were applied to each substrate to replicate the three most typical UK extensive green roof types:

1. Sedum Carpet (Sedum) – a pre-cultivated mat, from Blackdown Greenroofs, comprising Sedum species that are ideally suited to green roofs (Monterusso et al., 2005) due to the high rate of survival without irrigation (Cook-Patton & Bauerle, 2012). Applied on TB1, TB2 and TB3;
2. Meadow Flower (MF) – a treatment comprising a broader mix of species, including flowers, grasses and succulents, that can benefit biodiversity (Benvenuti, 2014) – an important driver for green roofs in the UK. The higher biomass and larger roots of Meadow Flower, relative to Sedum, is expected to result in poorer drought tolerance (Lu et al., 2014). Added to TB4, TB5 and TB6; and
3. Non-vegetated (NV) – microcosms with a bare soil surface are often referred to as "brown roofs" in the UK. The intention is for the roof to self-colonise with local native flora and fauna over time. However, in the interim, non-vegetated roofs are characterised by a reduced surface area from which evaporation can occur and the absence of plant transpiration. Here, this treatment represents a basis against which the contribution of the vegetation to ET can be evaluated. Relevant to TB7, TB8 and TB9.

2.2.2 Substrate types

Three substrates were trialled. Each substrate has different soil-water characteristics. These are broadly as reported in Berretta et al. (2014) with only minor differences in the sample sets.

1. Alumasc ZinCo Sedum Substrate (SCS) – a commercial extensive substrate with few fine particles (1.9% < 0.063 mm), median particle diameter (d_{50}) of 5.1 mm and low organic content (2.3%). Used on TB2, TB5 and TB8;
2. Alumasc ZinCo Heather & Lavender Substrate (HLS) – a commercial semi-intensive mix with a greater proportion of fines than SCS (2.7% < 0.063 mm), higher organic content (3.8%) and the lowest median particle diameter (d_{50} = 4.1 mm). Used on TB1, TB4 and TB7;
3. A mix based on Lightweight Expanded Clay Aggregate (LECA) with a mean particle diameter (d_{50}) of 5.0 mm, but a high proportion of large particles (66.6% in excess of 4 mm) and voids (such that air content at field capacity is 49.8%). Used on TB3, TB6 and TB9.

Figure 3 shows the particle size distribution of each substrate and includes the acceptable limits for an extensive green roof substrate (FLL, 2008). All three substrates are almost wholly composed of sand and gravel sized particles, with minimal silt content. The composition of SCS and LECA falls marginally outside FLL limits due to the low proportion of fine particles. HLS has the greatest proportion of fine particles, with 32% of particles less than 2 mm in diameter (i.e. sand); 9% of this can be classified as ‘fine’ sands. SCS (27%) and LECA (22%) contain smaller proportions of sand particles and have a greater fraction of larger particles. 58% of LECA is composed of particles between 4 and 8 mm in diameter; compared to 40% of SCS and 35% of HLS.

[Approximate location of Figure 3]

Both vegetation treatments were grown to establishment in late winter and early spring within a climate-controlled glasshouse. Meadow Flower did not establish well on the LECA substrate.

No microcosms were therefore suitable for testing during the first completed spring trial. As such, only two data records were obtained for TB6 under spring conditions.

2.3 Data collection methods

The nine microcosms were submersed in water for 2 hours, drained to field capacity over a further period of 2 hours and placed on to calibrated RLS010 single-point compression load cells (with a safe working capacity of 10 kg). The allocation of configurations to load cells was randomly selected for each replication. The signal (in mV) was amplified and recorded on an hourly basis by a Modular 600 multi-channel signal conditioning and datalogging unit. Prior to the experiments, each load cell was tuned to a low of zero and a full scale value, at 10 kg, of 9.775 volts. The signal was then recorded for each cell at 2 kg intervals up to 10 kg, enabling the signal to be converted to mass (in kg) using simple linear regression equations with high accuracy (R^2=1) for each load cell. The published maximum linearity error of the load cell (0.02% of full scale value, equivalent to 0.032 mm of moisture) was checked experimentally; apparently identifying greater linearity errors ranging between 0.05 - 0.21% and 0.07 - 0.18% in the spring and summer trials respectively. However, the mean linearity error of every load cell was 0.00%. It is therefore expected that the higher-than-anticipated errors were attributable to manual or rounding-up errors from the visual display on the datalogger during the calibration exercise. Changes in mass from each microcosm were inferred to be moisture loss/gain in mm/m^2. The chamber’s climatic data was captured via a separate, central logging system.

2.4 Controlled condition settings

Target climatic settings were derived from hourly temperature and RH data, as recorded by a Met Office weather station in Sheffield (NGR: 4339E 3873N; Altitude of 131 m) during 2009, this being the first year in which hourly weather station data was published.

For trials in spring conditions, the diurnal temperature range was 5.06 to 9.75 °C, with a mean daily temperature of 7.13 °C and mean RH of 81.43% (ranging from 75.5% to 87.18%). For summer trials, the diurnal temperature range was 13.76 to 19.84 °C. Mean daily temperature was 16.72 °C and mean RH was 75.96% (ranging between 70.44 and 83.59%).

The lighting system provided a daylight source. 16 Metal Halide and Tungsten Halogen incandescent lamps and 16 Phillips Halogen A Pro lamps provided lighting with an intensity of 1000 μmol/m^2/s (at a distance of 1 m) when turned on to replicate daylight hours. Daylight hours were derived from sunrise and sunset data recorded in Sheffield, via the US Naval Observatory website (accessed 2010). For spring trials, lights were switched on for 12 hours each day (between 07:00 and 19:00). For summer trials, lighting was switched on for 17 hours per day; between 05:00 and 22:00.

The capacity of the climate chamber to generate wind was limited to a vertical airflow of up to 24 l/s. Airflow was uniformly dispensed into the chamber via plenums and out via exhausts. Based upon a floor area of 1.6 m^2, this air exchange equates to 15 l/s/m^2 and therefore a wind speed of 0.015 m/s. Whilst this is sufficient to maintain uniform plant canopy temperatures and disturb the boundary layer of water on the plants' leaf surface, these settings are lower than typical mean wind speeds (e.g. at an elevation of 10 metres in Sheffield [Grid reference: SK 34867 87326], estimated average wind speed is 3.7 m/s (Renew-Reuse-Recycle website, accessed 2010). As windier conditions would be expected to induce higher ET, measurements are expected to be on the conservative side. Spatial patterns of air flow within the chamber were not monitored, although it is acknowledged that they are unlikely to have been particularly uniform. The random distribution of microcosms for each test was intended to mitigate against any bias that this may have introduced.

2.5 Data analysis and interpretation

2.5.1 ET values

The term ET is employed here to encompass moisture loss from both vegetated and non-vegetated configurations. Transpiration only occurs from vegetated treatments. ET from non-vegetated configurations therefore results solely from evaporation. Several ET values are analysed and discussed here:

1) Configuration-mean ET: established for each of the nine configurations by taking the mean of the values derived from the 3 trial replications under each climatic regime. Given the heterogeneous nature of green roof substrates and vegetation, some variation in the individual loss rates was expected. Considering the cumulative loss over the first 14 days of the trial, the mean standard deviation over the 18 different test configurations was 7.3%, ranging from 0.5 to 19.2%. The smallest variations occurred on the non-vegetated configurations and the largest variations were generally associated with the spring tests. Figure 4 shows the individual loss profiles for the three replicate tests for spring and summer associated with the Sedum on HLS configuration (TB1), which had a 14-day variation of 6.9% (10.5% in spring and 3.3% in summer), and is therefore typical of the full test set. When ADWP>14 days, ET is derived from the single 28-day long replication;
2) Vegetation- and substrate-mean ET: a mean of the nine values covering the three configurations with the relevant vegetation treatment or substrate.
3) Seasonal-mean ET: mean ET from all nine configurations for each climatic condition.

References will be made to daily (ET_D) and cumulative ET (ET_{CUM}). ET_D was calculated as the sum of hourly ET data over each 24 hour interval. ET_{CUM} was simply derived by summing

ET_D measured up to the time interval in question. The statistical significance of configuration and climatic factors to ET_{CUM} was evaluated using Kruskal-Wallis and Mann-Whitney U tests at ADWPs of 3, 7, 14, 21 and 28 days.

[Approximate location of Figure 4]

2.5.2 Moisture balance values

Residual stored moisture content, S_t, is an important influence upon ET. S_t is calculated as S_{MAX} minus SMD_t and will therefore vary depending upon antecedent ET occurring during the ADWP. There is no established protocol for determining the S_{MAX} of a vegetated configuration. It was not appropriate to start trials with an oven-dry substrate, due to the plants' requirements for water. The adopted method is predicated on an assumption that the maximum moisture storage capacity that can practicably be regenerated via ET under UK atmospheric conditions is equal to the known moisture loss (i.e. ET_{CUM}) at Day 28 of summer trial conditions, when wilting was clearly observed. Residual moisture after this time was considered to be hygroscopic moisture ($\theta_{<PWP}$). $\theta_{<PWP}$ was measured through the post-test, destructive oven drying of the substrate only configurations. To validate this approach, values of θ_{FC} for non-vegetated configurations were derived (through summation of ET_{CUM} and $\theta_{<PWP}$) and compared to related values obtained during substrate characterisation tests (see Table 1).

[Approximate location of Table 1]

Pressure plate tests established θ for ψ_m values of 33 kPa and 1500 kPa - values that define field capacity and permanent wilting point (and therefore plant-available moisture) in soil science (Richards & Weaver, 1944). No meaningful results could be ascertained for LECA. For HLS and SCS, at $\psi_m = 33$ kPa, θ is lower than both maximum water-holding capacity

(MWHC) and the derived values of θ_{FC}. At ψ_m = 1500 kPa, θ is higher than $\theta_{<PWP}$. According to these test results, θ available to plants would be 14.0 and 13.5% for HLS and SCS respectively; values that are significantly lower than observed ET_{CUM} (or S_{MAX}). However, this conventional scientific definition of field capacity may not be wholly applicable to green roof substrates. Green roofs are multi-layered structures that differ from natural soils with homogeneous textures. The highly porous and heterogeneous composition of green roof substrates is such that moisture is apparently retained at ψ_m lower than 33 kPa; being readily available between 10 and 100 kPa (Fassman & Simcock, 2011). MWHC is determined at atmospheric pressure (following FLL protocol). The differences between MWHC and θ at ψ_m = 1500 kPa of 31.2% (HLS) and 30.2% (SCS) are comparable to the respective derived S_{MAX} values. From a stormwater management perspective, S_{MAX} is a more relevant moisture storage term than the absolute values of field capacity and permanent wilting point; representing the proportion of the retention capacity that can be regenerated between storm events.

2.6 Modelling ET losses

The experimental data will be used to evaluate the simple moisture balance model that was proposed by Stovin et al. (2013). This accounts for climatic factors (in the calculation of PET) and moisture content (through consideration of S_{MAX} and S_t) to predict ET (ET_{Pred}).

There is no single universally-adopted approach for calculating PET; with several methods widely adopted, including Priestley-Taylor, Hargreaves, Thornthwaite and Penman-Monteith. There is a significant body of literature evaluating the suitability of each method (Zhao et al., 2013; Tabari et al., 2011; Voyde, 2011; Oudin et al., 2005). The FAO-56 Penman-Monteith (FAO-56) approach – recommended in the FAO Irrigation and Drainage Paper # 56 (Allen et al., 1998) – is adopted here due to its physical basis. The FAO-56 approach predicts PET on the basis of atmospheric conditions, and assumes that the grass is actively growing and has abundant plant-available water. This approach was also adopted by Locatelli et al. (2014). It should be noted however that Stovin et al. (2013) demonstrated that the simpler Thornthwaite PET model, when combined with a moisture content factor, could provide good predictions compared with measured data, whilst Berretta et al. (2014) confirmed that the precise choice of PET model may be of less importance than the need to ensure that moisture restriction effects are properly accounted for.

A balancing factor will then be applied to reflect the fact that ET is not always equal to PET. Zhao et al. (2013) present numerous soil moisture extraction functions (SMEFs) that factor PET and obtain a more realistic forecast of ET as moisture availability changes. The SMEFs considered by Zhao et al. (2013) all factored PET by an equation that included θ_t as a proportion of θ_{FC}. However, here, S_{MAX} is considered instead of θ_{FC}. It is expected that this is a more relevant parameter, as $\theta_{<PWP}$ will not typically be released through ET. This moisture balancing factor is consistent with the approach adopted by Stovin et al. (2013); taken as the ratio of available, S_t, to maximum storage, S_{MAX}; such that:

$$ET_{Pred} = \frac{S_t}{S_{MAX}} \times PET \qquad \text{Equation 1}$$

It is envisaged that this generic model might subsequently be refined to account for the subtler variations associated with different vegetation and substrate configurations. However, at this preliminary stage, it is appropriate to demonstrate the model's validity using the seasonal-mean data averaged across all nine configurations.

3 RESULTS

Configuration-mean ET trends are presented here and analysed (in Section 4) to identify the underlying physical trends. A Kruskal-Wallis test identified that seasonal differences in configuration-mean ET_{CUM} are significant (p=0.05) at all ADWPs; 3 days (p=0.0003), 7 days (p=0.001), 14 days (p=0.004), 21 days (p=0.009) and 28 days (p=0.024). It is therefore pertinent to consider the responses of configurations to each climatic regime separately. Figure 5 shows the configuration-mean ET_{CUM} for the spring and summer test series.

[Approximate location of Figure 5]

Overall, cumulative ET losses were greater in summer (19-35 mm) compared with spring (17-29 mm). In both climatic regimes the maximum ET_{CUM} was associated with TB4 (Meadow Flower on HLS), and the minimum was associated with TB9 (non-vegetated LECA). After 14 days in summer twice as much moisture had been removed from TB4 than TB9 (33 mm as opposed to 16 mm). In general the 28-day ET_{CUM} was highest for configurations vegetated with Meadow Flower and lowest for non-vegetated microcosms, although initial ET rates for non-vegetated microcosms were amongst the highest observed. Although the variations with respect to vegetation treatment appeared to be more pronounced than the effects of substrate type, systematic differences with respect to substrate were also evident, with the LECA-based configurations generally exhibiting the lowest ET rates and HLS-based configurations the highest. Variations due to substrate type were least evident with the Sedum vegetation, and most apparent with non-vegetated microcosms.

Figure 6 shows configuration-mean ET_D over the preceding 7 days for ADWPs of 7, 14, 21 and 28 days. Every three groups of columns correspond to a vegetation treatment. These plots reinforce the observations made above, with relatively high ET losses from non-vegetated configurations (TB7, TB8 and TB9) over the initial 7 days being exceeded by the vegetated systems in the later stages of the trials. Within each group the consistent behaviour between the three substrate types was readily apparent; losses were consistently greatest from HLS (TBs 1, 4 and 7) and least from LECA (TBs 3, 6 and 9). It is also clear that for several of the configurations, losses after 14 days in summer conditions were reduced to zero or close to zero. Indeed, a net moisture gain was observed in TB6 when ADWP exceeds 21 days.

[Approximate location of Figure 6]

In all cases there was an observable decrease in ET rate with time. This phenomenon has been widely reported elsewhere (Voyde et al., 2010; Stovin et al., 2013, Berghage et al., 2007). This effect was particularly pronounced in non-vegetated configurations, and also evident in the Meadow Flower configurations in summer. Initial ET rates were of the order of 1.5 mm/day in spring and 2.5 mm/day in summer. In contrast, ET rates during the final seven days dropped to below 0.5 mm/day.

Statistical analysis of the 3, 7, 14, 21 and 28 day cumulative ET values showed that differences as a result of vegetation treatment were generally only significant ($P = 0.05$) when contrasting ET from vegetated and non-vegetated configurations. No statistical differences existed between Sedum and Meadow Flower.

In view of the significant influence that moisture constraints have upon ET rates when ADWP exceeds 14 days, it is pertinent to assess the variations in ET_{CUM} as a function of configuration and season after an ADWP of 14 days (see Table 2).

[Approximate location of Table 2]

Seasonal-mean ET_{CUM} is greater in summer (24.7 mm) than in spring (17.4 mm) after an ADWP of 14 days. This is consistent with the phenomenon of warmer conditions inducing greater ψ (leading to higher ET). The higher standard deviation (σ) in summer (5.1 mm) compared to spring (2.8 mm) is expected due to (a) the lower absolute seasonal-mean ET_{CUM} in spring and (b) the greater influence that the range of S_{MAX} values has upon ET_{CUM} following high antecedent ET in summer. Comparing the spring and summer losses over the first 14 days, the seasonal difference in substrate-mean ET_{CUM} is greatest with HLS (9 mm), compared with SCS (6.1 mm) and LECA (7 mm). The seasonal differences are far greater in the vegetated configurations (around 10 mm) compared with non-vegetated configurations (2 mm). The small σ of 0.6 mm for Sedum in spring indicates a lesser reliance of Sedum's transpiration rates upon substrate soil-water characteristics; particularly in cooler climatic conditions. However, in summer, as ET_{CUM} from Sedum-vegetated configurations exceeds ET from non-vegetated configurations, σ also increases to 3.0 mm. Here, the differences in configuration specific S_{MAX} lead to greater contrasts in ET_{CUM} between LECA and HLS. The variance in substrate-mean ET_{CUM} is greatest from HLS, where low ET_{CUM} from Sedum contrasts with high ET from Meadow Flower and non-vegetated configurations. Variance is further increased in summer, as the low ET_{CUM} from non-vegetated configurations contrasts with the very high ET_{CUM} from Meadow Flower.

4 DISCUSSION

The key physical parameters that influence ET - climate, moisture content and configuration (i.e. vegetation and substrate) - will now be considered.

4.1 The influence of climate upon ET

Conceptually, the climate can be considered to be a source of potential energy that acts upon the green roof to extract moisture via ET. Assuming abundant and constant S_t, summer conditions would be expected to induce ET at higher rates than during the cooler spring conditions. ET is directly related to temperature. Higher temperatures will lead to higher absolute cumulative losses as a greater proportion of the moisture that is held with higher ψ_m in the small pores of a substrate can be removed under increased levels of heat energy. In spring, the lower source of energy generated in the cooler conditions is often not sufficient to break the bonds that act to retain moisture in the substrate to the same extent as observed under summer conditions.

The physical characteristics of each configuration govern its moisture retention behaviour, affecting the level of resistance to the extraction of moisture from within. However, on average, once S_t fell to approximately one quarter of S_{MAX}, moisture appeared to be held too tightly for ET to occur during spring conditions, as S_t remained relatively high, even after an ADWP of 28 days. Summer conditions were often sufficient to induce ET until S_t reached less than 10% of its S_{MAX}, emptying moisture from a higher proportion of the substrate's pores. The influences of climate and S_t are therefore intrinsically linked, as warm conditions generally induce faster initial losses; but in so doing, decrease S_t which then leads to lower subsequent ET losses.

Under constant climatic conditions, PET should remain constant. However, ET appears to fall relative to PET even at short ADWPs (see Figure 7). It is hypothesised that this almost instant decline can be attributed to a combination of short-rooted vegetation and highly porous substrates.

[Approximate location of Figure 7]

Seasonal-mean ET_D was greater in summer conditions than in spring for ADWPs of up to 12 days; such that seasonal-mean ET_{CUM} was 7.6 mm greater in summer by this time. However, at longer ADWPs, ET appeared to have been constrained by the lower S_t that results from high antecedent rates of ET. Summer ET_D subsequently fell below spring rates (in many cases approaching zero). Lower antecedent ET in spring resulted in more sustained, consistent ET_D; contrasting with the exponential decay in ET observed in summer trials.

The influence of season upon ET_D was most apparent when moisture availability was abundant (i.e. at short ADWPs). Median ET_D in summer fell from 3.4 mm to 1.9 mm over 7 days, then to 0.5 mm, 0.3 mm and 0.2 mm after 14, 21 and 28 days respectively. In spring, initial median ET_D of 2.0 mm was then consistently maintained at approximately 1.2 mm between day 2 and day 12, before falling to 0.7 mm after 21 days and 0.3 mm after 28 days.

Seasonal climate differences were significant to ET; most notably when moisture availability was not constrained by high antecedent moisture losses. In general terms the decay of ET over time reflects the effects of reduced moisture availability.

4.2 The effect of moisture content upon ET

S_t had an underlying influence upon ET rates. Highest ET was recorded at the highest values of S_t; the lowest when S_t was low. In most cases, this decline in ET occurred simultaneously with a reduction in moisture availability, as evidenced by the contrasts of rapidly declining ET_D during summer and the more consistent reduction in ET_D in spring. By considering ET/PET, and expressing moisture availability as a ratio of residual, S_t, to maximum storage, S_{MAX}, the constraints imposed upon ET by moisture availability can be seen (see Figure 8).

[Approximate location of Figure 8]

In all instances, ET reduced as S_t fell. A best-fit regression line (R^2=0.73) with a gradient of 0.89 reflects a relatively linear reduction in ET/PET as S_t/S_{MAX} fell. ET/PET in summer fell largely above the best-fit line. Certain configurations (e.g. TB1) were also seen to have non-linear relationships between ET/PET and S_t/S_{MAX}.

The importance of moisture availability to ET_D is also apparent in Figure 9; comparing ET over a mean diurnal cycle when moisture was abundant (i.e. week 1) with conditions when moisture availability was constrained (i.e. week 4).

[Approximate location of Figure 9]

ET_D was highest when moisture was abundantly available, with seasonal-mean ET of 1.5 mm/day in spring and 2.3 mm/day in summer. In moisture-constrained conditions, ET_D of between 0.2 and 0.3 mm/day was measured; albeit actual ET of 0.8 mm was observed during the day when moisture gains of 0.5 mm were taken into account. Moisture gain was most pronounced in the conditions where moisture was most constrained (i.e. in week 4 of summer). This is consistent with the fact that the highly negative pressures within a dry soil will create a vapour pressure gradient that would typically lead the moisture from the relatively humid air above to be drawn into the soil matrix.

The distinct change in ET as a result of reducing moisture availability highlights the importance of including moisture content as a key parameter in any modelling approach.

4.3 The effects of green roof configuration

4.3.1 Vegetation treatment

The incorporation of vegetation will typically provide some level of additional moisture storage capacity (Morgan et al., 2013). ET losses will be positively influenced by plant transpiration but negatively affected by reduced evaporation relative to bare soil surfaces (Nagase & Dunnett, 2012). On average, the addition of vegetation increased 28-day ET_{CUM} by 17% in spring and 23% in summer. The incremental effect of adding Sedum was greatest in summer (26%) than in spring (10%), with additional losses in summer ranging between 7.2 mm (representing 22% of ET_{CUM}) and 9.5 mm (33%) compared to the equivalent non-vegetated configuration. The higher figure was witnessed from the LECA substrate, which has the highest permeability. It is believed that the greater incremental effect of adding Sedum into LECA can be attributed to the binding effect of the roots penetrating this highly porous substrate. The incremental effect of Sedum on HLS and SCS was lower – 7.8 mm and 7.2 mm respectively. Vegetating with Meadow Flower led to an increase in 28-day ET_{CUM} of 25% in spring and 21% in summer. The substrate type was an influence; particularly in summer when the increment ranged between 3.5 mm or 12% (SCS) and 7.7 mm or 29% (LECA). Adding Meadow Flower to HLS increased ET_{CUM} by 7.7 mm.

However, any incremental effect of vegetation upon ET will vary as a function of the substrate's soil-water characteristics, ADWP and climatic conditions. Figure 10 presents vegetation-mean ET_D over each of the 4 weeks.

[Approximate location of Figure 10]

Initially, the addition of vegetation had a detrimental impact on ET. The duration of this lag varied seasonally and by vegetation treatment. However, vegetation ultimately made a positive net contribution to ET_{CUM}. In spring, this contribution was positive after 12 days (with Meadow Flower) or 20 days (for Sedum), ultimately increasing ET_{CUM} by 6 mm and 2 mm respectively. In summer, the net contribution to ET by vegetation was evident at an earlier stage – after 4 and 6 days for Meadow Flower and Sedum respectively – and to a much greater degree. ET_{CUM} increased by as much as 9 mm (after 14 days) through the addition of Meadow Flower (subsequently reducing below 6 mm after 28 days due to permanent wilting of the vegetation) or 9.5 mm when Sedum was added.

It was expected that the Sedum vegetation would improve the hydrological response of the green roof (compared to both Meadow Flower and non-vegetated configurations), due to its extensive (90-95%) plant coverage and to its Crassulacean Acid Metabolism (CAM). However, Sedum's tendency to regulate transpiration actually restrained ET losses in certain circumstances. In spring, vegetation-mean ET_D from Sedum was lower than from Meadow Flower at virtually all stages. This was also the case for the first two weeks under summer conditions. This is consistent with the findings of Farrell et al. (2012), who identified slower ET from Sedum (compared to C3 plants) over an initial 20 day period. Sedum species typically have relatively shallow fibrous roots, whereas grasses and forbs tend to have larger root and shoot biomass that can be conducive to more effective moisture retention (Nagase & Dunnett, 2012). However, the CAM photosynthesis and leaf succulence of Sedum ensure stronger drought tolerance (MacIvor & Lundholm, 2011) compared to grasses and forbs (Lu et al., 2014). The seasonal differences in ET_{CUM} for Sedum were the greatest of the tested vegetation treatments; as low, regulated ET in spring contrasts with faster ET and subsequent exponential decay in summer. Unlike other vegetation treatments, ET losses were observed from Sedum for more prolonged periods, even after long summer ADWPs. Yet there were no observations of higher transpiration from Sedum during night conditions; a trait that is often associated with CAM plants. Differences in ET rates attributable to substrate were marginal when Sedum was the chosen vegetation treatment.

The different transpiration rates of Meadow Flower, compared with Sedum, were most apparent in summer. Generally high ET was measured for an initial 7 day period, as vegetation-mean ET_D from Meadow Flower exceeded ET_D from Sedum in both spring (1.4 versus 1.25 mm/day) and summer (2.7 versus 2.4 mm/day). However, an almost linear decline in vegetation-mean ET_D from Meadow Flower towards zero by Day 14 (with virtually no subsequent ET thereafter) supports a hypothesis that the fast initial transpiration of Meadow Flower leads to ET_D that is constrained by a configuration's S_{MAX} at longer ADWPs. The highest ET_{CUM} (of 34.7 mm) was measured from the substrate with the greatest θ_{FC} (i.e. HLS). Yet all plant-available moisture appeared to have been consumed; as confirmed by observations of permanent wilting.

Three key trends distinguish patterns of ET for non-vegetated configurations from their vegetated equivalents:

a) Faster initial rates of ET, as ET_{CUM} exceeded ET_{CUM} from Sedum and Meadow Flower configurations for 12, 15 and 10 days (for HLS, SCS and LECA respectively) in spring and for 3, 6 and 1 day in summer;
b) Lower ET_{CUM} after 28 days; and
c) Smaller seasonal ET differentials.

In spring, vegetation-mean ET_D from non-vegetated configurations was as high as 2.8 mm/day. Vegetation-mean ET_D over the first week was 1.8 mm/day and continued to fall in the second week (to a mean of 0.7 mm/day), averaging just 0.15 mm/day in the fourth week. As a result, ET_{CUM} was limited to between 17.3 and 22.9 mm after 28 days. In summer, higher ET rates of up to 4.2 mm/day were observed, but declined instantly towards zero by Day 14. Generally, the faster decay in ET from non-vegetated configurations (relative to vegetated configurations) can be attributed to a lower albedo (i.e. the absence of a plant cover that would otherwise serve to moderate evaporation from a highly porous, dark, bare substrate surface) and to the lower S_{MAX}. The smaller seasonal increase in ET_{CUM} from non-vegetated configurations reflects (a) the constraints imposed on ET by low S_{MAX}, and (b) the greater plant transpiration in warm conditions.

The vegetation treatments trialled here were relatively young. Further root development as the vegetation ages would be expected to change the organic content and porosity of the substrate (Berndtsson, 2010). A more developed root distribution, filling a higher proportion of large voids in the substrate, would act to increase moisture retention capacity (Nagase & Dunnett, 2012).

4.3.2 Substrate

ET varied as a function of a substrate's soil-water characteristics; both in vegetated and non-vegetated configurations. Figure 11 presents substrate-mean ET_D over each of the 4 weeks.

[Approximate location of Figure 11]

Substrate type appeared to influence ET less than vegetation treatment. However, in both climatic regimes and at all ADWPs, substrate-mean ET_D generally reflected the substrate's θ_{FC}

with substrate-mean ET_D greatest from HLS configurations and least from LECA. The extent to which a substrate's θ_{FC} affected ET_{CUM} varied according to the climate. In spring, the range of substrate-mean ET_{CUM} was lower (22-25 mm) than in summer (25-33 mm). The seasonal increase in substrate-mean ET_{CUM} was greater from HLS (8 mm) than SCS (4 mm) after 28 days. This indicates that, in warm conditions, higher θ_{FC} will generally facilitate higher ET_{CUM}. A greater proportion of the moisture that is held with higher ψ_m in the small pores of HLS can be removed via ET with the greater heat energy that is generated in warmer climatic conditions. Yet, in cooler conditions, a substrate's S_{MAX} is unlikely to be fully depleted via ET and other characteristics, such as permeability, will influence the rate of ET.

HLS is the substrate with the greatest θ_{FC}, yet also the highest proportion of fines (and lowest permeability). SCS has a lower θ_{FC}. Yet, substrate-mean ET_{CUM} was virtually identical (24 mm) from both substrates after 28 days in spring. This is consistent with a hypothesis that the lower heat energy in spring can induce slower moisture balance changes (particularly in the substrate's smaller pores, where moisture is retained with greater tenacity). In cooler climates, no discernible increase in ET is therefore likely to result from substrates with high θ_{FC} and low permeability (e.g. HLS) compared to substrates with lower θ_{FC} and higher permeability (e.g. SCS). Indeed, despite the low θ_{FC} and very high permeability of LECA, substrate-mean ET_{CUM} was only marginally lower than from SCS in spring. However, in warm conditions that are conducive to high PET, a lower S_{MAX} would be expected to constrain ET, as was evident from the small seasonal difference in substrate-mean ET_{CUM} of 3 mm measured with LECA after 28 days.

4.4 Summary of key influences

Overall, moisture content is a very important influence upon ET. ET will be greatest when moisture availability is high, but will almost instantly fall below PET when available moisture is less than S_{MAX}. A configuration's S_{MAX} varies according to vegetation treatment and substrate type. The rate at which the retention capacity is generated will be affected, significantly, by the climate (with warmer temperatures inducing greater initial rates of ET) and by the response of the vegetation treatment to the ambient conditions.

4.5 Model Application

Significant differences in the cumulative ET profiles were evident in Figure 5, and the paper has highlighted the relative importance of vegetation and substrate characteristics in determining these differences. Notwithstanding these influences, all nine configurations clearly respond similarly to two critical driving forces, the PET rate (i.e. the seasonal influence) and the available soil moisture. In all configurations, reductions in actual ET were clearly evident when moisture became restricted. Here the experimental data is used to validate the simple two-part ET model presented in section 2.6. The model predicts actual ET from an estimate of PET and the application of a moisture balancing factor.

The FAO-56 PET calculation was used to estimate ET for a reference crop (green grass) of uniform height (0.12 m), surface resistance (70 s/m) and albedo (0.23) in response to climatological factors, i.e. radiation, air temperature, relative humidity and wind speed. Factoring in the chamber's climatic settings, reference PET, ET_O, was calculated to be 1.8 mm/day and 4.5 mm/day for spring and summer conditions respectively. A SMEF (see Equation 1) was then applied. The model was implemented at hourly/daily time intervals, with the actual substrate moisture content being continuously updated.

PET, seasonal-mean ET_{CUM} and ET_{Pred} are presented for both spring and summer in Figure 12.

[Approximate location of Figure 12]

Here, the improved accuracy achieved by applying a SMEF to factor PET is immediately apparent. The use of PET alone would result in significant errors (e.g. a near 50% overestimation of ET after 7 days in summer). A Percent Bias (PBIAS) metric was applied to quantify the accuracy of ET_{Pred} based on the average tendency of modelled values to be larger or smaller than observed values. Optimum PBIAS is zero. Positive values reflect an over-prediction in the modelled ET value and negative values are calculated where the model under-predicts ET. A very good prediction would have PBIAS of less than or equal to +/-10%. For spring, PBIAS values were 0.6% (ET_{CUM}) and 2.0% (ET_D). For summer, PBIAS values were 6.1% (ET_{CUM}) and -0.8% (ET_D). ET_{CUM} was therefore predicted with very good accuracy. In summer, initially, ET_{Pred} was over-predicted (with a peak error of 3 mm after 4 days). However, this over-prediction is gradually eroded so that $ET=ET_{Pred}$ from day 23 onwards. In spring, ET_{Pred} was virtually identical to ET at all stages of the trial.

5 CONCLUSIONS

- Trials under controlled conditions concluded that statistically significant differences in ET from green roofs can be attributed to climatic differences and, in certain conditions, to vegetation treatment and substrate.
- ET was higher in warmer summer conditions than in lower spring temperatures. Seasonal differences in ET were significant. As ADWP increased, statistical significance fell slightly.

- Moisture content is a critical influence upon ET rates and retention capacity. A factor must be applied to PET to reflect a decay in ET with falling moisture availability.
- Significant differences in ET existed between vegetated and non-vegetated configurations, particularly after long ADWPs (28 days).
- No significant differences in ET were identified between systems vegetated with Sedum and Meadow Flower. However, practical differences were observed (e.g. the permanent wilting of Meadow Flower after an ADWP of 14 days in summer).
- Substrates with high θ_{FC} led to the greatest ET_{CUM} in most circumstances.
- Differences in a substrate's soil-water characteristics can have a significant influence upon ET (e.g. LECA vs HLS). However, where soil-water characteristics are relatively similar (e.g. HLS vs SCS), differences were not significant.
- ET can be predicted with very good accuracy by a simplistic model that accounts for climate (with a PET calculation) and moisture balance (using a SMEF).

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Table 1: Soil-water characteristics of the trialled substrates

		HLS	**SCS**	**LECA**
$\boldsymbol{\theta_{<PWP}}$	(% m^3/m^3)	6.6	2.9	2.1
$\mathbf{S_{MAX}}$	(% m^3/m^3)	33.7	31.5	24.2
$\boldsymbol{\theta_{FC}}$	(% m^3/m^3)	40.3	34.3	26.3
Permeability	(mm/min)	2.41	14.8	33
MWHC	(% m^3/m^3)	41.2	39.1	35
$\boldsymbol{\theta\ [\psi_m = 33\ \mathrm{kPa}]}$	(% m^3/m^3)	25	22.4	-
$\boldsymbol{\theta\ [\psi_m = 1500\ \mathrm{kPa}]}$	(% m^3/m^3)	9	8.9	-

Table 2: Mean ET_{CUM} after a 14 day ADWP, by vegetation treatment and substrate

		Vegetation:	**Sedum**	**Meadow Flower**	**Non-Vegetated**	**Mean**	**Std Dev (σ)**
Spring ET_{CUM} (mm)	**Substrate**	**HLS**	15.8	21.8	20.5	**19.4**	**3.2**
		SCS	15.9	18.9	19.2	**18**	**1.8**
		LECA	14.8	15.7	13.7	**14.7**	**1.0**
	Mean		**15.5**	**18.8**	**17.8**	**17.4**	**-**
	Std Dev (σ)		**0.6**	**3.1**	**3.6**	**-**	**2.8**
Summer ET_{CUM} (mm)	**Substrate**	**HLS**	28.8	33.2	23	**28.4**	**5.1**
		SCS	23.7	27.8	20.9	**24.1**	**3.5**
		LECA	23.5	26.3	15.4	**21.7**	**5.7**
	Mean		**25.4**	**29.1**	**19.8**	**24.7**	**-**
	Std Dev (σ)		**3.0**	**3.6**	**3.9**	**-**	**5.1**

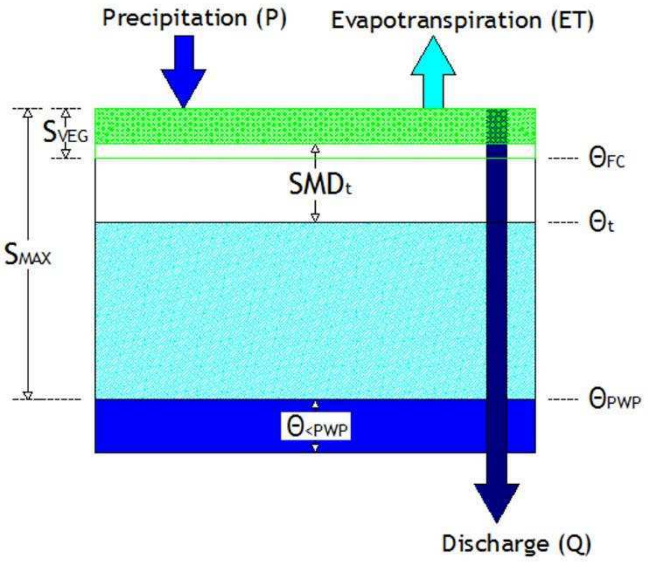
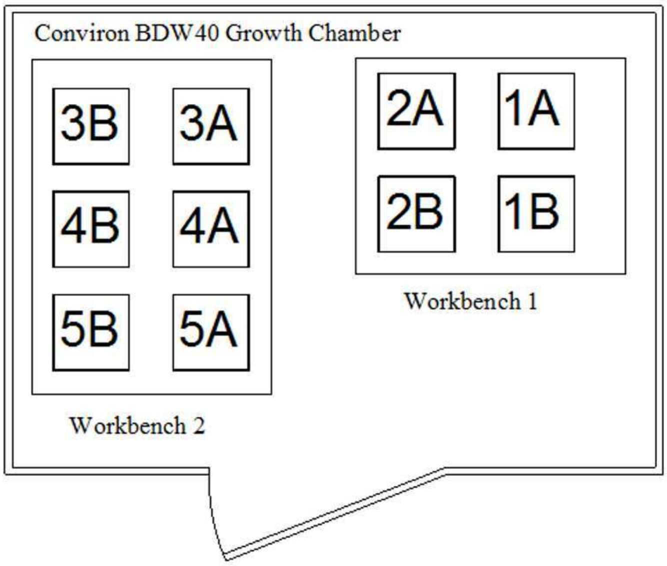


Figure 1: Conceptual Moisture Balance Retention Model

(a) Photograph



(b) Plan drawing

Figure 2: Microcosms in Climate-Controlled Chamber

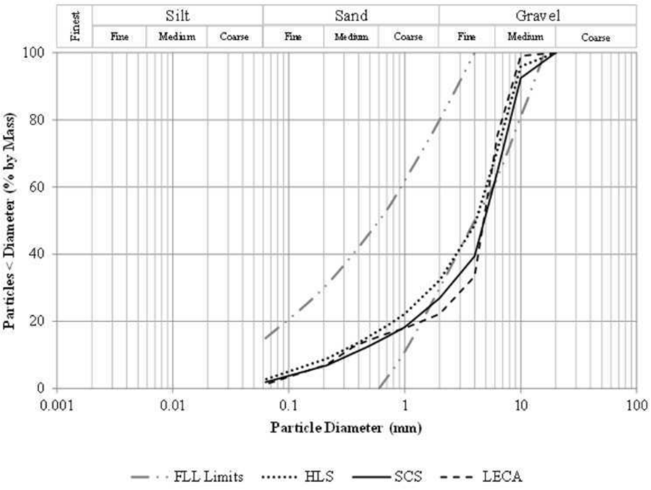


Figure 3: Particle size distributions of HLS, SCS and LECA

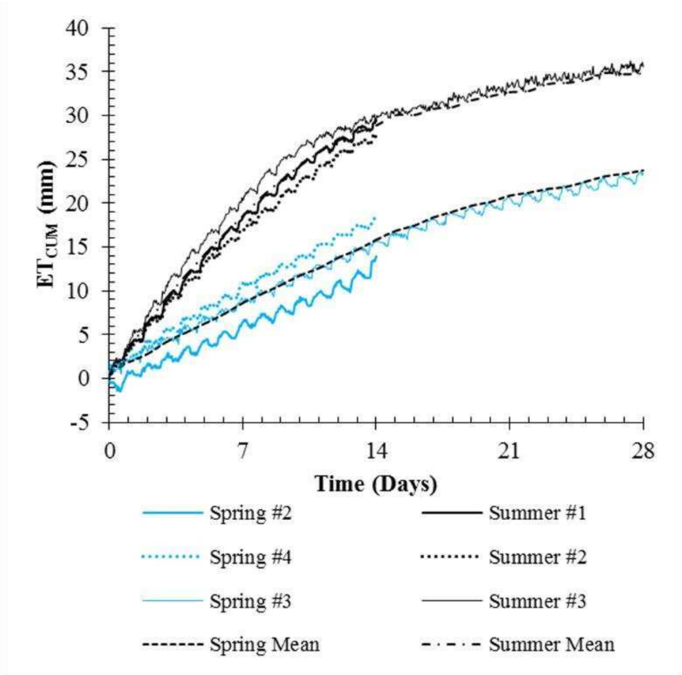


Figure 4: ET_{CUM} for Sedum on HLS (6 replications)

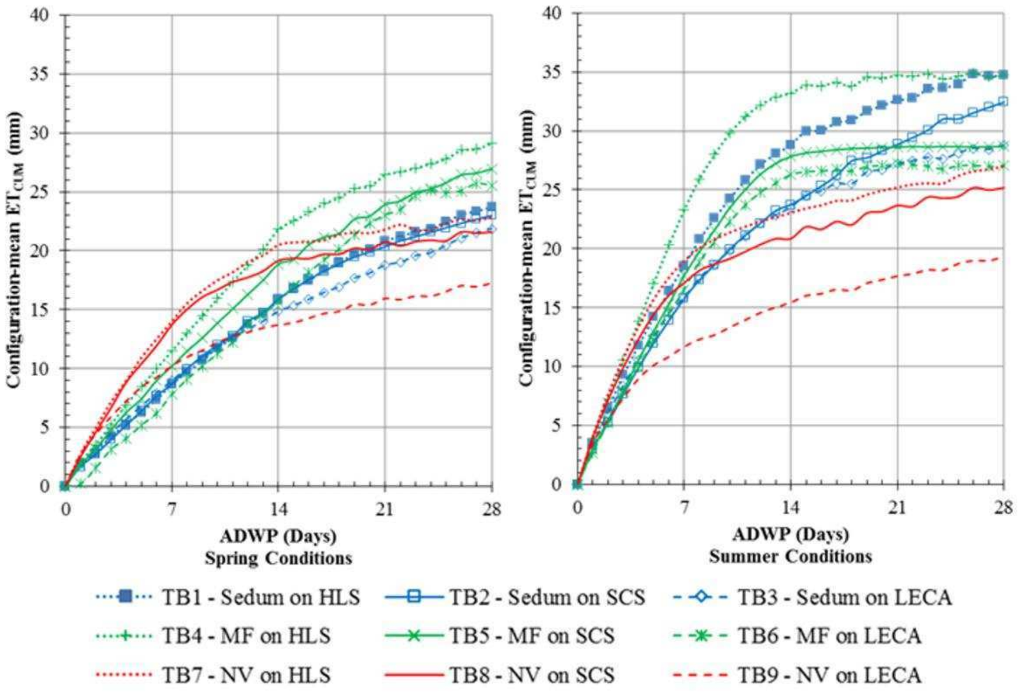


Figure 5: Configuration-mean ET_{CUM}

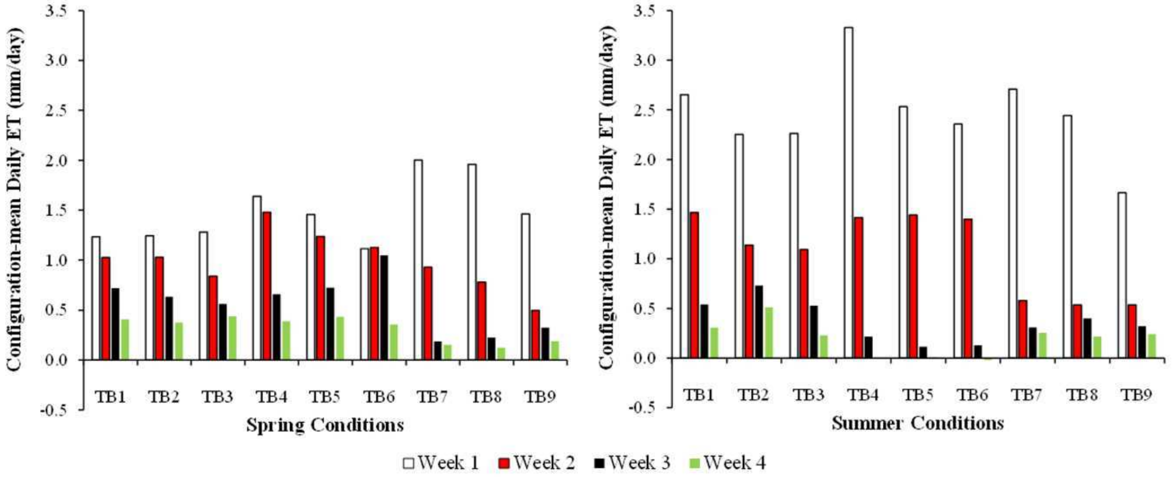


Figure 6: Configuration-mean ET_D

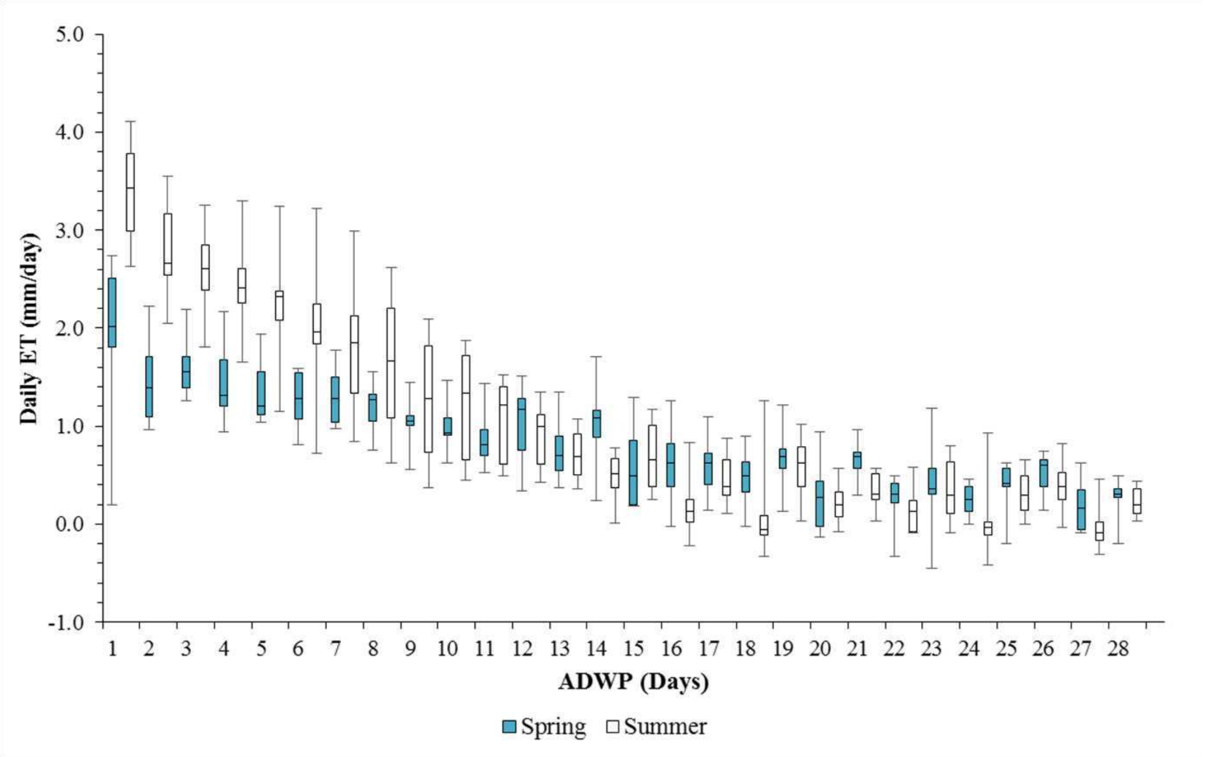


Figure 7: Seasonal-mean ET_D

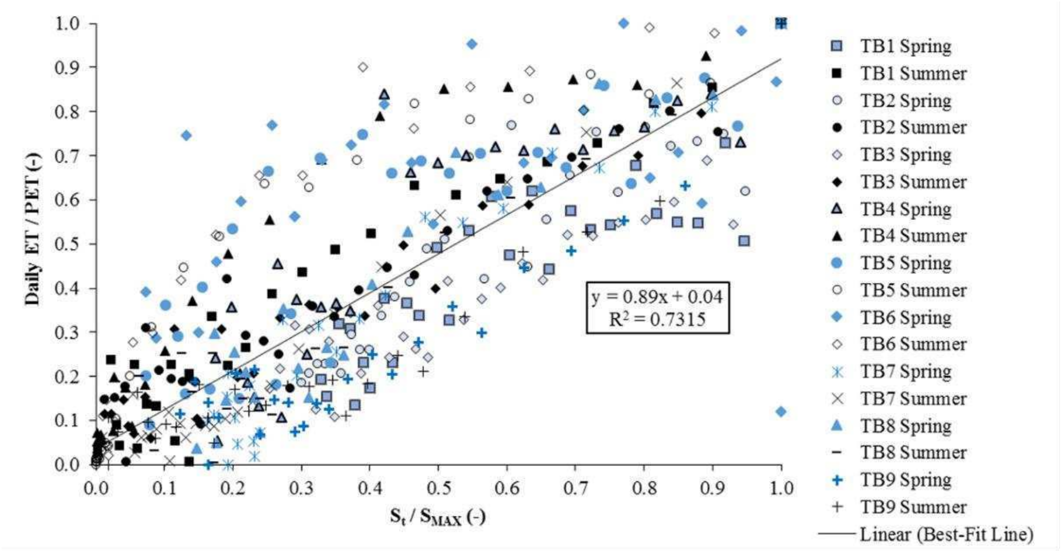


Figure 8: ET/PET versus S_t / S_{MAX}

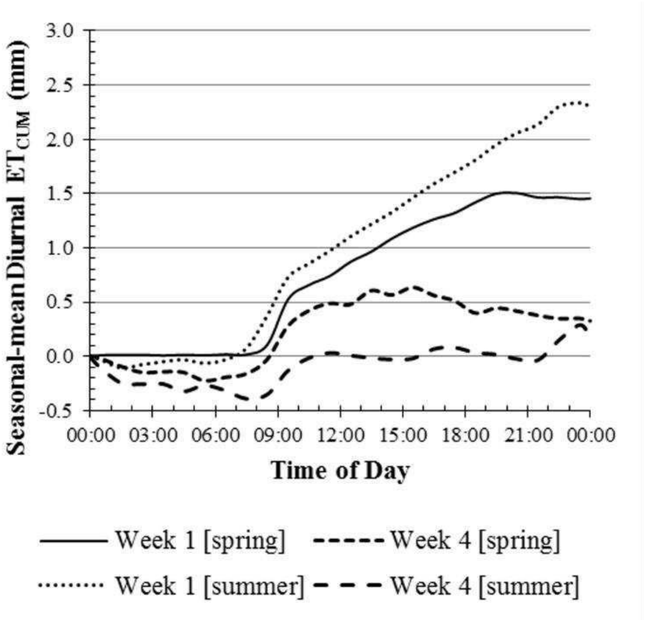


Figure 9: Mean Diurnal ET$_{CUM}$

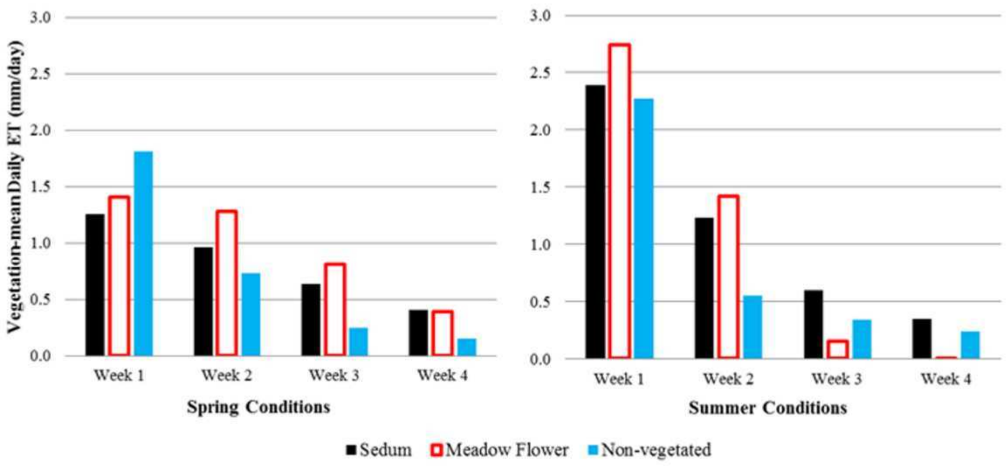


Figure 10: Vegetation-mean ET_D

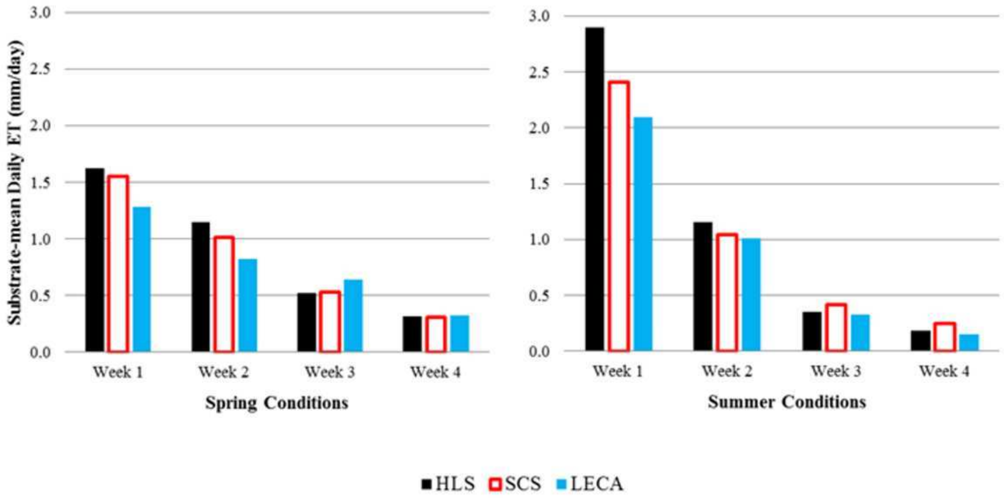


Figure 11: Substrate-mean ET_D

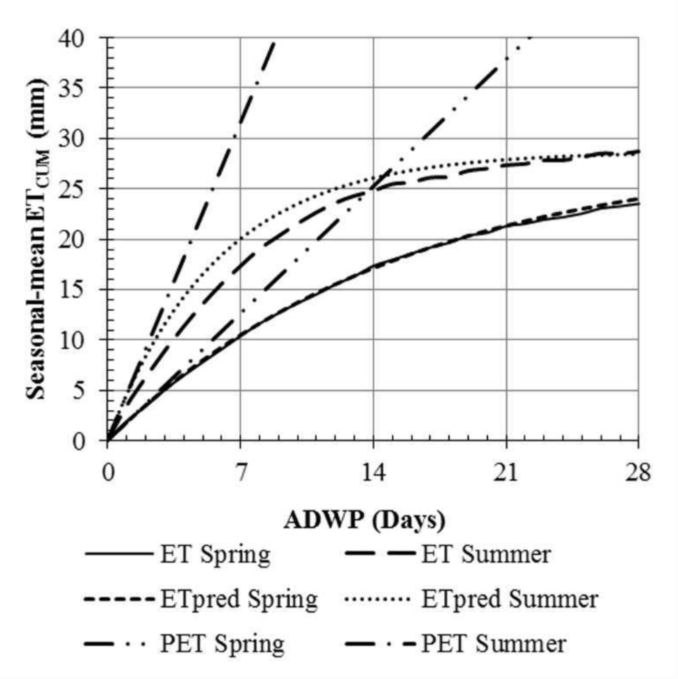


Figure 12: Observed versus predicted ET using FAO-56 PET calculation and SMEF