# ABSTRACT

| | |
|---|---|
| Title of Document: | THE COMPARATIVE EFFECTS OF THREE SEDUM SPECIES ON GREEN ROOF STORMWATER RETENTION |
| | Olyssa Starry, PhD, and 2013 |
| Directed By: | Professor John Lea-Cox,<br>Plant Sciences and Landscape Architecture |

Green roofs are typically dominated by Sedum species because they can tolerate hot, xeric environments. However, due to their high water use efficiency, some have questioned the selection of these species for stormwater management. We investigated (1) how three common Sedum species contribute to overall stormwater retention efficiency by green roofs in the mid-Atlantic region, and (2) whether species-specific differences in water use could be explained by morphological and physiological characteristics.

Water use and $CO_2$ exchange were continuously monitored in growth chamber studies under increasing drought stress for *S. album*, and *S. kamtschaticum*, two species known to variably cycle between CAM and C3 metabolisms. Under fall temperature conditions, *S. kamtschaticum* had gas exchange rates akin to C3 photosynthesis and used 35% more water compared to *S. album*. Interestingly, *S. album* conserved water and had malic acid accumulation confirming CAM

metabolism for the duration of the experiment, even under well-watered conditions.

In field studies, sixteen replicate green roof platforms (n=4 per species) were planted with *S. album*, *S. kamtschaticum*, *S. sexangulare*, or left unplanted during summer 2010. The platforms were monitored intensively for canopy growth, leaf area, root biomass, substrate moisture and runoff for two years (2011 and 2012). Plant treatment effects on stormwater runoff were significant, but most discernible for small and intermediate-sized rainfall events less than 62.5mm. The two species with the greatest stormwater retention efficiencies, *S. kamtschaticum* and *S. sexangulare*, also had the highest rates of evapotranspiration ($E_T$), and higher $E_T$ rates resulted in less total runoff.

Because evapotranspiration was identified as important for predicting performance by plants in the field study, I investigated how $E_T$ data from this study, combined with environmental data collected from a weather station at the study site, could be used to improve the application of the FAO56 Penman-Monteith evapotranspiration equations to green roofs. The incorporation of specific seasonal crop coefficients were found to improve correlations between predicted and measured rates of $E_T$ and these coefficients were related to plant characteristics. The refinement of $E_T$ equations can lead to more accurate hydrologic models of green roofs and design and management tools.

# THE COMPARATIVE EFFECTS OF THREE SEDUM SPECIES ON GREEN ROOF STORMWATER RETENTION

By

Olyssa Starry

Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
[2013]

Advisory Committee:
Professor [Dr. John Lea-Cox], Chair
[Dr. A. Ristvey]
[Dr. S. Cohan]
[Dr. J. Sullivan]
[Dr. R. Pouyat]

## Dedication

This work is dedicated to my grandparents,
Helen and Ned Willard
and
Martha (née Forney) and Art Starry

# Acknowledgements

I would like to acknowledge the support of my family, friends, mentors, and colleagues throughout the completion of this work and especially my dear fiancé Toma Solano. I would also like to thank my very helpful and caring committee: Dr. Steven Cohan, Dr. Andrew Ristvey, and Dr. Joseph Sullivan, and Dr. Richard Pouyat, who started me down this path. They provided thoughtful reviews which greatly improved the quality of work presented here. My major advisor, Prof. John Lea-Cox, could not have been more supportive. He bravely accompanied me from project planning to completion with enthusiasm, and I am very grateful for all the insight he has given me throughout this journey.

Dr. Marc van Iersel and his team at the University of Georgia provided access to their specialized equipment in chapter 2 as well as technical support; his care and guidance greatly improved this work. I further benefitted greatly from discussions and interactions with the University of Maryland's green roof research group. Assistance with sampling provided by them as well as several undergraduate research assistants was greatly appreciated as was help constructing the experiments in chapter 3 from students at the Chesapeake Center for Youth Development.

This work was further supported by federal funding from a United States Department of Agriculture specialty crop research initiative (SCRI 2009-51181-05768) grant to Dr. Lea-Cox as well as a National Science Foundation interdisciplinary graduate education and research (IGERT) traineeship I received from 2007-2009. Additional instrumentation and technical support from Decagon Devices was invaluable. Other corporate supporters who provided materials at discounted rates or as donations in kind included Conservation Technology, Emory Knoll Farms, Hydrological Services, Stancills, and Unitech Scientific. My work was also supported through two grants from Sigma Xi, a Botany in Action Fellowship from Phipps Botanical Conservatory, and a Dean's Fellowship via the College of Agricultural and Natural Resources and the Department of Plant Science and Landscape Architecture.

## Table of Contents

## List of Tables

## List of Figures

# **Chapter 1.** General Introduction

## 1.1 Overview and objectives

Urbanization is associated with a substantial increase in impervious surface or hardscape in cities (Booth and Jackson 1997). This impervious surface is one of the major drivers of the urban stream syndrome (Walsh et al. 2005, Konrad and Booth 2002), which refers to associated negative effects of impervious surface water runoff on stream hydrology, chemistry, and ecology. Roofs are major contributors to this imperviousness, together with roads, parking lots and other hard surfaces. Green roofs are examples of low impact remedial designs that involve the planting of roof surfaces with vegetative cover, to reduce immediate stormwater runoff. Our understanding of water storage by green roofs is still relatively poor, despite much research that has been summarized in a few review papers (Oberndorfer et al. 2007, Berndtsson, 2010, Palla et al. 2010). Additional research is necessary to understand the dynamics of water movement in green roof systems, including the influence of climate and plants.

Plants typically installed on extensive green roofs which are primarily designed for stormwater mitigation are drought-adapted facultative Crassulacean acid metabolism (CAM) species of Sedum, which have the potential to cycle between CAM and a less water efficient (C3) metabolism, under suitable environmental conditions. Variation in green roof plant performance reported in the literature (VanWoert et al. 2005, Wolf and Lundholm 2008, Dunnett et al. 2008) may be explained by this physiological variation as well as difference in key environmental parameters that vary seasonally including temperature and relative humidity. I hypothesize that transpiration by plants provides a putative mechanism for water removal from green roofs for environmental conditions in the mid-Atlantic region.

The research in this dissertation is focused on three primary issues:

**1)** How pronounced is the switch from C3 to CAM metabolism in facultative CAM species under drought stress, under what conditions does this switch typically occur, and how substantial is this effect on plant gas exchange and evapotranspiration ($E_T$) rates?

**2)** How do rates of $E_T$ compare among three common, but morphologically different green roof species which are the focus of these studies, namely *Sedum album* (L.), *Sedum kamtschaticum* (Fisch. & C.A. Mey) and *Sedum sexangulare* (L.). What are the relative seasonal differences in growth and water use between these species, and how do these differences change with increasing canopy coverage and root density? In addition, how might stormwater retention vary during different seasons and for storms of different size in College Park, MD which was the site of this research?

**3)** Can this information be assimilated into a predictive stormwater retention model for green roofs, with any degree of certainty? What is the predictive capacity of standard $E_T$ equations, how do crop coefficients apply to green roof species, and how effectively can these equations be used to predict daily soil moisture loss from green roofs (i.e. compared with measurements of volumetric water content) and the resultant substrate retention capacity?

Conceptualizing green roofs as urban ecosystems will enable the exploration of design components contributing to stormwater retention, while testing fundamental hypotheses on relationships between green roof structure and function. Only with a clearer understanding of how much rainwater green roofs can retain with varying evaporative conditions and planting scenarios (within regions), will urban stormwater planners and managers be able to consider or refine policies regarding permitting and incentives for this type of roof construction.

## 1.2 Review of the Literature

### 1.2.1 Urban stream syndrome

Many urban watershed are showing the negative effects of the urban stream syndrome (Walsh et al. 2005), whereby hydrologic flow paths in urban areas have become disjoined and highly controlled, while run-off generating processes have changed the frequency and magnitude of storm hydrographs. Run-off in urban systems is largely the result of compacted soils around constructed areas, combined with a reduction of pervious surface such as buildings, roads, or sidewalks (Dunne and Leopold 1978). These changes reduce interception, infiltration, subsurface flow, and evapotranspiration (Konrad and Booth 2002). These changes result in a much greater and faster delivery of stormwater to receiving water bodies such as the Chesapeake Bay watershed. This increased runoff is a major mechanism by which inorganic pollutants such as nutrients and heavy metals, and organic compounds (e.g. pesticides and herbicides) are delivered to urban streams (Paul and Meyer 2001) and are a negative influence on macroinvertebrate communities (Roy et al. 2003).

### 1.2.2 Traditional Roofs as contributors to the problem

A significant proportion of the impervious surface associated with these issues may be attributed to rooftops in highly urbanized areas. In a study of the Glyndon watershed, a relatively suburban watershed located near Baltimore, Starry et al. (Fig. 1.1, *unpublished*) found that roofs with gradual slopes (<30 degrees, suitable for greening) comprised nearly 30% of all impervious surface in this watershed. Note that runoff from traditional roofs is also known to contain potential toxins (Foerster 1998).

**Figure 1.1** Glyndon watershed: A suburban watershed northwest of Baltimore City. Roofs suitable for greening with slopes less than 30 degrees are highlighted in green.

### 1.2.3 Green roof description and ecosystem services

Green roofs are pervious roof designs that incorporate plants and growing media above a water-proofing membrane. Instead of soil, green roof plants grow in a non-soil media or substrate, primarily composed either of baked slate or clay, volcanic pumice or scoria with a low percentage of organic matter content. Typically most green roof substrates exhibit high porosity and hydraulic conductivity. Extensive green roofs are distinguished from intensive green roofs (typically referred to as roof top gardens) largely by substrate thickness; definitions are slightly variable,, but extensive green roofs typically only have between 6 and 15 cm (2.5 – 6 inch) substrate depth, due to structural roof and live load (weight) considerations (Berndtsson 2010). Though there are a few older greenroofs in the US, this technology is not as widely adopted here as in other regions of the world such as Germany, that has some of the highest square footage of green roof per city area globally (Koehler et al. 2012).

The many benefits of green roofs are becoming recognized at building and watershed scales. Green roofs can extend roof life and they may also absorb some of the urban heat island effect (Ryerson University 2005, Oberndorfer et al. 2007, Carter and Keeler 2008). They may even enhance urban biodiversity (Jones 2002). Green roofs have been shown to retain up to 80% of potential roof runoff (Carter and Rasmussen 2006), but this type of retention efficiency is likely only for small rainfall events. Most reported measures of retention efficiency are between 40 and 60% (Palla et al. 2010), as further discussed below.

### 1.2.4 Green roof design factors known to influence stormwater retention

Carter and Rasmussen (2006) showed that green roof performance declines from an average of 80% stormwater retention for small storms to less than 35% for large storm events. Design factors that influence water storage by green roofs include slope and media depth (Mentens et al. 2003, VanWoert et al. 2005, Getter et al., 2007). According to the German Research Society for Landscape Development and Landscape Design standards (FLL 2008), the target plant coverage on extensive green roofs is a minimum of 60%, to achieve adequate stormwater retention. Unfortunately, this recommendation is not based on experimental evidence, and many German green roofs standards are based on studies in which the test roofs were not planted (M. Koehler - Hochschule Neubrandenburg, Germany *pers.comm;* Krupka 1992).

### 1.2.4 The role of plants in stormwater retention

The importance of plants in stormwater retention in green roofs is debated. Dunnett et al. (2008) found runoff volumes from vegetated green roof microcosms to be less than non-planted ones, but effects were only significant for non-*Sedum* species such as grasses, i.e. *Festuca ovina*. For those species, inverse relationships between stormwater runoff and both root biomass and plant height were significant. This same study found no relationship between shoot dry mass and runoff and suggests that other aspects of plant structure such as leaf size or branch angle may be important.

A single year study of experimental green roof platforms in Michigan found that green roofs held 3% more water than roofs covered with substrate but not planted, but these findings were not robust when the data were categorized by storm size (VanWoert et al. 2005). Another outdoor study in Georgia (Prowell 2006) did not observe more retention by *Sedum* covered green roof modules compared to unplanted ones, and suggested this may be due to the small plants used in the study. None of these studies thoroughly addressed why no plant effect on water retention was observed. VanWoert et al. (2005) suggest it was due to the harsh winter in their outdoor study in Michigan, but they do not report information about plant characteristics other than they had started with seed in late winter and achieved 100% coverage at the start of their study three months later. Dunnett et al. (2008) argues for more detailed observation of the effects of plant structures, such as size and leaf area, on water capture.

These differing findings about the role of plants in green roof systems could also be explained by the effect of differing substrate moisture content at the time of watering/runoff sampling, or antecedent moisture conditions. If sampling occurs too soon after a watering event, the effects of transpiration may be masked by high rates of evaporation from both planted and unplanted experiments. This argument was used to explain lack of increased stormwater retention by vegetated green roofs compared to non-vegetated ones for the cool winter rainy season in Orgeon (Schroll et all 2011). Conversely, weeks after a watering event, both transpiration and evaporation may be negligible due to lack of water availability. Green roof plants may enhance stormwater retention at a certain rain frequency, but these effects could be negligible in the context of the annual water cycle. Outside of rain frequency, the other two factors influencing substrate moisture content (VWC) of a green roof at any specific time are the quantity of water retained by the substrate due to previous rainfall and subsequent evapotranspiration.

### 1.2.5 Studies comparing different plant species.

As of 2009, only a dozen or so studies of green roof vegetation were found in peer reviewed journals, and the findings of such research is often hard to compare to different types of green roof systems used or lack of reporting thereof (Dvorak and Volder 2010). Many of these earlier studies confirmed that succulents outperformed both grasses and herbaceous plants in terms of survival on thin, dry, extensive green roofs (Dvorak and Volder 2010). One notable exception was big bluestem grass, *Andropogon gerardii,* that was able to persist on two non-irrigated extensive roofs in Chicago, IL (Dvorak and Carroll, 2008). More recent work has shown some interesting comparisons between Sedum species and drought adapted native herbaceous plants. In Canada, *Artemisia stelleriana* had the highest rates of transpiration compared to other plant species including *Sedum floriferum* and *Sedum album* in a module study (Grant 2013). In a roof top pot study in Colorado, seven different herbaceous species were found to survive greater than two weeks before dieback and use more water than the succulent species in the study (Bousselot et al. 2011).

### 1.2.6 Factors influencing substrate moisture content

1. *Water holding capacity*

Green roof plants may sequester more water than unplanted roofs, increasing water holding capacity by adding organic matter to the substrate (Berghage et al., 2007). A greenhouse study simulating summer conditions in Nova Scotia, Canada (Wolf and Lundholm, 2008) found that green roof plants reduced runoff by 1/3 compared to unplanted experimental test pots, but only under dry conditions where plants were watered to field capacity every 24 days. They attributed these findings to both lowered $E_T$ rates due to shading as well as greater substrate water holding capacity, due to plant roots.

Although there has been historical debate as to whether or not increased percentages of organic matter increase substrate water holding capacity, the majority of studies that control for other factors such as particle size find this relationship to be positive (Huntington 2006; Hudson 1994). Getter et al. (2007) suggest that increases in organic matter were responsible for a three-fold increase in water storage, though this was not the focus of their study. According to the authors, over a period of five years, the substrate water holding capacity increased from 17 to 67%, and organic matter content increased from 2.33 to 4.25 percent.

2. *Evapotranspiration*

Most green roofs are planted with species that are tolerant of very harsh roof climates, including extremes of temperature, wind and drought (Snodgrass and Snodgrass 2006). Many of these plants have a Crassulacean Acid metabolism (CAM), whereby plants are able to keep stomata closed during the day to conserve water lost through transpiration, and open them at night to take in carbon dioxide ($CO_2$). The $CO_2$ is then fixed in the form of malic acid; malate salts are then converted to pyruvate and $CO_2$ which is supplied to the Calvin cycle for respiration during the day (Wolf 1960). The range of $E_T$ from four green roof experiments conducted globally in greenhouses and on rooftops, and summarized by Sherrard and Jacobs (2012) was on average, between 0.37 and 3.5 mm/day. Daily averages from an experimental module on a rooftop in New Hampshire reported by Sherrard and Jacobs (2012) of 0.9mm/day indicate that $E_T$ was not maximized most of the time. Though most *Sedum* species have some CAM metabolic capability, it is known that some *Sedum* species can cycle between CAM and C3 metabolism during times of adequate water availability (Cushman and Borland 2002). This interaction between climate and the physiological state of the plant may be especially important in climates with frequent rain events; by switching to a metabolically more efficient (but less water efficient) C3 metabolism, plants can remove water from green roofs more quickly under well-watered conditions.

### 1.2.6 FAO56 $E_T$ equations and green roof modeling

Since $E_T$ is difficult to quantify in real-time because of changing environmental fluxes, it is often modeled on a daily basis. Attempts to adapt numerous existing $E_T$ equations such as the Hargreaves Samani, the Penman Monteith and the FAO56 version of the Penman Monteith equation (Rezaei and Jarrett 2006, Schneider, Hilten 2004, Prowell 2006) have been somewhat successful. These equations were also included in a study by Voyde (2011) which tested several additional equations and found the FAO version of the Penman-Monteith (FAO56, Allen 1998) to be the most robust tool for predicting $E_T$ for green roof experiments using *D. australe* and *S. mexicanum*.

The FAO56 equation is derived from the Penman Monteith equation. The Penman Monteith equation (Equation 1) for calculating $E_T$ combines two approaches: a mass balance approach and an energy balance approach. The mass balance approach assumes water will diffuse away from the leaf surface in direct proportion to the vapor pressure deficit (VPD) of the surrounding air and the velocity of the wind at any given time. The energy balance approach infers $E_T$ from the difference between energy going into and out of the leaf, assuming no storage component. The format of this equation is:

$$\mathrm{ET} = \frac{\Delta(Rn - G) - \rho a c_p \frac{e_s - e_a}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \quad \textbf{... Equation 1}$$

where $R_n$ is net radiation at the crop surface, G is soil heat flux density, $\rho_a$ is the density of water, $c_p$ is the specific heat of dry air, $e_s$ is saturation vapor pressure, $e_a$ is actual vapor pressure, $r_s$ is the canopy surface resistance, $r_a$ is the bulk surface aerodynamic resistance, and $\Delta$ is the slope of the vapor pressure curve, and $\gamma$ is the psychometric constant. This is a widely used equation; further details about how to apply this equation can be found in a variety of textbooks (e.g., Campbell 1998).

The FAO version of the Penman Monteith equation (Equation 2) assumes some constant parameters for a clipped grass reference crop, i.e., a surface resistance of 70s $m^{-1}$ and an albedo value of 0.23.

$$ET_0 = \frac{0.408(R_n - G) + \gamma \frac{900}{T + 273} \mathrm{u}_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\mathrm{u}_2)} \quad \text{... } \textbf{Equation 2}$$

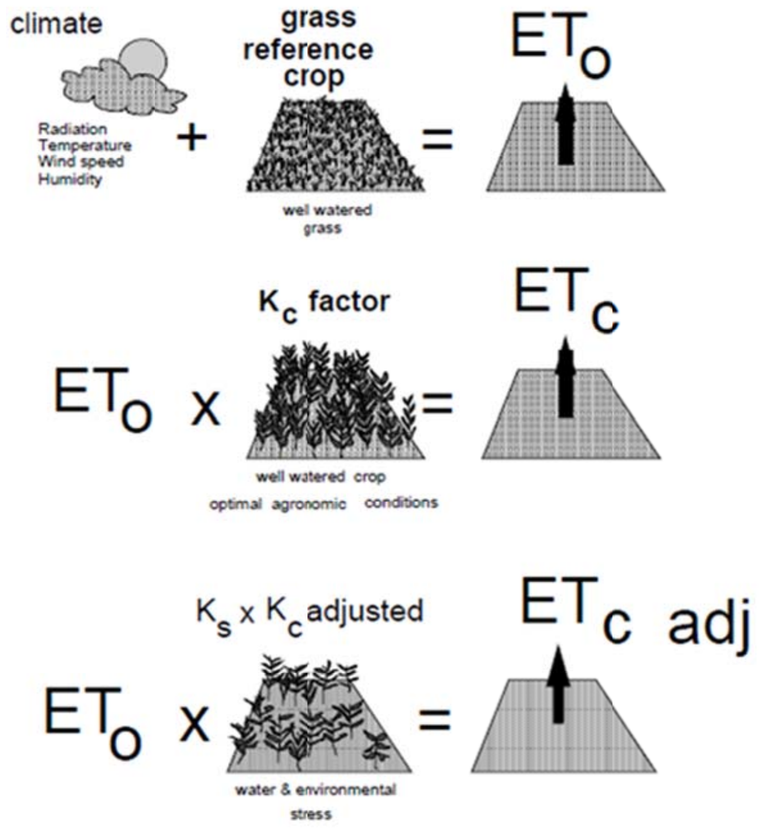
where T is the average daily temperature and $u_2$ is average daily wind speed. The equation can be adjusted for different crops by a "crop coefficient" multiplier (Figure 1.2; $k_c$ value) to account for species-specific differences in $E_T$. $K_c$ is calculated as the ratio of $E_{To}$ to actual $E_T$. For seasonal crops, different values are typically assigned throughout the year for changes in growth (leaf canopy).

A further adjustment is made to account for less than well-watered conditions, by introducing a water stress coefficient, $k_s$ (Chapter 8; Allen et al. 1998). This equation is described as:

$$k_s = \frac{TAW - D_r}{TAW - RAW} \quad \text{......}\textbf{Equation 3}$$

where TAW is total available water, $D_r$ is root zone depletion (mm), i.e., water deficit relative to field capacity, and RAW is water that is readily available to the plant (Figure 4.3). The coefficient ($k_s < 1$) is then used in conjunction with $k_c$.

**Figure 1.2** The FAO 56 adjusts ETo for crop specific characteristics and less than well watered conditions with $k_s$ and $k_c$ factors (from Allen et al., 1998).

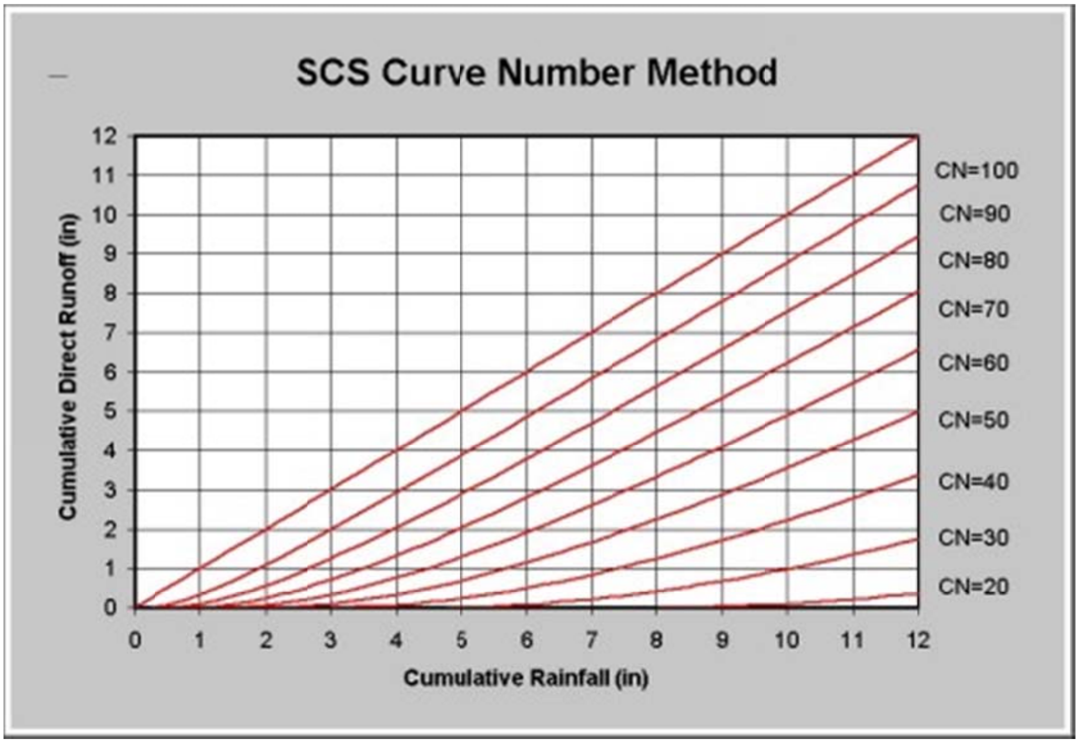


A general concern has been expressed regarding a lack of information available for determining appropriate crop coefficients (Voyde 2011, Sherrard and Jacobs 2012). Some unpublished work (DiGiovanni 2012, Voyde 2011) has suggested an overall green roof $k_c$ value is near 1 for well-watered conditions, indicating little difference in $E_T$ rates between *Sedum* plants and cool season grasses for which these equations were modified. Other studies have used one $k_c$ value (0.53; Sherrard and Jacobs 2012) for the whole year. The mid-season crop coefficients for the only CAM species in the FAO manual, pineapple, is 0.3, but is estimated to increase up to 0.5

later in the season (Allen et al. 1998). Establishing correct crop coefficients is important for mechanistic modeling of green roofs (see below).

To date, most models of stormwater retention by green roofs have been empirically constructed. Mentens et al. (2006) used a regression model to predict stormwater runoff from roofs in Belgium based on storm size. Similarly, US researchers and planners (Carter and Rasmussen 2006, MDE 2009) typically calculate how green roof implementation might affect the "curve number," or an empirically derived line representing a relationship between runoff and rainfall, for a given area (Figure 1.3).

**Figure 1.3** The United States Department of Agriculture (USDA) Natural Resources Conservation Service formerly the Soil Conservation Service (SCS) curve number method.

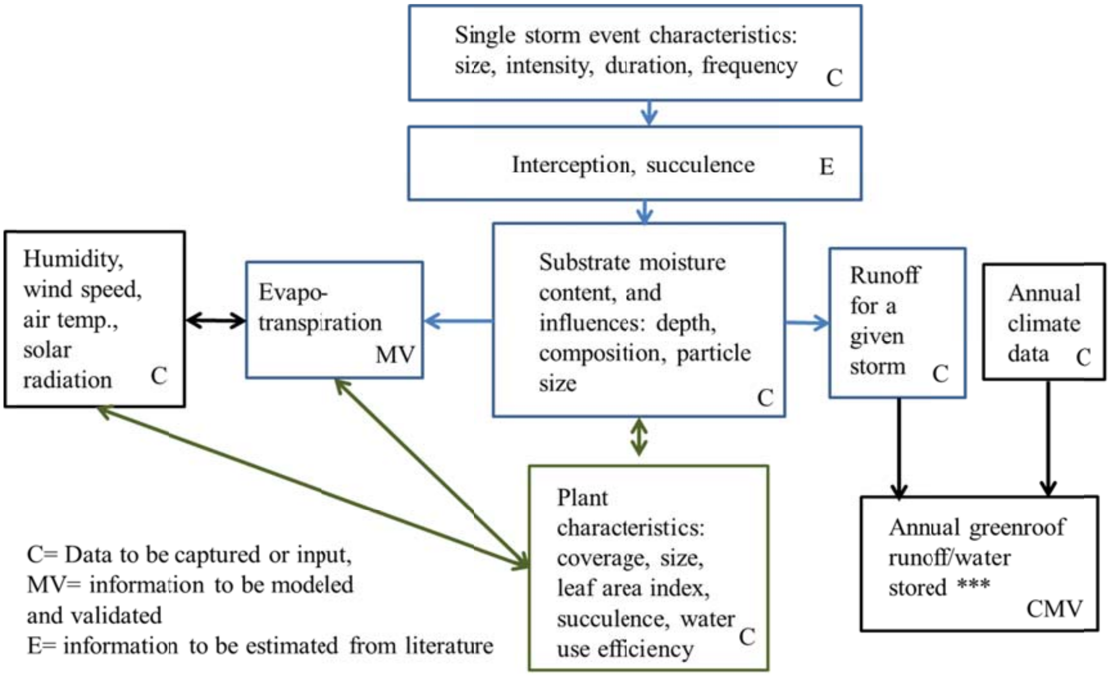


In contrast, mechanistic models of the green roof water cycle switch the focus on the underlying structures and functions responsible for stormwater storage by these systems. Mechanistic models are usually much more flexible to a wide range of data inputs. Current mechanistic models of green roofs are adaptations of the Hydrus 1-3-D models with green roof parameters (Prowell 2006, Palla et al., 2009). These have been proven to predict aspects of the green roof water cycle, such as spatial variation in substrate moisture content, very well, especially for the intensive roof in the latter Italian study. At the same time, Hydrus does require substantial parameterization (Prowell 2006) and possibly too much extraneous information. For example, these models predicted $E_T$ using the FAO Penman-Monteith equation, and more work is needed to adapt these equations for green roofs. A refined approach to parameterizing $E_T$ equations for these models is needed to improve mechanistic models.

### 1.2.7 Conceptual water balance model

Figure 1.4 describes a simple conceptual water balance model that illustrates how stormwater retention by green roofs might vary, associated with changes in daily environmental factors, plant characteristics and rainfall patterns, such as storm frequency and intensity. The elements of the basic water balance are shown in blue (Figure 1.4). I expect plant characteristics to have an effect on this balance and these influences may be related to coverage, height, leaf area index, and succulence (Figure 1.4 shown in green). Of course this influence is constrained by environmental parameters (Figure 1.4, shown in black).

**Figure 1.4** Conceptual model of how plants might influence the green roof water balance indicted by the green boxes and arrows



### 1.3 Research objectives and hypotheses

The goal of the research proposed here was to better understand how plants and climate influence the green roof water cycle, in order to better predict how green roofs retain stormwater. I hypothesized that *Sedum* plants contribute to stormwater retention, however the extent of this influence will vary for different planting and climate scenarios. In order to test this hypothesis, experiments were conducted in environmentally controlled plant chambers as well as in the field.

In experimental plant chambers, rates of photosynthesis and water use were monitored for *S. album* and *S kamtschaticum* with increasing drought stress in order to assess different physiological responses by these species. I predicted that *Sedum album* would switch to CAM metabolism at a higher moisture content, and as such be more tolerant to drought with a greater water use efficiency.

In the field, 16 experimental green roof platforms were constructed and planted in either *S. album*, *S. sexangulare*, *S. kamtschaticum* or left unplanted (n=4). I predicted that (a) planted green roofs would have higher water-holding capacities than non-planted ones and a positive correlation between substrate WHC and root biomass would be observed over time; (b) planted platforms would have higher rates of $E_T$, which would be correlated with leaf area and total leaf area; (c) planted green roofs would have greater overall stormwater retention efficiencies, and that differing efficiencies could be related to species-specific differences in $E_T$ and WHC between rainfall events.

Finally, data from the aforementioned experiments were used to parameterize the FAO56 $E_T$ equations and to generate $k_c$ coefficients for the different species by seasons over two years. These rates of $E_T$ were tested in simple water balance models. I predicted that $k_c$ values would vary by season for each of the different species investigated, which could be used to increase the precision and accuracy of the FAO56 Penman-Monteith equation, to predict daily water use from green roofs.

# **Chapter 2.** A comparison of CAM expression and water use efficiency by *Sedum album* and *Sedum kamtschaticum*, with decreasing water availability

## 2.1 Introduction

Crassulacean acid metabolism (CAM) is the process via which plants fix carbon dioxide ($CO_2$) in the form of malic acid at night, so it can be metabolized the following day with stomates closed, which reduces plant water loss (Wolf 1960). There are many proposed evolutionary benefits of this process ranging from a reduced need to compete for $CO_2$ in aquatic plants, to photoprotection and enhanced reproduction; however, it is primarily thought to be an adaptation to drought stress in land plants (Herrera 2009). Four stages of CAM (Osmond 1981, Dodd et al. 2002) have been described: 1) nocturnal uptake of $CO_2$ and fixation by phosphoenolpyruvate carboxylase; 2) a short period of $CO_2$ uptake with stomates opening at dawn; 3) daytime release and assimilation of $CO_2$ via the Calvin cycle; and 4) a final period of stomatal opening at dusk when stored acid has been depleted.

Varying degrees of CAM have been described, ranging from “CAM idling” whereby plants recycle their respiratory $CO_2$ (Martin et al. 1988, Borland and Griffiths 1990), to obligate CAM, to “CAM cycling” in which plants switch between CAM and C3 photosynthesis (Borland 1990, Cushman and Borland 2002, Dodd et al. 2002, Luttge 2004). Important environmental cues eliciting CAM response from CAM cyclers include temperature and climate (Kluge 1977, Schuber and Kluge 1981, Pilon-Smits et al. 1991), water availability (Osmund 1989, Cushman and Borland 2002), light (Brulfert et al. 1973), and nutrient availability (Nobel 1983). Though general patterns are emerging, the relative importance of these CAM triggers has been shown to be species-specific (Pilon-Smits et al. 1991).

S*edum* species constitute a large number of the CAM species described in the literature (Smith and Winter 1996, Sayed 2001), and economic and ecological interest in this genus has grown in recent years due to their use for green roofs (Snodgrass and Snodgrass 2006). Green roofs are living roof systems that incorporate planted substrate above waterproofing and roof drainage layers. These roofs provide a number of ecosystem services, including stormwater management (Oberndorfer et al. 2007, Palla et al. 2010). Sedum species are especially successful in green roof installations in the American northeast and Midwest (Duhrman et al. 2006, Butler and Orians 2011), where green roof habitats are analogous to open rocky areas such as shale barrens (Lundholm and Marlin 2006). The long-term success of *Sedum* in these green roof installations has been attributed to their drought tolerance and CAM metabolism (Duhrman et al. 2006). At the same time, it has been questioned whether *Sedum* species are able to contribute to stormwater management by green roofs if the plants are not contributing as much as C3 plants would, to roof water loss between storms (Wolf and Lundholm 2008). CAM cyclers, with the ability to use water rapidly when it is available but also conserve water in times of drought, may be the best suited to green roof conditions, to optimize stormwater reduction benefits.

Environmental factors which trigger CAM are better understood for some green roof species such as *S. album*, compared other species such as *S. kamtschaticum*, a broad leafed *Sedum* native to central China and Siberia (Stephenson 1994). In fact, the status of the latter as a CAM species, has been questioned (Kim and Choo 2007), while some have classified it as a facultative species (Lee and Kim 1994). *Sedum album*, native and common to most areas of Europe (Stephenson 1994), is a facultative CAM plant, and induction is thought to be triggered by many factors, including drought, leaf turgor, light (Bachereau et al. 1998), and particularly temperature (Earnshaw et al. 1985, Sayed et al. 1994, Castillo 1996).

Less is known about how photosynthetic plasticity might affect water use efficiency by CAM plants and thus, overall green roof water balance. Estimates of water use by CAM plants in natural systems have been variable (Herrera 2009). The water use efficiency (WUE), or amount of water used relative to carbon fixed, of several Sedum species, *S. kamtschaticum* and *S. album* excluded, was not significantly related to the amount of nighttime $CO_2$ fixed (Gravatt and Martin 1992). This may be due to the influence of morphological features of these plants that aid in water conservation independent of stomatal opening (Herrera 2009). Results may be different comparing responses within vs. among species. Virzo de Santo and Bartoli (2009) found water use efficiency to increase with increasing drought stress for the CAM plant *Cissus quadrangularis*. Finally, one challenge to understanding the relationship between CAM and WUE may be the scale and duration at which investigations are conducted; most have typically measured gas exchange from a few detached leaves or shoots for a few hours. Few, if any, previous studies have investigated water use efficiency for CAM plants continuously at the whole plant scale.

The objectives of this study were to 1) compare $CO_2$ exchange, rates of evapotranspiration (ET), and water use efficiency for *Sedum album* and *Sedum kamtschaticum*, two commonly used green roof species, and 2) assess the effect of CAM cycling on water use efficiency with increasing drought stress at the whole plant scale. I predicted that *S. kamtschaticum* would enter into CAM photosynthesis at lower VWC than *S. album* and that this would affect overall carbon gain, ET rates, and WUE.

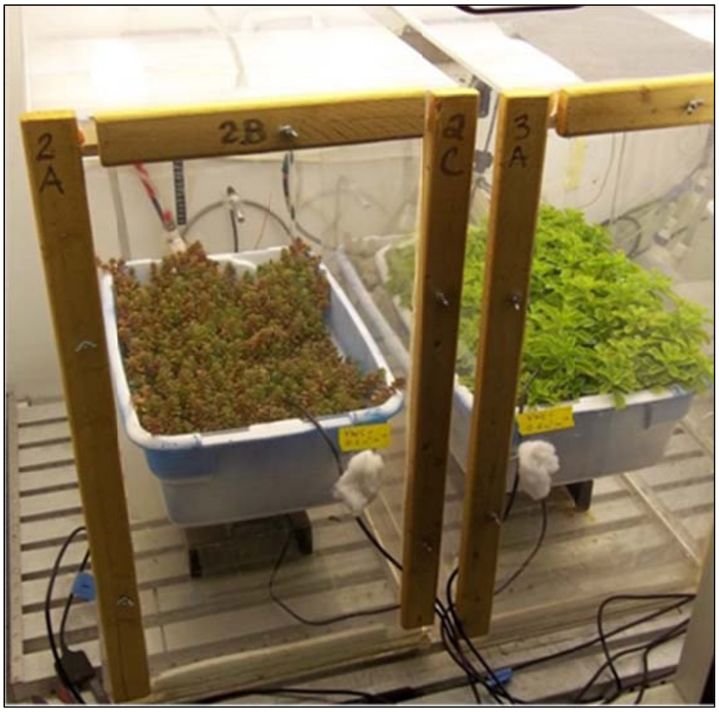
## 2.2 Materials and Methods

Two separate experimental trials were conducted to address these questions. The first experiment took place during March 2011; the second was conducted during September 2012.

### 2.2.1 Experiment One

Plant Preparation: *S. album* and *S. kamtschaticum* were started as plugs in early October, 2010 and grown for approximately five months in plastic containers (16.5 L) with holes in the bottom for drainage, filled to a depth of ten centimeters with approximately 5 kg of green roof substrate (M2 substrate, Stancills Inc., Perryville MD). The substrate was a baked clay with an initial bulk density of 0.75g/mL, with 8% of particles less than 0.5mm; pH was 7.2, and organic matter content was 3.8% by mass (Pennsylvania State University, 2010). The plants were grown in an experimental greenhouse at the University of Georgia in Athens, Georgia, until 28 February 2011 when they were transferred into growth chambers (Conviron E-15, PGR15, Winnipeg, Canada), which had been retrofitted for whole plant gas exchange (van Iersel and Bugbee, 2000; Fig. 2.1). Four acrylic gas exchange chambers (0.32 × 0.5 × 0.6 m) were fitted within each of two larger growth chambers, for a total of eight gas exchange chambers. Four replicate containers planted in each species were distributed into the gas exchange chambers such that each larger growth chamber contained two replicate trays of each species.

**Figure 2.1** Two of the 10 acrylic chambers in which gas exchange was monitored. *S. album* is pictured on the left, and *S. kamtschaticum* is pictured on the right. Wires leading from the moisture sensors in the substrate are visible. All containers were placed on load cells to quantify changes in weight loss due to evapotranspiration.



Gas Exchange Measurements. This gas exchange system (van Iersel and Bugbee 2000) has been used in numerous physiology studies and is described in detail (Kim and van Iersel 2011). The $CO_2$ exchange from eight planted containers, each within its own acrylic gas exchange chamber was continuously measured and recorded using a datalogger (CR10T; Campbell Scientific, Logan, UT). Air flow through each gas exchange chamber ($\approx$17 mmol $s^{-1}$) was measured with mass flow meters (HFM200; Teledyne Hasting Inst., Hampton, VA) and the difference in $CO_2$ concentration between the air entering and exiting the gas exchange chambers was measured with an infrared gas analyzer in differential mode (LI-6262; Li-Cor, Lincoln, NE). Whole-plant $CO_2$ exchange rates (µmol $s^{-1}$) were calculated as the product of mass flow (mol $s^{-1}$) and the difference between the $CO_2$ concentration of the air entering and exiting chamber (µmol $mol^{-1}$). Two empty gas exchange chambers were placed outside of the growth chambers and were measured to determine the zero drift of the differential $CO_2$ analyzer. Gas exchange data were corrected for this zero drift by subtracting the $CO_2$ exchange rate of the empty chambers from that of the chambers with plants in them. The $CO_2$ exchange of each chamber was measured for 30 s, once every 10 min. The daily light period in each chamber was 12 hours, and photosynthetically active radiation (PAR) was approximately 400 µmol $m^{-2}$ $s^{-1}$ at the canopy level. Plants were kept well watered until March 11, 2011 when the experiment began, and watering ceased. Environmental variables (temperature, relative humidity, $CO_2$ concentration, vapor pressure deficit) were monitored continuously in all experimental replicates.

### 2.2.2. Experiment Two

Plant Preparation. Seedlings of *S. album* and *S. kamtschaticum* were grown from plugs (Emory Knoll farms, Street, MD) in the same plastic containers described for experiment one. Starting in late March of 2012, four replicate containers with six plants of each species were maintained in a growth chamber for four weeks in College Park, MD. Plants were kept on a 12 hour light cycle at 15 and 10 °C during light and dark periods respectively at PAR levels of approximately 1100 µmol $m^{-2}$ $s^{-1}$ using high intensity (HID) lights, watered weekly to saturation, and drained to field capacity. After two weeks, temperatures for both dark and light periods were increased by 5 °C, respectively. In early May 2012, irrigation ceased and plants were brought outside the greenhouse facility at the University of Maryland, College Park, MD, where they remained until 19 September, 2012. During this time average air temperature ranged from 16-25 °C, average relative humidity was 65%, and average daily PAR was 473 µmol $m^{-2}$ $s^{-1}$. In September, the trays were transported to Athens Georgia, where the gas exchange experiments were conducted.

Gas Exchange and Daily Carbon Gain. Gas exchange experiments were conducted following the same protocol for experiment one, except the day / night temperature regime was varied. On average, chambers were kept at 19.5 °C during the day and 15 °C at night, as these temperatures are typical for the month of September in Maryland (Appendix D). The photoperiod was 12 hours, and PAR at the canopy level ranged from 331 to 363 µmol $m^{-2}$ $s^{-1}$ among chambers. Daily carbon gain was calculated as the net carbon assimilated by each species over a 24-hour period.

Water use monitoring and water use efficiency. Plants were thoroughly watered on both 20 and 21 September, at which point gas exchange and soil moisture monitoring began. Trays were not re-watered until Day 22 of the experiment (12 October) and again on the 15 October. The volumetric water content (VWC), reported here as the volume of water/total volume sensed basis, of each tray was measured by a soil moisture sensor (5TM, Decagon, Pullman, WA), placed in the center of each container, vertically positioned at 2.5 cm depth, and parallel to the long side of the container. The Echo-TM sensors were calibrated for this M2 green roof substrate, following the Decagon calibration procedure (Cobos and Chambers 2010). Due to the rapidly draining feature of this substrate, the calibration procedure was amended to include one point relating sensor output to VWC at conditions above field capacity (see Appendix B). The weights of each container were also recorded continuously by individual load cells (ESP-10; Transducer Techniques, Temecula, CA). Daily evapotranspiration was calculated as the total water weight lost from each container of plants over a 24 hour period, expressed on a shoot dry weight basis. Water use efficiency was calculated as daily carbon gain divided by daily evapotranspiration.

Plant Harvest and Malic Acid Analysis. Approximately five grams of plant material were harvested from each tray at the beginning and end of the light cycle on two occasions during the study. The first sample set was taken on the evening of Day 22, and on the morning of Day 23 at which point VWC for *S. kamtschaticum* and *S. album* was 0.04 and 0.07 $m^3 m^{-3}$, respectively. The second set of samples were taken one week later after re-watering on Day 29 and 30 when VWC averaged $0.18 m^3 m^{-3}$

and 0.21m$^3$ m$^{-3}$ for *S. kamtschaticum* and *S. album*, respectively. Samples were frozen in liquid nitrogen and stored at -80 °C. These plant samples were analyzed for malic acid content in early January 2013. Approximately one gram of sample was thawed, ground in 3 mL of malic acid buffer, and centrifuged. Malic acid in the supernatant was determined via spectroscopy (Spectrogenesis III) according to an adaptation of Mollering (1974), modified by Unitech Scientific, CA. At the end of the experiment, the remaining aboveground plant material was harvested and dried at 80 ºC for two weeks before dry weights were determined.

Experimental Design and Statistical Analysis. The experimental design for both experiments was a randomized complete block design with four replicates of each plant species. All differences in experimental response variables including overall water use and daily carbon gain, were compared between treatments using t-tests for equal variance in Excel (Microsoft Corp. Seattle WA). The same test was also used to compare average experimental conditions including temperature, relative humidity, $CO_2$ concentration, as well as plant and tray dry weight, for each treatment. Malic acid concentrations at the beginning of dark and light periods were compared for each species using paired t-tests.

## 2.3 Results

### 2.3.1 Materials used and experimental conditions

Small but significant differences were observed in the dry weight of the materials used in both experiments (Table 2.1). For experiment one, the average dry weight of the *S. album* plants (41.62 ± 2.8) was significantly different (*p= 0.035*) from that for *S. kamtschaticum* (29.97±3.4). The dry weights of the containers, including substrate, used in experiment are unavailable. For experiment two, the dry weight of the containers planted with *S. album*, not including plant material, was on average 4 % less than that of the trays in which *S. kamtschaticum* were planted, but this difference was not significant (*p = 0.056*).

**Table 2.1** Average aboveground biomass (g) from both experiments. Asterisks indicate significant differences between species (t-test, p<0.05). Standard error (SE) is also indicated.

| | *S. album* | SE | *S. kamtschaticum* | SE | t |
|---|---|---|---|---|---|
| Biomass Experiment 1 | 41.62 | 2.77 | 29.97 | 3.35 | 2.70* |
| Biomass Experiment 2 | 43.44 | 2.64 | 31.87 | 2.48 | 2.76* |

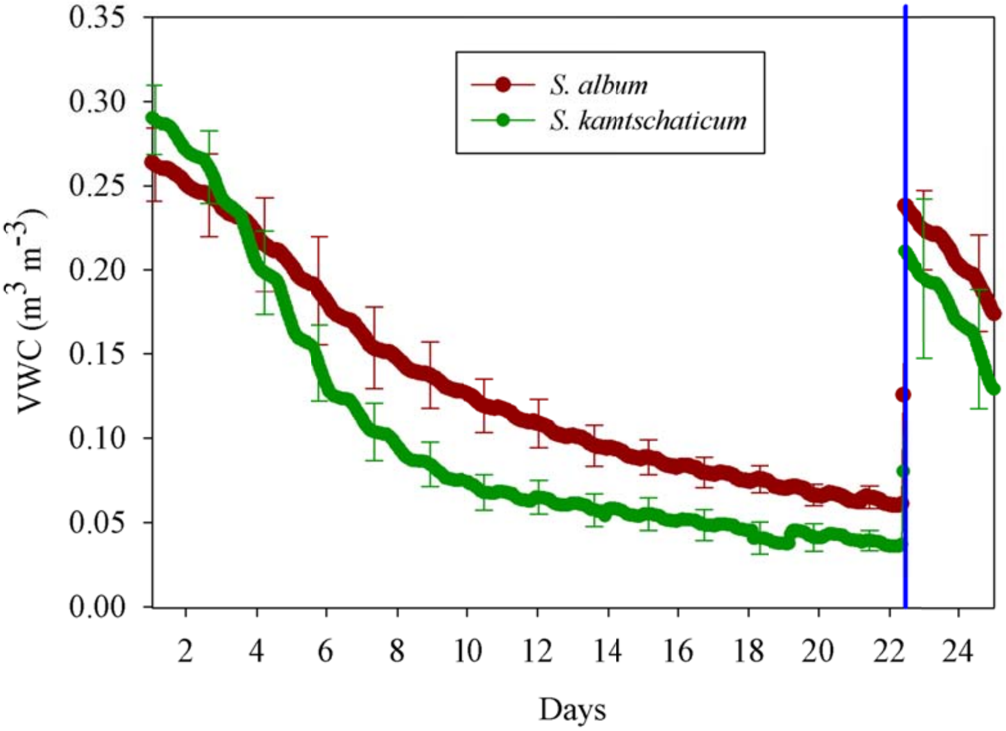
The average dry weight of the *S. album* plants (43.44 ±2.6 g) used in study 2 was 30% greater that of *S. kamtschaticum* (31.87±2.5 g, *p*= 0.032). Because of these differences, we normalized our physiological data based on plant dry weight. Experimental conditions are provided in Table 2.2. Temperature settings were very constant throughout the study period and on average deviated less than 2 ºC from desired set points. Relative humidity declined as the experiment progressed and vapor pressure deficit increased (Table 2.2).

**Table 2.2.** Environmental conditions averaged, for dark and light periods, for all four replications of each treatment. Minimum (Min), maximum (Max), and average (Avg) values for all days of the experiment from 9/21 until re-watering on October 12 are also provided.

| Parameter | Period | *S. Album* | | | *S. Kamtschaticum* | | |
|---|---|---|---|---|---|---|---|
| | | **Min** | **Avg** | **Max** | **Min** | **Avg** | **Max** |
| Relative Humidity (%) | dark | 52.27 | 60.14 | 77.65 | 50.82 | 58.79 | 79.25 |
| | light | 41.50 | 53.01 | 71.58 | 39.98 | 52.85 | 76.23 |
| Vapor Pressure Deficit (kPa) | dark | 0.42 | 0.76 | 0.97 | 0.39 | 0.79 | 0.93 |
| | light | 0.76 | 1.26 | 1.60 | 0.62 | 1.26 | 1.67 |
| Temperature (°C) | dark | 16.33 | 16.58 | 20.33 | 16.26 | 16.55 | 20.29 |
| | light | 20.66 | 20.89 | 22.61 | 20.57 | 20.92 | 21.77 |
| Incoming $CO_2$ (ppm) | All 24 hours | 369.40 | 420.40 | 485.57 | 372.95 | 418.90 | 490.40 |

Vapor pressure deficit was lower during the dark hours and relative humidity was higher, but there were not significant differences among treatments. The range in incoming $CO_2$ spanned approximately 100ppm for each species but this variation was randomly distributed amongst treatments.

**Figure 2.2** Stepwise decline in volumetric moisture content ($m^3$ $m^{-3}$) presented for *S. album* (red) and *S. kamtschaticum* (green) for the duration of the experiment. Standard errors are shown every 36 hours. The vertical blue line indicates time of re-watering.



### 2.3.2 Volumetric water content and evapotranspiration

Throughout Exp. one net $CO_2$ exchange was rarely above zero during the dark hours (Fig. 2.6a), for reasons explained in the discussion. Because we did not observe CAM, nor any species-specific differences during Exp one, results presented refer to Exp. two, unless noted. The range of substrate VWC was similar for both species from a maximum of 0.28$m^3$ $m^{-3}$ to a minimum of 0.04 $m^3$ $m^{-3}$ (Fig. 2.2). After re-watering, water content increased to 0.26 and 0.25 $m^3$ $m^{-3}$ for *S. album* and *S. kamtschaticum*, respectively.

Rates of evapotranspiration were higher during the day than at night for both species, demonstrated by the stepwise decline in VWC (Fig. 2.2). For *S. kamtschaticum* day-time rates were four times higher than night-time rates, and this proportion increased as the experiment progressed. For *S. album*, day-time rates were only three times as great as night-time rates and this proportion *decreased* as the experiment progressed (Fig. 2.3). Evapotranspiration was reduced with decreasing VWC, and was sigmoidal for both species (Fig. 2.4). For *S. album*, total daily $E_T$ ranged from 213mL at 0.21 $m^3$ $m^{-3}$ VWC, down to 28mL at 0.05 $m^3$ $m^{-3}$ VWC, before correcting for dry weight. Dividing by the surface area of the containers (984$cm^2$) results in an $E_T$ range for *S. album* of 2.15 to 0.28 mm $day^{-1}$. For *S. kamtschaticum*, total daily rates of $E_T$ (before correcting for dry weight) ranged from 287mL at 0.25 $m^3$ $m^{-3}$ VWC down to 12mL at 0.02 $m^3$ $m^{-3}$ VWC, equivalent to an $E_T$ range of 2.91 to 0.12 mm $day^{-1}$. After correcting for average dry weight, the ranges were 0.04 to 0.006 mm $d^{-1}$ $gdw^{-1}$ for *S. album* and 0.09 to 0.003 mm $d^{-1}$ $gdw^{-1}$ for *S. kamtschaticum*.

**Figure 2.3** Evapotranspiration per unit dry weight for *S. kamtschaticum* (green, left) and *S. album* (red, right) during a gradual dry down (day 1 – 21) and following re-watering (day 22-24). Vertical blue lines indicate re-watering on the 22nd day of the experiment.

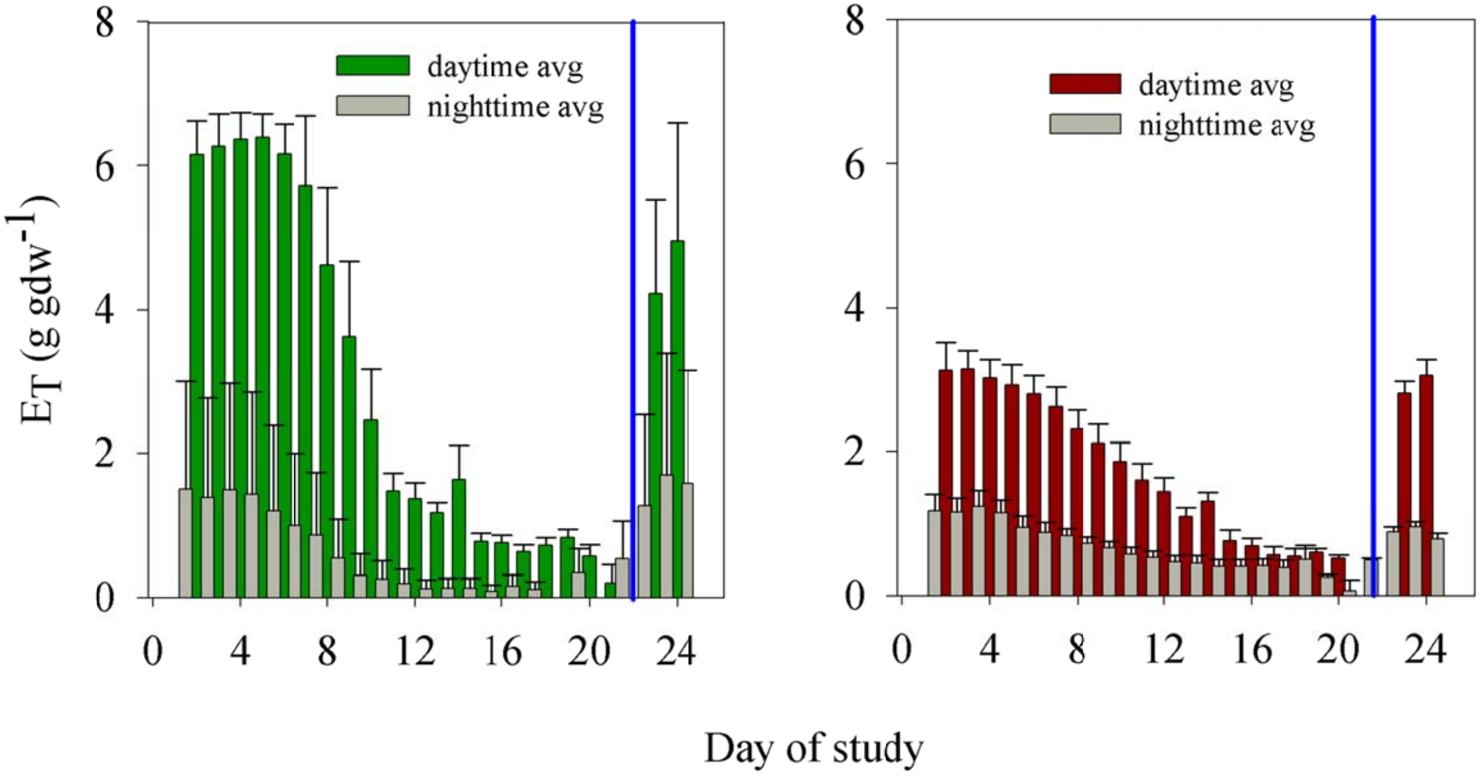
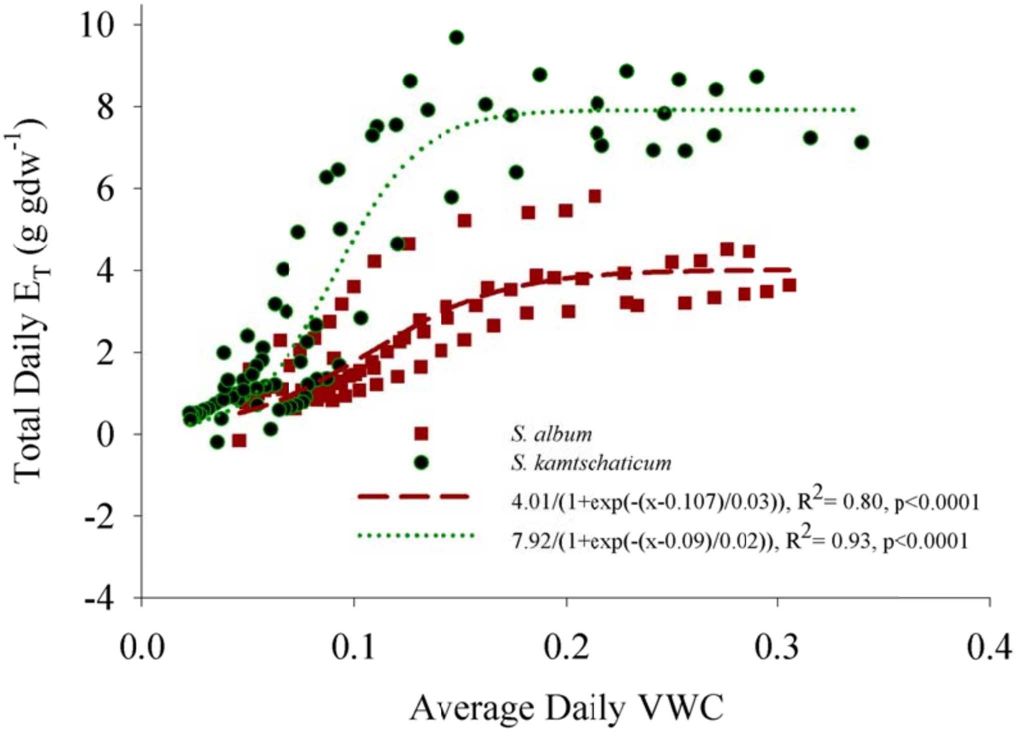


**Figure 2.4** Change in $E_T$ with change in VWC for both *S. album* (red) and *S. kamtschaticum* (green). Data points are daily averages taken for each chamber over the course of the experiment but prior to re-wetting. Data is fitted with sigmoidal equations for each species.

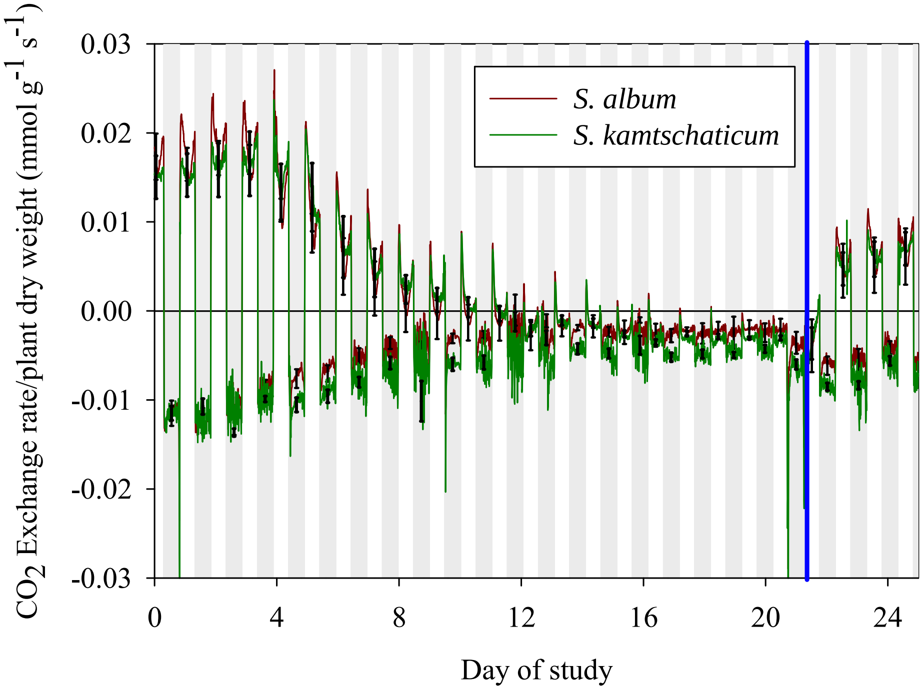


2.3.3 $CO_2$ exchange and malic acid content.

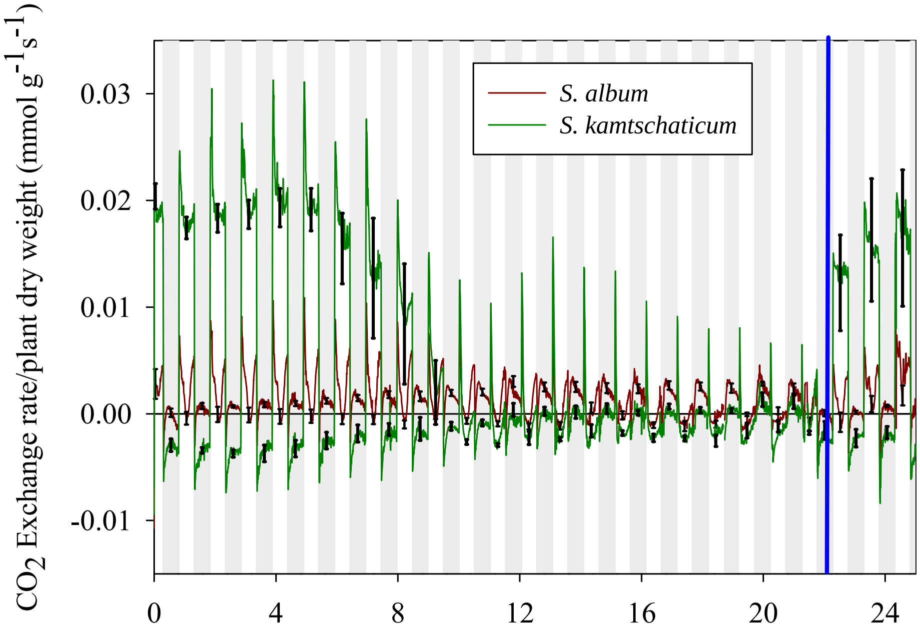
*Sedum kamtschaticum* generally had higher rates of $CO_2$ exchange during the day and *Sedum album* had higher rates of $CO_2$ exchange during night-time hours (Fig. 2.5b). Daytime rates of $CO_2$ exchange for *S. kamtschaticum* remained fairly constant even after seven days of drought, after which day-time gas exchange was reduced; night-time rates became positive around day 14 (Fig. 2.5b, Figs. 2.6a-c). Rates of nighttime $CO_2$ exchange were positive from the onset of the experiment for *S. album*, whereas night-time rates of exchange increased as daytime rates declined throughout the drought stress period (Figs. 2.6a-c).

**Figure 2.5** Changes in $CO_2$ exchange after watering ceased by each species for (a) experiment one and (b) experiment two. The blue line indicates re-watering. Gray and white lines distinguish between light and dark periods. Average rates and standard errors are shown every 12 hours.

**a.**



**b.**



Rates of $CO_2$ exchange for both species recovered quickly to match pre-drought conditions after re-watering (Fig. 2.5a-b). However, after re-watering, *S. album* continued to exhibit $CO_2$ exchange typical of CAM. On both dry and wet sampling dates, malic acid content of *S. album* increased overnight ( $p$=0.01) while that of *S. kamtschaticum* did not ($p$ = 0.18; Fig. 2.8).

**Figure 2.6a-c** $CO_2$ exchange for *S. album* (red) and *S. kamtschaticum* (green); (**a)** after only 4 days without watering on 9/26/2012, day 6 of the study, at on average 0.19 and 0.15 $m^3$ $m^{-3}$ volumetric water content (VWC), respectively (**b)** on 9/30/2012, day 10 of the study, at on average 0.13 and 0.07 $m^3m^{-3}$ VWC, respectively, and (**c)** on the driest day of the experiment, 11/11/2012, day 21 of the study, at on average 0.06 and 0.08 $m^3m^{-3}$ VWC, respectively.

**a.**

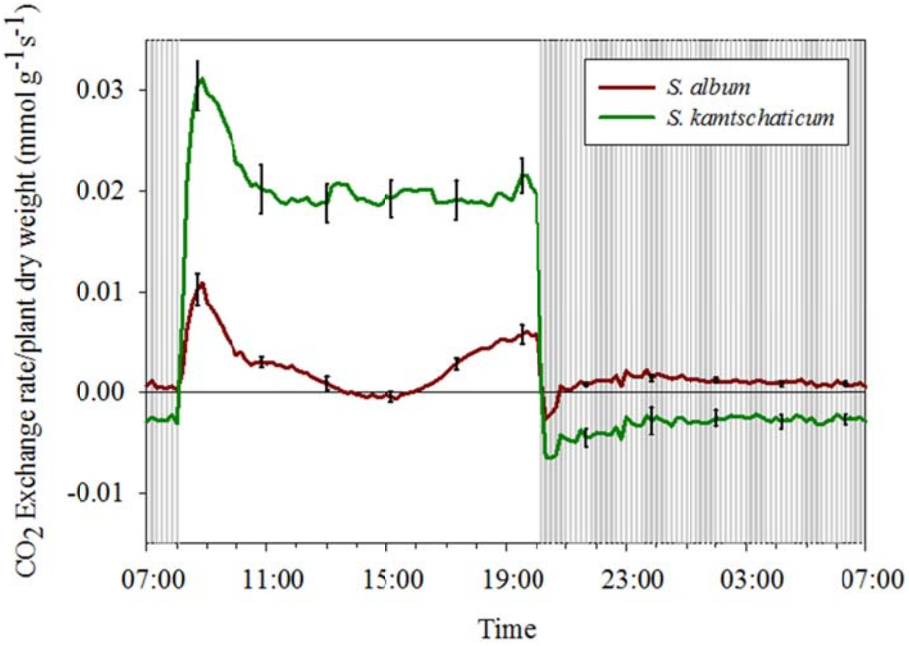
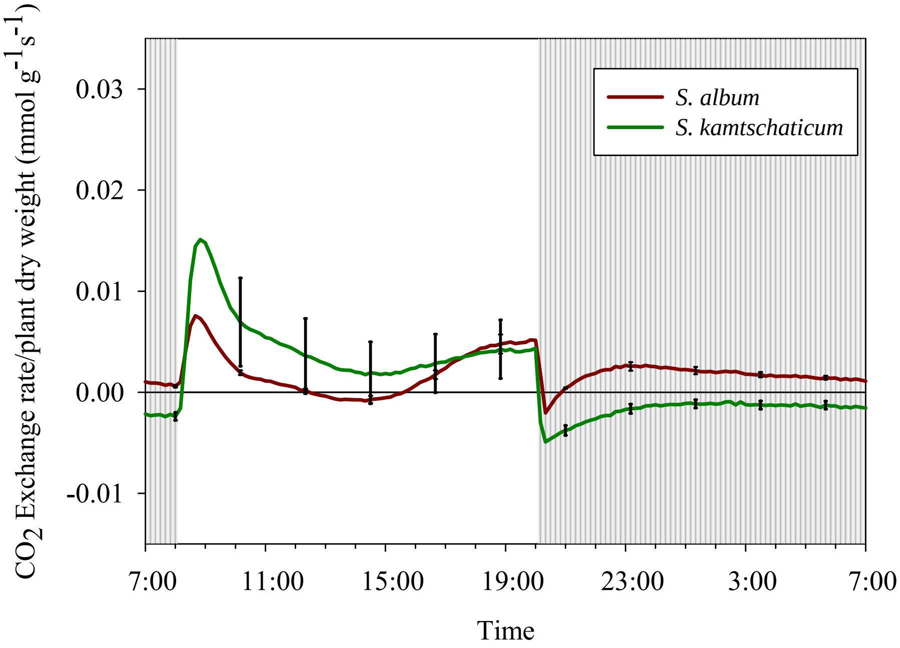


**Figure 2.7b-c** $CO_2$ exchange for *S. album* (red) and *S. kamtschaticum* (green); (**b)** on 9/30/2012, day 10 of the study, at on average 0.13 and 0.07 $m^3m^{-3}$ VWC, respectively, and (**c)** on the driest day of the experiment, 11/11/2012, day 21 of the study, at on average 0.06 and 0.08 $m^3m^{-3}$ VWC, respectively.

**b.**



**c.**

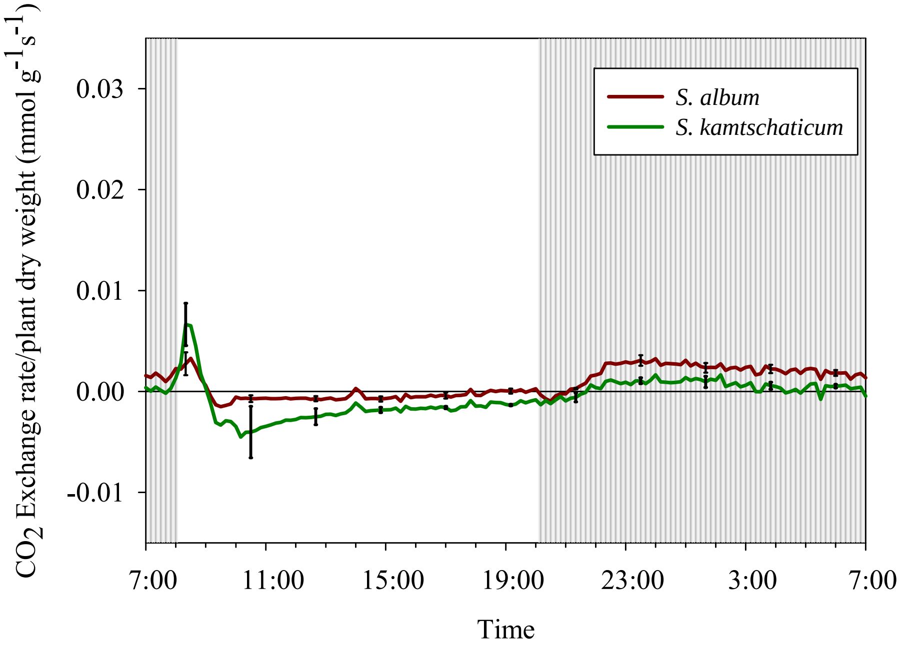
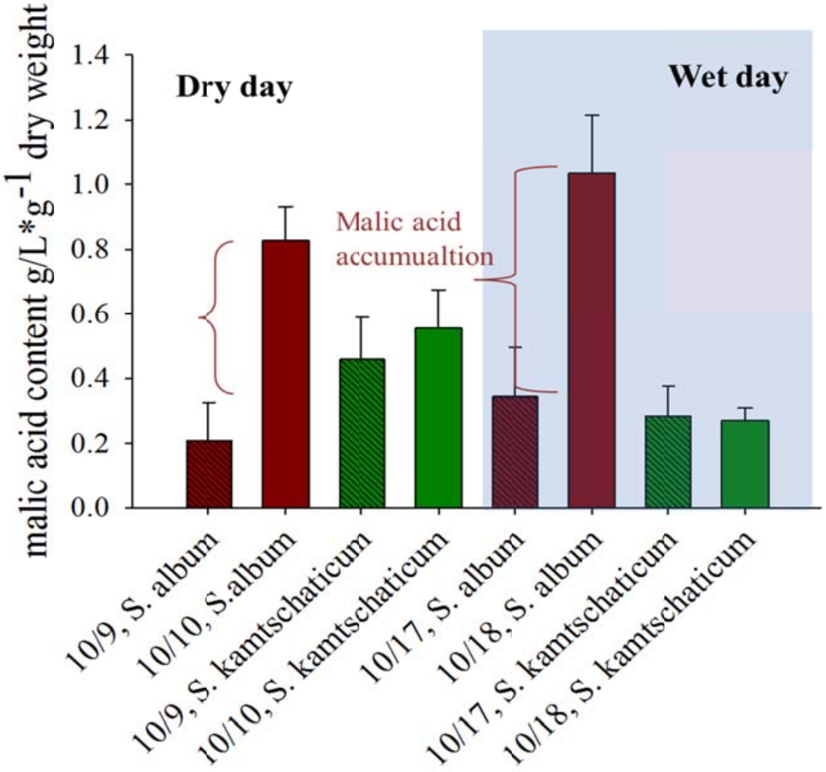


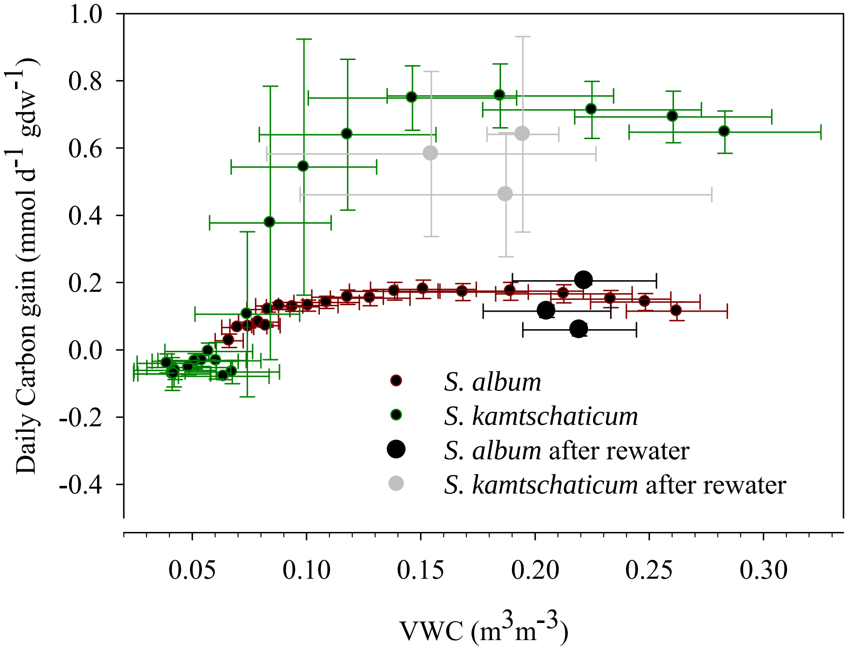
**Figure 2.7** Malic acid content of plant leaves at which point volumetric water content (VWC) was 0.07 and 0.04 m$^{3}$ m$^{-3}$ for *S. album* and *S. kamtschaticum* (dry day) and at which point VWC was 0.21 and 0.17 m$^{3}$ m$^{-3}$ for *S. album* and *S. kamtschaticum* respectively (wet day).



### 2.3.4 Daily carbon gain

In total, *S. album* fixed significantly less carbon during the dry down period (2.55 ±0.30 mmol C per gram dry weight) in comparison to *S. kamtschaticum* at 4.68 (±0.74) mmol per gram dry weight (*p=0.04*). The DCG of *S. album* was between 0.08 and 0.13 mmol d$^{-1}$ g$^{-1}$ as the VWC decreased from 0.21 to 0.08 m$^{3}$ m$^{-3}$ and decreased more rapidly as VWC dropped below 0.07m$^{3}$ m-$^{3}$. DCG of *S. kamtschaticum* was between 0.6 and 0.8 mmol d$^{-1}$ g$^{-1}$ at VWC between 0.30 and 0.12 m$^{3}$ m$^{-3}$, but decreased rapidly as the VWC decreased below 0.12 m$^{3}$ m$^{-3}$ and became negative at a VWC of 0.06 m$^{3}$ m$^{-3}$ (Fig. 2.8).

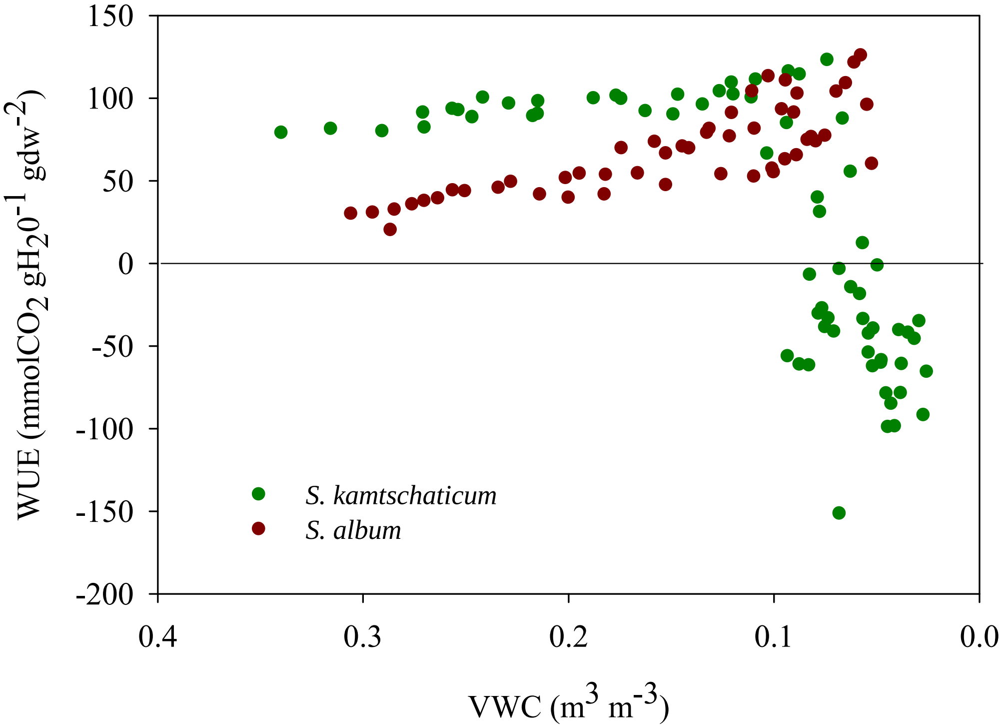
**Figure 2.8** Daily carbon gain as a function of substrate water content during a gradual dry down and following re-watering for *S. album* (red, black) and *S. kamtschaticum* (green, grey).



### 2.3.5 Water use efficiency

*Sedum album* became increasingly water efficient with drought stress, and WUE for *S. kamtschaticum* remaining constant before rapidly declining at around 0.08m$^3$ m$^{-3}$ VWC (Fig. 2.9). In total, 45.82 (±4.15) and 68.87 (±8.15) g of water evapotranspired from *S. album* and *S. kamtschaticum* containers per gram of plant dry weight respectively; this 35% reduction in ET for *S. album* compared to *S. kamtschaticum* was significant (p = 0.045).

**Figure 2.9** Water use efficiency (WUE) relative to VWC for *S. album* (red) and *S. kamtschaticum* (green).



## 2.4 Discussion

### 2.4.1. Experiment 1: Results and Implications

During the first experiment (Fig. 2.6A), neither plant species strongly demonstrated CAM metabolism. The most plausible explanation for this was the constant day and night temperature; diurnal variation in day and night temperatures are optimal for growth in this species under drought stress, and it is presumed that being able to switch to CAM metabolism during drought was responsible for this increase in growth (Sayed et al. 1994). Other CAM species such as *S. acre* have also been shown to require a variation in day and night temperature in order to switch into CAM (Kluge 1977). If this pattern were generalized for a number of other Sedum species used on greenroofs, this could present a challenge for Sedum species in geographic areas that do not experience large shifts in day and night temperatures (Livingston et al. 2004).

Furthermore, green roof substrates which are known to retain heat well into the night (Susca et al. 2011) create dampened temperature cycles which could impede CAM. Plant age or size may have also influenced induction, but this is less likely. Ontogenetic CAM induction for *Mesembryanthemum,* the species for which this phenomenon is most referenced, has been shown to be more influenced by salinity and relative humidity (Winter and Holtum 2005). Further research is necessary, but it is likely a lack of CAM in the first experiment was due to the constant day/night temperatures used in this experiment.

### 2.4.2 Comparing carbon exchange and acid accumulation

In contrast during Exp. two, both species demonstrated all four stages of CAM metabolism (Osmond 1981, Dodd et al. 2002) with some modification (Fig. 2.5b; Figs. 2.6a-c). Both plant species clearly showed stages 2-4, i.e., where $CO_2$ exchange is highest just after dawn, reduced during the midday hours, and increased again at dusk. *Sedum album* demonstrated this pattern throughout the experiment, but for *S. kamtschaticum*, this pattern only becomes markedly clear around Day 14, at 0.08 $m^3\ m^{-3}$ VWC. Stage one of CAM, whereby $CO_2$ exchange becomes positive at night was also evident throughout the experiment for *S. album*, and nighttime exchange increased with drought stress for this species. For *S. kamtschaticum* positive nighttime $CO_2$ exchange was minimal, but did occur between Days 17- 26 at range of 0.06-$m^3$ $m^{-3}$ substrate moisture content (Fig. 2.5b; Figs. 2.7a-c). These results indicate that *S. album* was carrying out CAM metabolism throughout the experiment; they are supported by increased concentrations of malic acid observed in plant tissues at the end of the dark period on Day 23 at 0.07 $m^3$ $m^{-3}$ VWC (Fig. 2.7) compared to concentrations at the beginning of that dark period. *Sedum kamtschaticum* was carrying out C3 photosynthesis at the onset of the experiment. Net $CO_2$ eventually became positive at night, but not until Day 23 at very low substrate water content (0.04 $m^3$ $m^{-3}$); average malic acid content was higher at the end compared to the beginning of the dark period, though this difference was not significant. I therefore conclude that this species is capable of CAM metabolism, though night-time carbon assimilation was small. Of course, it is possible that I did not find the key set of environmental variables that trigger a strong CAM response in *S. kamtschaticum*.

### 2.4.3 Species effects on water use efficiency and evapotranspiration

*Sedum album* demonstrated a clear increase in water use efficiency with increasing drought stress (Fig. 2.9) because of its ability to maintain steady carbon gain (Fig. 2.8), but showed decreased water use (Fig. 2.4) as VWC decreased from 0.15 $m^3m^{-3}$ to 0.06 $m^3$ $m^{-3}$. *S. kamtschaticum* was the most water efficient while undergoing C3 metabolism under well-watered conditions. The carbon gained during C3 photosynthesis was so much greater than that gained during the CAM phase starting at 0.06 $m^3m^{-3}$ VWC on day 14 (Figs. 2.5b and 2.8), that WUE declined under drought stress even when water consumption decreased (Figs 2.3-2.4). The range of WUE efficiency reported here, from 5 to 150 μmol $CO_2$ $g^{-1}$ $H_2O$ translates to about 0.23 to 6.75 mg $CO_2$ $g^{-1}$ $H_20$, which was lower than values reported for other *Sedum* species from 9.6 to 18.7 (Gravatt and Martin 1992); this may be explained by lower rates of $CO_2$ exchange measured in our experiment. Decreased water use by *S. album* in CAM was evidenced by reduced overall rates of evapotranspiration compared to *S. kamtschaticum* (Figs. 2.2 - 2.4). Findings also suggest that CAM can prolong water availability (Fig. 2.3 - 2.4). Despite its larger aboveground biomass, the decline in VWC was much more gradual for *S. album* than for *S. kamtschaticum* (Fig. 2.2).

### 2.4.4 Implications for the green roof industry

The implications of these findings for green roofs depends on how frequently either species is induced into CAM, and for how long in different climates. For geographic areas with extended dry periods, or dry green roof microclimates such as at the top of a roof slope, *S. album* is probably the preferred species, compared to *S. kamtschaticum* since it strongly conserves water. In Michigan, S. album was the most persistent in green roof platforms with thin layers of substrate (Rowe et al. 2012). In cooler, wetter times, this species may not transpire water fast enough to contribute substantially to green roof stormwater efficiency. Nevertheless, in the Pyrenees, carbon isotope analysis revealed that *S. album* gains most of its carbon through C3 photosynthesis, and it was speculated that this is due to rapid growth at the beginning of the growing season (Earnshaw et al. 1985). Future work might compare plant success rates in different climates over longer time periods (i.e., Pilon-Smits et al. 1991), taking into account the effects of drought on growth and water use efficiency of various obligate and facultative CAM plants. Furthermore, this study provides insight about the level of drought at which green roof plants experience physiological stress.

This information can be used to parameterize evapotranspiration equations (Allen et al. 1998) that require information about plants such as wilting point or stomatal conductance that would help us better understand stormwater management by green roofs (Prowell 2006). For example, traditional approaches to determining wilting point as a quantity of water held in soil at a given pressure (-1500J/kg) may not apply to porous green roof substrates planted in plants that rarely show physical signs of wilting. In contrast, according to Fig. 2.8, a value of 0.06 $m^3$ $m^{-3}$ could be chosen as a "wilting point" for *S. kamtschaticum* because a negative daily carbon gain was found for this species under these conditions. *Sedum album* did not show a negative carbon gain throughout the study, so wilting point may be determined based on relationships in Figs. 2.1 – 2.2. A VWC of 0.04 $m^3$ $m^{-3}$ might be considered a wilting point for *S. album* because at this point the change in $E_T$ with VWC becomes very low. These values are substantially lower than those measured by others for green roofs of 0.12 and 0.14 $m^3$ $m^{-3}$ (DiGiovanni et al. 2013, Voyde et al. 2010).

## 2.5 Conclusions

Three weeks of replicated, continuous data on water use and $CO_2$ exchange of two different facultative CAM species support our prediction that these two different succulent species can have variable physiological responses when substrate moisture becomes limiting. In our experiment, *S. kamtschaticum* outperformed *S. album* in terms of carbon gain and WUE at VWC above 0.07 $m^3$ $m^{-3}$. Interestingly, *S. album* was photosynthesizing via CAM, growing more slowly and using less water (Figs. 2.8, 2.3 – 2.4), even at the start of the experiment under well-watered conditions, suggesting that other induction mechanisms besides drought stress might also be important for this species. Nevertheless, these findings suggest that *S. album* was the more drought tolerant species under the environmental conditions in this experiment, gaining more carbon and using water more efficiently at substrate water contents below 0.07 $m^3$ $m^{-3}$. This data further supports suggestions by others (Cushman and Borland 2002) that a main purpose of CAM is to promote survival via prolonged water availability coupled with a consistent, if low, level of carbon gain.

# **Chapter 3.** The comparative effects of three different *Sedum* species on stormwater retention by experimental green roof platforms in the Mid-Atlantic

## 3.1 Introduction

Our understanding of factors contributing to rainfall storage efficiency by green roofs is still relatively poor, despite a number of review papers on this subject (Oberndorfer et al. 2007, Palla et al. 2010). More research is necessary to understand the dynamics of water movement in green roof systems, including the impacts of different climates and plant species. Green roofs have been shown to retain up to 80% of potential roof runoff (Carter and Rasmussen 2006), but this type of efficiency is likely only for small (<12mm), interspersed and low intensity rainfall events. Most reported measures of retention efficiency are between 40 and 60% (Mentens et al. 2006, Carter and Rasmussen 2006, Palla et al. 2010), and many of these studies rely on short-term (< 1-year) studies.

Design factors such as roof slope and media depth (Mentens et al. 2003, VanWoert et al. 2005, Getter et al. 2007, Dunnett et al. 2008) influence the efficiency of how rainfall is stored by green roofs. According to the German Research Society for Landscape Development and Landscape Design standards (FLL 2008), the target plant coverage on extensive green roofs is a minimum of 60%, to achieve adequate stormwater retention. Unfortunately, this recommendation is not based on experimental evidence, and many German green roof standards are based on studies in which the test roofs were not planted (M. Koehler - Hochschule Neubrandenburg, Germany *pers.comm*, Krupka 1992).

The importance of plants for removing water from green roofs has been debated. Dunnett (2008b) found runoff volumes from vegetated green roof microcosms to be less than from non-planted ones, but significant effects were only noted for non-*Sedum* species such as grasses. Inverse relationships between stormwater runoff and both root biomass and plant height were significant. This same study found no relationship between shoot dry mass and runoff and suggests that other aspects of plant structure such as leaf size or branch angle may be important. A year-long study of experimental green roof platforms in Michigan in 2002 found that green roofs held 3% more water than unplanted roofs covered with substrate, but these findings were not robust when the data were categorized by storm size (VanWoert et al. 2005). Another outdoor study in Georgia (Prowell 2006) did not observe more retention by *Sedum* comparing planted vs. non-planted green roof modules, and they suggested this may be due to the small size of plants used in the study.

None of these studies thoroughly addressed why there were no observed effects of plants on water retention. In the VanWoert et al. (2005) study, it was suggested that the harsh winter in their outdoor study in Michigan may have been responsible, but they do not report information about plant characteristics, other than they had started with seed and achieved 100% coverage at the start of their study three months later. Dunnett et al. (2008) argues for more detailed observation of the effects of plant structures on water capture, such as size and leaf area. A lack of plant treatment effect on green roof performance could also be explained by known variations in green roof performance at different rain frequencies (Stovin et al. 2012). If rainfall events occur within a few days, the effects of transpiration could be masked by the low retention capacity of the system, with little opportunity to transpire water from the green roof substrate. Conversely, if a number of weeks pass between rainfall events, both transpiration and evaporation may be negligible due to lack of water availability. Green roof plants may therefore enhance stormwater retention at a certain rain frequency, but significant evapotranspirative effects could be negated by frequent rainfall events. In addition to rain frequency, the other two major factors that could influence substrate volumetric moisture content (VWC) of a green roof at specific times are: (1) substrate water-holding capacity (WHC) and (2) rates of evapotranspiration ($E_T$).

With regard to WHC, planted green roofs may sequester more water than unplanted roofs, due to increased surface area created by root biomass and increased organic matter composition, leading to enhanced water-holding capacity (Berghage et al. 2007). Getter et al. (2007) suggest that increases in organic matter were responsible for a three-fold increase in water storage on experimental green roof platforms, although this was not the focus of their study. Over a period of five years, the substrate WHC increased from 17 to 67%, and organic matter content increased from 2.33 to 4.25 percent. Though there has been historical debate as to whether or not increased percentages of organic matter increases substrate WHC, the majority of studies which control for other factors (such as reduced particle size) find this relationship to be positive (Huntington 2006, Hudson 1994).

Increased WHC is only beneficial if this enhanced storage is balanced by increased rates of plant $E_T$, which actively removes water from lower substrate depths. A greenhouse study simulating summer in Nova Scotia, Canada (Wolf and Lundholm 2008) found that *Sedum acre* lost less water than unplanted controls under wet conditions; these findings were attributed to both lowered rates of $E_T$ due to shading,that could not compensate for higher WHC due to increased plant root mass. In the same study, rates of $E_T$ were faster for planted containers compared to unplanted ones under intermediate and dry conditions. In these experiments, grasses had significantly higher rates of $E_T$ compared to both *Sedum* and herbaceous species, between which no significant difference in $E_T$ rates were found (Wolf and Lundholm 2008).

Rates of $E_T$ have been studied extensively for different green roof plant species. In areas with frequent rainfall events, higher rates of $E_T$ are probably necessary to maintain mitigation green roof efficiency. Laboratory experiments simulating a variety of rain frequencies and environmental conditions have shown that $E_T$ rates for *Sedum* species are 40 to 80% greater than evaporation from unplanted controls (Rezaei 2005, Berghage et al. 2007, Voyde et al. 2010). Based on empirical models for climate conditions in 2007-8 in New Zealand, which receives 1240 mm of rain annually with 137 wet days > 1.0 mm (Voyde 2011), a 9-10% increase in stormwater retention was predicted for green roofs planted with two different species *Sedum mexicanum and Dysphyma australe*, between which a 3-5% difference in retention efficiency was also expected (Voyde et al. 2010).

In order to accurately assess the role of *Sedum* or any plant on the green roof water cycle, relationships between plant characteristics and effects on both water holding capacity (WHC) and $E_T$ need to be accounted for in experiments carried out under regional environmental conditions with rainfall frequency and intensity which are typical for the study area of interest. In this study, we constructed replicated experimental green roof platforms that were either left unplanted or planted with *Sedum album*, *Sedum sexangulare*, or *Sedum kamtschaticum* (n=4 platforms per species). This was done to quantify (1) whether and how these commonly planted species contribute to overall stormwater retention by green roofs in the mid-Atlantic region, and (2) whether specific differences in water use exist between these three morphologically and physiologically distinct species. We predicted that (a) planted green roofs would have higher water-holding capacities than non-planted ones and that a positive correlation between substrate WHC and root biomass would be observed over time; (b) planted platforms would have higher rates of $E_T$, which would be correlated with leaf area and total leaf area; (c) planted green roofs would have greater overall stormwater retention efficiencies, and that differing efficiencies could be related to species-specific differences in $E_T$ and WHC between rainfall events.

## 3.2. Materials and Methods

### 3.2.1 Experimental platforms

Eighteen experimental green roof platforms (1.31 $m^2$ along the interior margins) were constructed and instrumented at the University of Maryland College Park campus from May – July, 2010 (Figure 3.1). Platforms consisted of a 12mm plywood decking covered with EPDM waterproofing membrane, a protection fabric, drainage layer, filter fabric and a baked clay substrate (M2 Stancills, Perryville, MD). Initial bulk density was 0.75g/mL, with 8% of particles less than 0.5mm; pH was 7.2, and organic matter content was 3.8% by mass (Pennsylvania State University, 2010).

**Figure 3.1** Installation as of spring 2010. The weather station is circled in red. An example ECRN-50 rain gauge, used to measure runoff, is shown in the inset.

Platforms were constructed and maintained according to FLL standards (FLL, 2008). They were installed to have a 2% slope. All green roof materials were purchased from Conservation Technology (Baltimore, MD). During late spring 2010, four replicate platforms were planted with monocultures of either *Sedum spurium*, *Sedum album*, or *Sedum sexangulare* planted as plugs (Emory Knoll Farms, Street, MD); four replicate platforms were left unplanted. For planted platforms, 25 plugs were planted per platform at evenly spaced intervals. As per German guidelines, (FLL 2008), slow release fertilizer was applied once per year in spring. Two additional platforms were constructed and left as roofing membrane-only controls; these platforms were used to ensure that equipment measuring water inputs and outputs were functioning correctly and to provide some data on how standard flat roofs might perform under the conditions of this study. All platforms drained into a gutter that was fitted with a rain gauge (see below).

### 3.2.2 Substrate moisture and runoff

In a preliminary study, volumetric moisture content (VWC) was collected for four months from August through November, 2010. Twenty-five sensors (a combination of 5TM and 5TE soil moisture / temperature sensors, Decagon Devices, Inc. Pullman, WA) were installed along the edges and in the center of four quadrants of three platforms (n=75): one unplanted, one planted in *Sedum spurium*, and one planted in *Sedum album*. The objective of this preliminary study was to determine if there were any significant effects of position (i.e. edges, center, and mid-way between portions) on VWC (See Appendix A).

Upon completion of this preliminary study, the sensors were evenly redistributed among all platforms in spring 2011so as to minimize any potential edge or slope effects on VWC. Four sensors were deployed in the center of four quadrants, in each of the 16 experimental platforms. The sensors were positioned so that the prongs were facing upslope, and were oriented vertically to minimize interference with rainfall.

**Figure 3.2** One of the 40mL tipping bucket rain gauges for collecting platform runoff, installed in May of 2011

Sensors were calibrated at various times throughout the study, to ascertain variations in sensor performance (Appendix B).

Low-volume rain gauges (ECRN-50, Decagon Devices Inc.) were initially installed on the gutter drains on each platform (Fig. 3.1). These single 5mL-tip rain gauges did not have the capacity and precision to handle larger storm events during summer 2010; because of this, a larger 40 mL double-tip rain gauge (TB-4, Hydrological Services, Lake Worth, FL) was added to all 16 experimental and 2 control platforms in February of 2011 (Fig. 3.2). Data was collected at 1-minute resolution using a CR-10 data logger and two SW8A multiplexers (Campbell Scientific, Logan, UT). The logger program included a calibration to account for water loss at high intensity. We also replaced the *Sedum spurium* plants with *Sedum kamtschaticum* plants in February 2011, to link the data from this long-term study more closely to the experimentation described in Chapter 2.

**Figure 3.3** The decagon weather station included a rain gauge, pyranometer, PAR sensor, Davis-cup anemometer, and a relative humidity sensor.

### 3.2.3 Environmental data and collection

Air temperature and relative humidity (VP-3sensor), wind speed (Davis cup anemometer), solar radiation (PYR, total radiation pyranometer), photosynthetic flux density (PPF, QSO-S PAR sensor) and rainfall (ECRN-100 tipping rain gauge) were continuously collected at the study site by a Decagon Devices weather station (Fig. 3.3). All environmental and soil moisture data were logged and transmitted using EM50R radio loggers (wireless sensor nodes; Decagon Devices Inc.). Sensor data was measured every minute, and 5-min averages were logged by the EM50R nodes for the environmental (weather) data and the soil moisture data from each platform. The data were transmitted and downloaded via a Decagon (RM-1) radio base station in the University of Maryland, College Park (UMCP) greenhouse complex, which was connected to a dedicated computer. Data was downloaded and viewed whenever necessary using DataTrac software v.3.2 (Decagon Devices, Inc.), and from anywhere on the web, using Logmein (Woburn, MA) software.

### 3.2.4 WHC and evapotranspiration

WHC was defined as the average substrate VWC sampled at the time at the end of each runoff period. A runoff period was defined as a period of time over which there was no gap in runoff for a period greater than six hours. Rain event boundaries were determined based on the ability to separate runoff responses. Evapotranspiration (= evaporation + transpiration) was calculated as the change in average daily moisture content between rainfall events. Evapotranspiration and WHC were evaluated by season as March-May (spring), June-August (summer), Sept-November (fall). No data are presented for winter months (December-February) due to the frequency of freezing events during this time. The VWC and runoff data were confounded, since substrate and runoff samples remained frozen for long periods of time, and could not be accurately related to rainfall events

### 3.2.5 Non-destructive analyses

Root samples and canopy coverage estimates were taken from each platform at the end of each season. Root biomass was sampled by taking three random 5-cm diameter soil cores, taken for the total platform depth (10 cm) from three quadrants of each platform (n=4), for a total of twelve samples per species. Root biomass samples from each core were washed, sorted, dried, and weighed. Additional cores of the same size were taken to assess changes in substrate bulk density, in August 2011 and

August 2012; the sample volume was divided by the dry weight. For bulk density analysis, one random sample was taken per platform (n=4 per species) to minimize platform disturbance.

Canopy coverage was determined by digital photography. Images were taken approximately 1.8m above each platform in May, August, and November of both study years. The number of pixels representing plants were divided by the number of total pixels for each platform using Adobe photoshop (San Hose, CA), following the procedure of Kim et al. (2012). Plant pixels were distinguished from others based on color using the select tool (Figure 3.4).

**Figure 3.4** Example coverage analysis. The number of pixels in the picture on the right would be divided by the number of pixels in the picture on the left. In this example, a platform planted in *S. kamtschaticum* is shown from the spring of 2012; 69.2% coverage was estimated.

In 2012, above-ground biomass and leaf areas samples were taken from each platform at the end of each season, when full coverage was largely achieved (Figure 3.5). Above-ground and root cores samples were collected according to the same protocols

**Figure 3.5** Experimental platforms at peak coverage during spring, 2012

as described above, and dried at 65C; all samples were then weighed to quantify average above-ground biomass. One additional sample per platform was taken during March, May and August of 2012 to assess leaf area to dry weight relationships for each species (Appendix C). *S. kamtschaticum* leaves were removed from their stems and run through a leaf area meter **(**Model: Li-3100 Area Meter, Lincoln, NB**)**. Due to the cylindrical shape of the *S. album* and *S. sexangulare* leaves, leaf area was determined using equations relating surface area to volume (Appendix C). The dry weight : leaf area ratios were then determined by regression analysis (Appendix C Fig. 3.1- 3.3) for each species. In this paper, we define leaf area index (LAI) as the amount of leaf area measured divided by the known area sampled, 6.28cm$^2$. This number was then further divided by two as per recommendations in the literature for non-flat leaves (Chen and Black 1992). Both dry weight and leaf area were then extrapolated to whole platform canopy leaf area from this non-destructive canopy coverage analysis, which we refer to as total leaf area.

### 3.2.6 Statistical analysis

The experimental design was a randomized complete block design with four blocks and four replicates of each treatment. Differences in $E_T$ and WHC were analyzed by season using mixed linear modeling (PROC MIXED, SAS version 9.2, SAS Institute, Cary, NC) as were differences in runoff by season and by storm size. Post-hoc comparisons were made using Tukey-Kramer honestly significant difference (HSD) testing and the macro pdmix800 (Saxton 1998). Bulk density samples were compared between years with paired t-tests. Root and above-ground biomass samples, as well as leaf area samples and coverage estimates, were analyzed using ANOVA with repeated measures and Tukey's HSD post hoc comparisons (PROC GLM, SAS version 9.2, SAS Institute, Cary, NC). Regression analyses (PROC REG, SAS version 9.2, SAS Institute, Cary, NC) were conducted to elucidate relationships between ET, WHC, root and above ground biomass, leaf area, and coverage data.

## 3.3. Results

### 3.3.1 Weather summary

Environmental conditions were fairly similar for both years (Table 3.1, Appendix D). Average daily air temp was slightly warmer in 2012 but only by one degree C. Average daily relative humidity was 69% for both years. Average daily PAR was 352 and 399 $\mu mol/m^2/s$ in 2011 and 2012 respectively, and average daily radiation was 173 and 197 W/m$^2$. Over the course of both years, wind speed ranged between 0.04 at a minimum in 2011 and 3.89 at maximum in 2012. VWC ranged from 2.3 to 33% in 2011 and from 2.4 to 34% in 2012 (Table 3.1).

### 3.3.2 Rainfall and Runoff

From 2011-2012, 42 events less than 12.5mm represented 50% of the 84 total events observed during the two-year study period, in terms of frequency (Table 3.2). Small storms accounted for only 14% of total rainfall, with medium-sized storms (12.5 to 62.5mm), representing 51% of the rain quantity (Table 2). Five large storms (> 62.5mm) accounted for over 30% of total rainfall quantity during the two years. The largest rain event (180.2 mm total rainfall), occurred on 09/8/2011 during tropical storm Irene; the second largest storm event was for hurricane Sandy, (165mm) measured on 11/28/2012.

During 2011, 1004 mm of rain fell at the study site; 965 mm of this total generated runoff from the platforms. During 2012, 802 mm of rain fell on the study, of which 746 mm resulted in measurable runoff. Multiplying the total annual rainfall by platform area, the total rainfall volume was equivalent to 1311 and 1048L for 2011 and 2012 respectively, which was used to estimate percent retention. If the five large storms are excluded, between 45 and 56% of rain was retained in 2011 by the green roof platforms. Annually, total runoff was 20% and significantly lower from platforms planted in *S. kamtschaticum* compared to the unplanted platforms (Table 3.3).

**Table 3.1** Summary weather data for both study years including maximum (Max), minimum (Min) and average (Avg) daily and annual estimates of temperature, relative humidity, wind speed and volumetric water content (VWC).

| Year | Min. Ai Temp (°C) | Avg. Daily Temp (°C) | Max. Air Temp (°C) | Avg. Daily Relative Humidity (%) | Avg daily PAR (µmol m$^2$/ s) | Avg daily Radiation W/m$^2$ | Min Wind Speed (m/s) | Avg Daily Wind Speed (m/s) | Max Wind Speed (m/s) | Min VWC (%) | Max VWC (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2011 | -1.50 | 17.10 | 33.16 | 0.69 | 352.36 | 173.41 | 0.15 | 1.41 | 3.89 | 2.30 | 33.00 |
| 2012 | 1.75 | 18.59 | 33.08 | 0.69 | 399.23 | 197.02 | 0.04 | 1.10 | 3.53 | 2.40 | 34.00 |

**Table 3.2** Rain quantity (mm) and frequency distribution combined and grouped by year.

| Storm size groups | <12.5 | 12.5-25 | 25-37.5 | 37.5-50 | 50-62.5 | 62.5-75 | 75-125 | 125-187.5 | Total |
|---|---|---|---|---|---|---|---|---|---|
| Year 1 Frequency | 31 | 12 | 5 | 3 |  | 1 | 1 | 1 | 54 |
| Year 2 Frequency | 11 | 13 |  | 2 | 2 | 1 |  | 1 | 30 |
| Combined | 42 | 25 | 5 | 5 | 2 | 2 | 1 | 2 | 84 |
| Combined percent total frequency | 50.00 | 29.76 | 5.95 | 5.95 | 2.38 | 2.38 | 1.19 | 2.38 |  |
| Cumulative frequency (%) | 50.00 | 79.76 | 85.71 | 91.67 | 94.05 | 96.43 | 97.62 | 100.00 |  |
| Year 1 Quantity (mm) | 165.4 | 203 | 144.6 | 123 |  | 63.6 | 124.6 | 180.2 | 1004.4 |
| Year 2 Quantity (mm) | 84.8 | 235.4 | 0 | 84.8 | 109.2 | 66.6 |  | 165.6 | 746.4 |
| Combined (mm) | 250.2 | 438.4 | 144.6 | 207.8 | 109.2 | 130.2 | 124.6 | 345.8 | 1750.8 |
| Combined percent total quantity (mm) | 14.29 | 25.04 | 8.26 | 11.87 | 6.24 | 7.44 | 7.12 | 19.75 |  |
| Cumulative quantity (%) | 14.29 | 39.33 | 47.59 | 59.46 | 65.70 | 73.13 | 80.25 | 100.00 |  |

**Table 3.3** Plant treatment effects on runoff (L) in 2011 by season, with large storms removed. Letters indicate significant treatment effects within each season on the same row. Percent retention was also calculated for each treatment. Percent treatment effect compares runoff from unplanted and planted platforms. Mean separations by Tukey-Kramer HSD at $p<0.05$.

| Treatment | *S. album* | *S. kamtschaticum* | *S. sexangulare* | Unplanted | p-value |
|---|---|---|---|---|---|
| Spring | 161.24 | 151.48 | 156.33 | 176.86 | 0.583 |
| Summer | $51.92^{ab}$ | $41.91^{b}$ | $57.55^{ab}$ | $64.44^{a}$ | 0.056 |
| Fall | $195.92^{ab}$ | $171.96^{b}$ | $183.77^{b}$ | $217.58^{a}$ | 0.001 |
| **Total** | $\mathbf{409.08^{ab}}$ | $\mathbf{365.35^{b}}$ | $\mathbf{397.65^{ab}}$ | $\mathbf{458.88^{a}}$ | **0.021** |
| Rain (L) | 826 | 826 | 826 | 826 | |
| % retained | 0.50 | 0.56 | 0.56 | 0.45 | |
| % treatment effect | 0.11 | 7 | 0.13 | N/A | |

Total runoff from platforms planted in *S. album* and *S. sexangulare* was 11% and 13% less, respectively, compared to the unplanted platforms, but these differences were not statistically significant (Table 3.3).

During 2012, between 62 and 74% of total rainfall was retained by the green roof platforms (Table 3.4), excluding large storms. In total, *S. kamtschaticum* stored more water compared to all other treatments except *S. sexangulare* (Table 3.4). During the spring of 2012, the unplanted and *S. album* treatments were not different from each other, but there was significantly lower runoff from the *S. kamtschaticum* and *S. sexangulare* treatments, between which no differences were observed. During summer, *S. kamtschaticum* had the least amount of runoff compared to all other species. In fall, *S. kamtschaticum* platforms again had significantly lower runoff

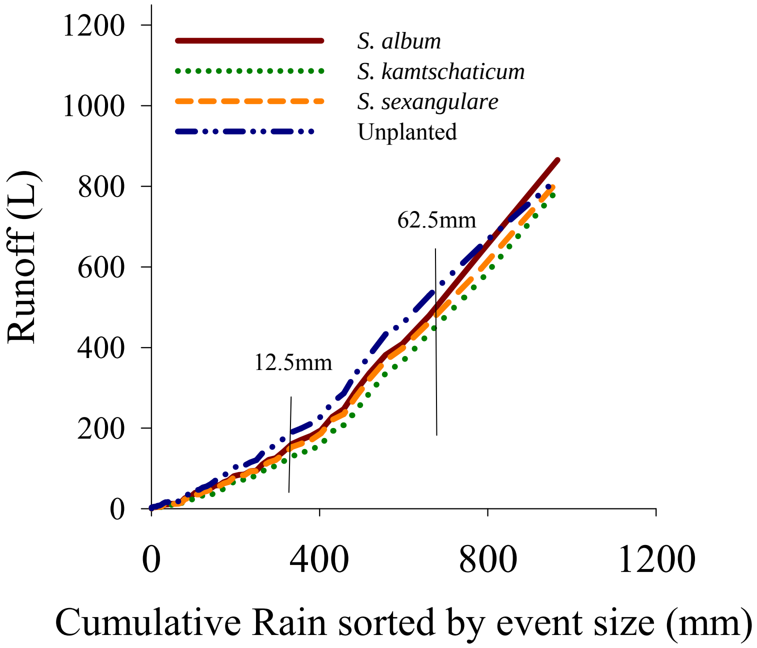
**Table 3.4** Treatment effects on runoff (L) in 2012 by season with large storms removed. Letters indicate significant treatment effects within each season on the same row. Percent retention was also calculated for each treatment. Percent treatment effect compares runoff from unplanted and planted platforms. Mean separations by adjusted Tukey-Kramer HSD at p<0.05.

| Treatment | *S. album* | *S. kamtschaticum* | *S. sexangulare* | Unplanted | p-value |
|---|---|---|---|---|---|
| Spring | $83.92^{a}$ | $68.17^{b}$ | $68.93^{b}$ | $94.98^{a}$ | 0.0004 |
| Summer | $67.79^{a}$ | $46.99^{b}$ | $65.19^{a}$ | $78.03^{a}$ | 0.002 |
| Fall | $77.81^{ab}$ | $55.12^{b}$ | $85.47^{a}$ | $84.76^{a}$ | 0.007 |
| **Total** | **$229.51^{a}$** | **$170.28^{b}$** | **$219.59^{ab}$** | **$257.75^{a}$** | 0.003 |
| Rain (L) | 668 | 668 | 668 | 668 | |
| % retained | 0.66 | 0.74 | 0.67 | 0.62 | |
| % treatment effect | 0.11 | 0.34 | 0.15 | N/A | |

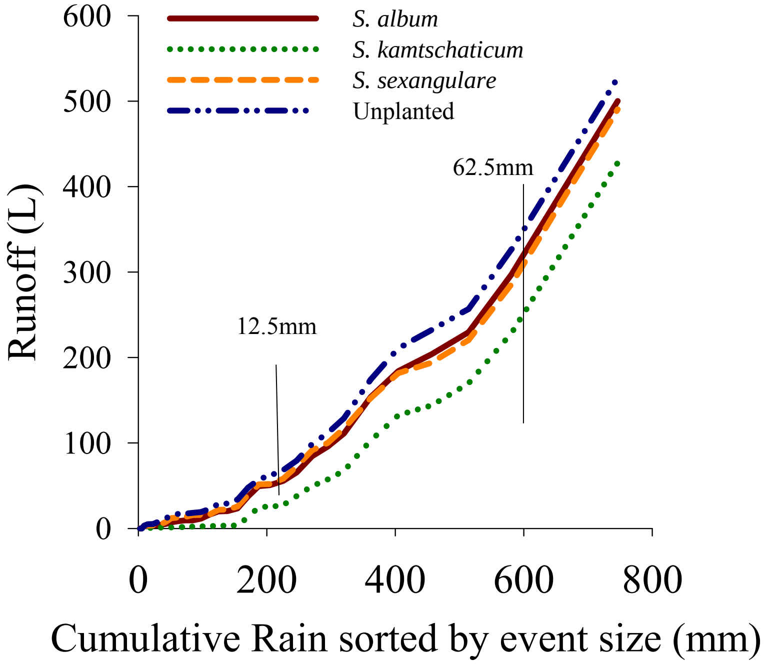
compared to the other treatments, except for the *S. album* platforms from which runoff was intermediate of the *S. kamtschaticum* and unplanted platforms. Runoff from *S. sexangulare* was not different from any other platforms in fall of 2012 except from runoff from *S. kamtschaticum* platforms (Table 3.4). By far, the variable that best predicted runoff was storm size (Figs. 3.6a-b) for both years. For small storms, the least amount of runoff was observed from platforms planted in *S. kamtschaticum* compared to all other platforms, and the most runoff was observed for unplanted platforms (Fig. 3.7a). In this storm category, platforms planted in *S. sexangulare* generated less runoff compared to the unplanted platforms, and runoff from *S. album* platforms was intermediate of that from unplanted and that from *S. sexangulare* (Fig. 3.7a). No significant treatment effects were observed between medium and large storms in 2011(Figs. 3.7b, c).

**Figure 3.6a-b** The influence of storm size on runoff and treatment effects for 2011(a) and 2012 (b) Cumulative rain, sorted by event size, is shown on the x-axis, and runoff in liters on the y-axis. Vertical black lines mark separations in storm size (small<12.5mm, medium<62.5, large>62.5) categories.

**a.**



**b.**



During 2012, storm size effects were only noted for small and medium storms (Figs. 3.7a-b). For small storms, *S. kamtschaticum* had the least runoff compared to other platforms except *S. sexangulare*. Runoff from *S. album* was not significantly different from the unplanted platforms or those planted in *S. sexangulare*. Runoff from unplanted platforms was different from all platforms except *S. album*. For medium storms, runoff from unplanted and platforms planted with *S. album* were not significantly different; however runoff from both these treatments were significantly greater than runoff from *S. kamtschaticum*. Runoff from *S. sexangulare* platforms was intermediate of these for medium size storms (Fig. 3.7b).

### 3.3.3 Evapotranspiration

Total runoff was significantly and inversely related to $E_T$ only during the second year of the study in 2012 (Fig. 3.8). An overall treatment effect was observed for seasonal rates of $E_T$, though there was no season effect or season by time interaction (Fig. 3.9). During spring 2012, *S. sexangulare* used significantly more water than the other treatments. During this same season, *S. kamtschaticum* used more water than the unplanted treatment, with *S. album* intermediate of these treatments. In summer and fall of 2012, $E_T$ rates were significantly higher from *S. kamtschaticum* compared to all the other treatments, among which no differences in water use were noted (Fig.3.9). When summed annually, higher rates of $E_T$ were observed for *S. kamtschaticum* and *S. album* compared to *S. album* and the unplanted treatments, but differences were only significant during the second year (Table 3.5).

**Table 3.5** Differences in total annual evapotranspiration (mm) by species. Different letters within the same row indicate significant differences between treatments within each year. Mean separations by adjusted Tukey-Kramer HSD at p<0.05.

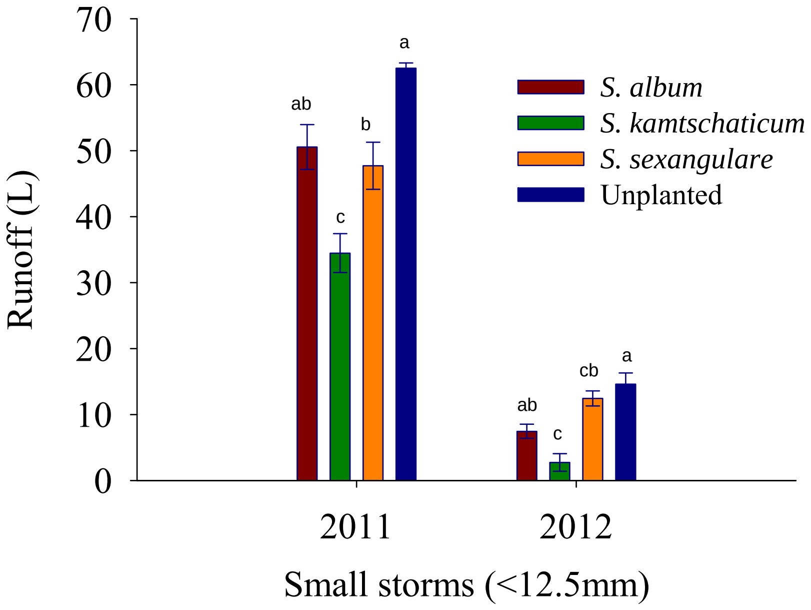
| Season | *S. album* | *S. kamtschaticum* | *S. sexangulare* | Unplanted | p-value |
|---|---|---|---|---|---|
| 2011 | 147 | 162 | 183 | 123 | 0.09 |
| 2012 | $147^{ab}$ | $184^{a}$ | $180^{a}$ | $122^{b}$ | 0.005 |

### 3.3.4 Aboveground biomass

There was no overall time or treatment effect on average aboveground biomass, but there was a significant time (season) by treatment interaction (Fig. 3.10). In fall 2011, *S. album* had significantly more aboveground biomass compared to *S. kamtschaticum*, with *S. sexangulare* being intermediate of the two. In summer of 2012, *S. kamtschaticum* had significantly greater biomass compared with *S. sexangulare*, with *S. album* being intermediate of the two (Fig. 3.8). There was no significant relationship between $E_T$ and biomass for any species (Table 3.6 - 3.7).

**Figure 3.7a-c** Treatment effects on runoff for (a) small (<12.5mm) and (b) medium (<62.5mm) sized storms, and c) large ( >62.5mm) sized storms. Mean separations by adjusted Tukey-Kramer HSD at p<0.05.

**a.**



**b.**

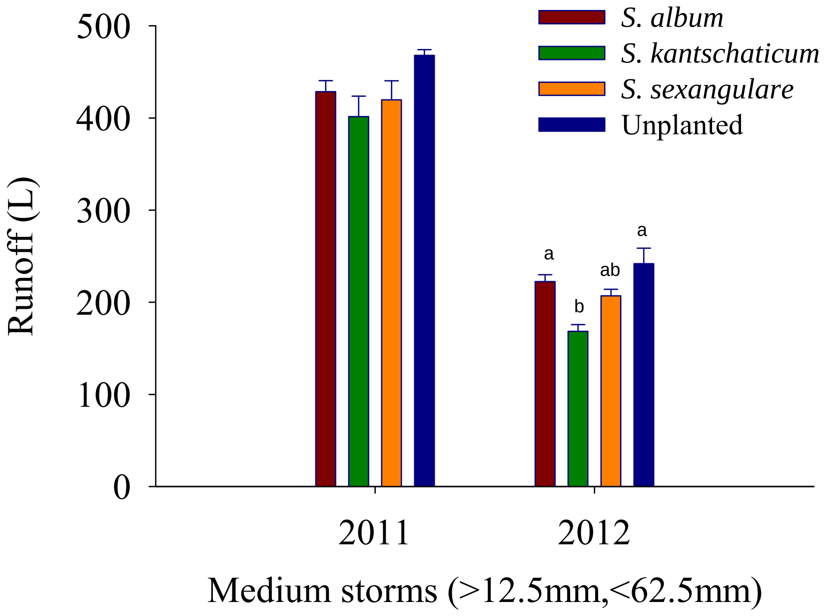


**Figure 3.7c** Treatment effects on runoff for (c) large ( >62.5mm) sized storms. Mear separations by adjusted Tukey-Kramer HSD at p<0.05.

**c.**

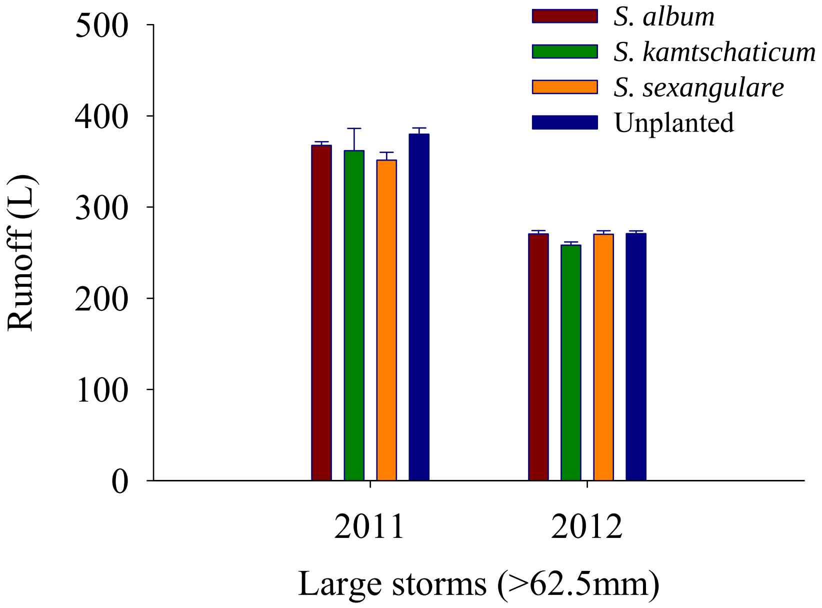


**Figure 3.8** Relationships between runoff and evapotranspiration summed by season for 2011 and 2012.

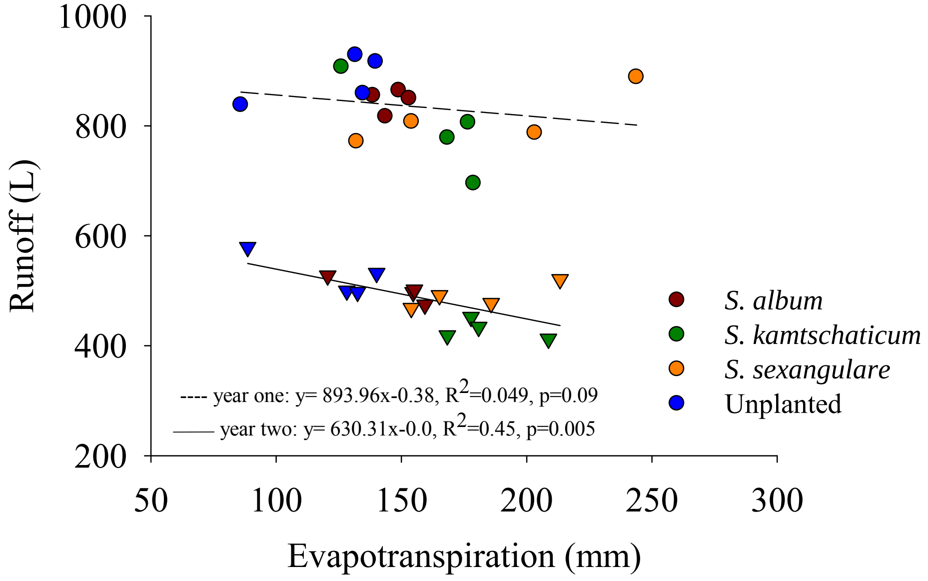


**Figure 3.9** Annual total evapotranspiration by treatment for each season in 2011 and 2012. Bars labeled with different letters represent significant treatment differences within each season. Mean separations by adjusted Tukey-Kramer HSD at p<0.05.

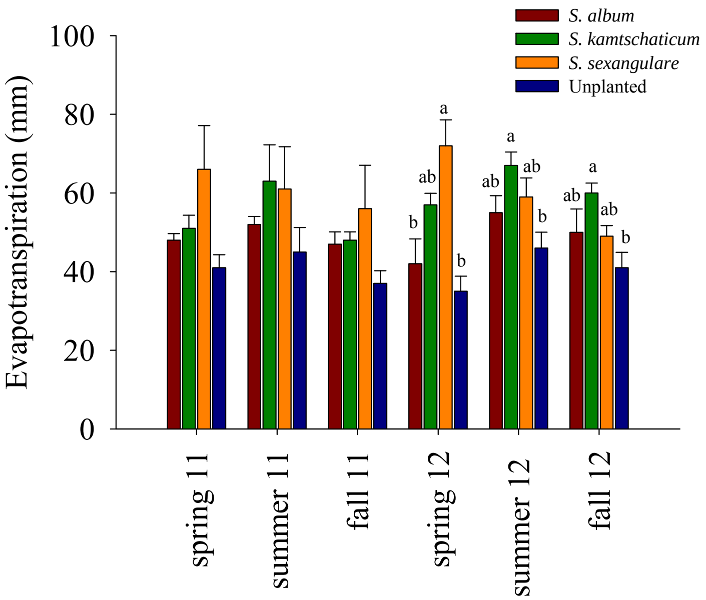


**Figure 3.10** Seasonal differences in aboveground biomass. Bars labeled with different letters represent significant treatment differences within each season. Mean separations by Tukey's HSD at p<0.05.

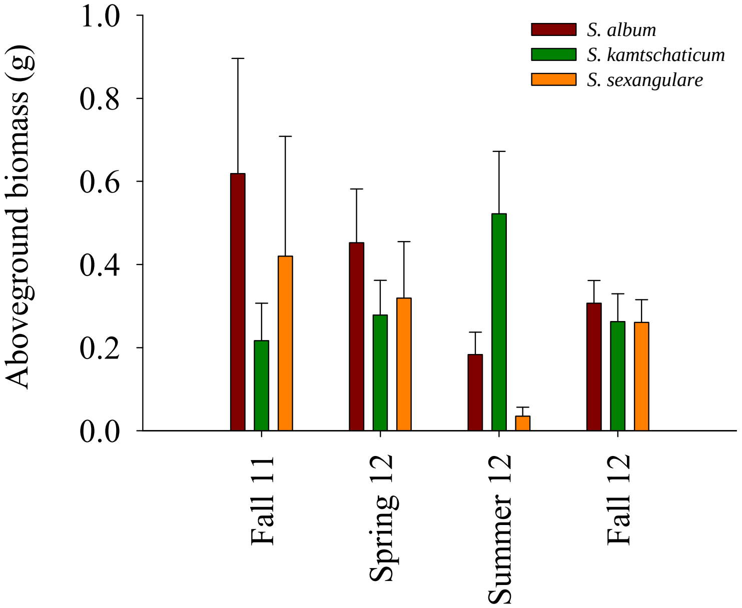


**Table 3.6** Regression tables indicating any significant relationships between runoff (RO) with large storms removed, evapotranspiration (ET), root biomass (RB), aboveground biomass (AGB), water holding capacity (WHC), leaf area index (LAI), coverage, and total leaf area for two Sedum species. Parameter estimates provided. Significant relationships at the $p<0.05$ level are in boldface.

***Sedum album***

| | RO | ET | RB | AGB | WHC |
|---|---|---|---|---|---|
| RO | . | . | . | . | . |
| ET | **-5.910** | . | . | . | . |
| RB | 16.910 | **-5.600** | . | . | . |
| AGB | 24.110 | -2.780 | 0.323 | . | . |
| WHC | 62.740 | 2.790 | 0.554 | 1.190 | . |
| LAI | 0.075 | -0.077 | 0.007 | **0.021** | -0.001 |
| Coverage | **63.200** | -5.050 | 0.547 | 1.190 | **0.261** |
| Total leaf area | **0.689** | -0.070 | 0.006 | **0.018** | -0.0001 |

***Sedum sexangulare***

| | RO | ET | RB | AGB | WHC |
|---|---|---|---|---|---|
| RO | . | . | . | . | . |
| ET | -1.710 | . | . | . | . |
| RB | -6.840 | 3.830 | . | . | . |
| AGB | 38.200 | 1.970 | -0.332 | . | . |
| WHC | **27.770** | **-18.230** | -0.616 | 0.109 | . |
| Leaf Area | -0.439 | **0.115** | 0.003 | 0.001 | -0.003 |
| Coverage | 24.580 | 1.460 | -0.122 | **0.551** | 0.958 |
| Total leaf area | 0.064 | **0.091** | -0.001 | **0.009** | -0.002 |

**Table 3.7** Regression tables indicating any significant relationships between runoff (RO) with large storms removed, evapotranspiration (ET), root biomass (RB), aboveground biomass (AGB), water holding capacity (WHC), leaf area index (LAI), coverage, and total leaf area for *Sedum kamtschaticum* and all data combined. Parameter estimates are provided. . Significant relationships at the p<0.05 level are in boldface.

| | ***Sedum kamtschaticum*** | | | | | | **All data** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | RO | ET | RB | AGB | WHC | | RO | ET | RB | AGB | WHC |
| RO | . | . | . | . | . | RO | . | . | . | . | . |
| ET | -5.250 | . | . | . | . | ET | **-5.290** | . | . | . | . |
| RB | **-52.90** | 1.250 | . | . | . | RB | -13.590 | -1.730 | . | . | . |
| AGB | 6.880 | -1.120 | -0.031 | . | . | AGB | 10.460 | -1.480 | 0.155 | . | . |
| WHC | 26.780 | -3.220 | -0.352 | -2.950 | . | WHC | **157.46** | **-11.180** | -0.244 | -0.620 | . |
| LAI | -0.333 | 0.018 | 0.009 | 0.009 | -0.002 | Leaf Area | 0.393 | 0.026 | -0.001 | 0.002 | -0.001 |
| Coverage | -57.480 | -1.750 | **0.924** | 0.372 | 0.083 | Coverage | **29.370** | -1.620 | 0.265 | **0.580** | 0.055 |
| Total Leaf Area | -0.779 | 0.005 | 0.016 | 0.017 | -0.002 | Total Leaf Area | **0.584** | 0.010 | 0.001 | **0.008** | -0.0005 |

### 3.3.5 Leaf Area and coverage

Each season, average percent coverage was significantly different between species (Table 3.8). In the spring, platforms planted in *S. kamtschaticum* had the least amount of coverage compared to the other two species, and in the summer, *S. sexangulare* had the least coverage. In the fall, coverage was significantly higher on platforms planted with *S. album* compared to the other two. There were also significant seasonal effects on total leaf area and leaf area index in 2012, in addition to season by treatment interactions (Table 3.8). In spring, the deciduous *S. kamtschaticum* had less total leaf area compared to the other species, and during summer 2012, total leaf area was lower for *S. sexangulare* and *S. album*, possibly due to drought conditions experienced throughout spring and summer, 2012.

**Figure 3.11** The relationship between evapotranspiration and leaf area index for the four experimental green roof platforms planted S. sexangulare measured each season in 2012.

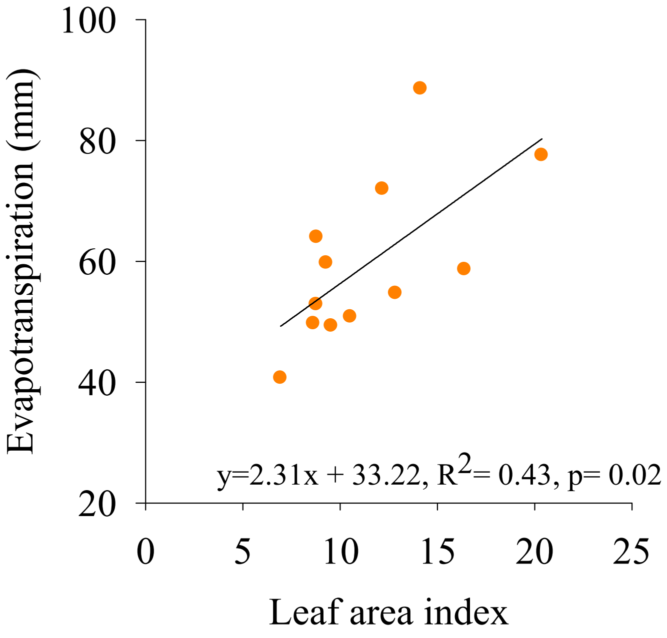


**Table 3.8** Seasonal and treatment effects on coverage and leaf area for platforms planted in *S. album* (A), *S. sexangulare* (S), and *S. kamtschaticum* (K). Within each season, numbers with different letters are significantly different from each other. Mean separation by Tukey's HSD at $p<0.05$.

| Season | Spring 12 | | | Summer 12 | | | Fall 12 | | |
|---|---|---|---|---|---|---|---|---|---|
| Treatment | A | K | S | A | K | S | A | K | S |
| Average coverage (%) | $86.63^{a}$ | $59.99^{b}$ | $79.74^{a}$ | $70.57^{a}$ | $67.94^{a}$ | $38.22^{b}$ | $88.82^{a}$ | $74.81^{b}$ | $74.03^{b}$ |
| Leaf area index ($cm^2$/ $cm^2$) | 10.725 | 7.045 | 13.15 | 5.945 | 6.875 | 7.87 | $6.65^{ab}$ | $5.93^{b}$ | $10.45^{a}$ |
| Total platform leaf area ($m^2$) | 12.185 | 5.52 | 14.09 | 5.52 | 6.11 | 3.905 | $7.76^{ab}$ | $5.81^{b}$ | $10.11^{a}$ |

During fall 2012, leaf area index and total leaf area for *S. sexangulare* were nearly double, and significantly greater than *S. kamtschaticum* (Table 3.8). Multiple regression analysis for the entire dataset, as well as subsets of the data grouped by treatment, showed few significant relationships between any measures of leaf area or coverage and rates of $E_T$ (Tables 3.6 -3.7); nevertheless, rates of $E_T$ were significantly and positively related to the total leaf area of S *sexangulare* (Fig. 3.11).

### 3.3.6 Water holding capacity

Water-holding capacity varied significantly between seasons (Table 3.9). There were no treatment (species) effects, but there was a significant treatment by time interaction. Averaging planted treatments together by season, WHC was significantly lower during summer of both 2011 and 2012, compared to the other seasons, except spring of 2012 (Table 3.9). Within treatments, significant seasonal differences in WHC over time were observed compared to the unplanted control (Table 3.9), for which the Tukey-Kramer post-hoc test did not show any significant change in WHC throughout the study. The WHC for *S. album* was lowest during summer of 2011 and 2012 and these values were significantly different from all other seasons except spring 2012. The WHC of *S. kamtschaticum* was the most variable of all treatments; measured values were highest in spring, 2011 and lowest in summer, 2012 (Table 3.9). For *S. sexangulare*, WHC was highest in fall of 2012 and significantly different from summer of 2011, with values from other seasons being intermediate. Overall WHC was found to be positively related to runoff (Table 3.6 -3.7).

**Table 3.9** Seasonal differences in water holding capacity for unplanted vs. planted platform treatments (n=4), during 2011 and 2012. Letters indicate significant differences between seasons, within treatments, over the two-year study period. Mean separations by Tukey's HSD at $p<0.05$.

| Treatment | Spring, 2011 | Summer, 2011 | Fall, 2011 | Spring, 2012 | Summer, 2012 | Fall, 2012 |
|---|---|---|---|---|---|---|
| *S. album* | $0.189^{a}$ | $0.131^{b}$ | $0.185^{a}$ | $0.171^{ab}$ | $0.142^{b}$ | $0.199^{a}$ |
| *S. kamtschaticum* | $0.186^{a}$ | $0.135^{bc}$ | $0.179^{ab}$ | $0.160^{abc}$ | $0.146^{c}$ | $0.192^{abc}$ |
| *S. sexangulare* | $0.157^{ab}$ | $0.122^{b}$ | $0.191^{ab}$ | $0.123^{ab}$ | $0.157^{b}$ | $0.216^{a}$ |
| Unplanted | 0.183 | 0.138 | 0.173 | 0.150 | 0.150 | 0.185 |
| **Seasonal Averages** | $\mathbf{0.179^{a}}$ | $\mathbf{0.132^{b}}$ | $\mathbf{0.182^{a,}}$ | $\mathbf{0.151^{b}}$ | $\mathbf{0.148^{b}}$ | $\mathbf{0.198^{a}}$ |
| **SE** | **0.007** | **0.004** | **0.004** | **0.010** | **0.003** | **0.007** |

### 3.3.7 Substrate bulk density and root biomass

Bulk density was constant from 2011-2012, except for platforms planted with *S. kamtschaticum* ($p<0.001$, Fig. 3.12). Root biomass increased significantly between 2011 and 2012 for all planted treatments (Table 3.10). On average, roots sampled in 2012 were nearly six-fold greater than and significantly different from roots sampled in 2011. Within seasons, the only significant treatment effect noted was in the spring of 2011 when *S. album* root biomass was significantly greater than that for *S. kamtschaticum*, and root biomass for *S. sexangulare* was intermediate of, but not significantly different from, these two (Table 3.10).

**Table 3.10** Average root biomass (g) per subsample (25cm3) by species for each season. Differences within season for each treatment are indicated by different letters across rows. Differences in annual seasonal values for all species averaged together are indicated by different letters within the seasonal average column.

| | *S. album* | *S. kamtschaticum* | *S. sexangulare* | Seasonal Average |
|---|---|---|---|---|
| spring 11 | $0.132^{a}$ | $0.012^{b}$ | $0.056^{ab}$ | $0.067^{a}$ |
| summer 11 | 0.103 | 0.049 | 0.065 | $0.072^{a}$ |
| fall 11 | 0.187 | 0.118 | 0.111 | $0.139^{a}$ |
| spring 12 | 0.454 | 0.250 | 0.202 | $0.302^{b}$ |
| summer 12 | 0.321 | 0.392 | 0.247 | $0.320^{b}$ |
| fall 12 | 0.340 | 0.341 | 0.173 | $0.285^{b}$ |

Although not significant, another apparent difference was for spring of 2012, when root biomass of *S. album* was more than double than that of *S. sexangulare* and root biomass for *S. kamtschaticum* was 25% greater, but not different from that for *S. sexangulare*. No significant relationship was found between root biomass and WHC over the two years, either when the data was grouped by species (Table 3.6-7) or by season. However a significant inverse relationship was observed between root biomass and runoff for *S. kamtschaticum* (Figure 3.13).

**Figure 3.12** Annual differences in substrate bulk density between unplanted and planted treatments, measured in August 2011 and August, 2012. Asterisk indicates differences at the p <0.05 level of significance.

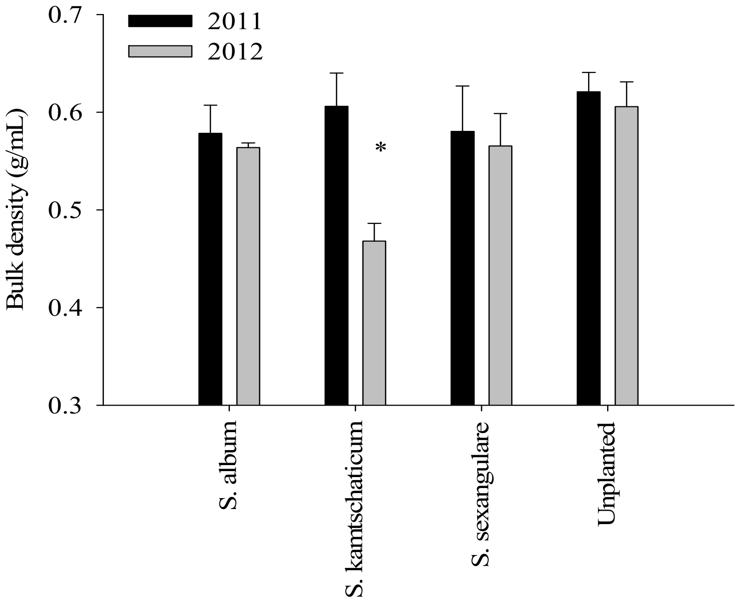
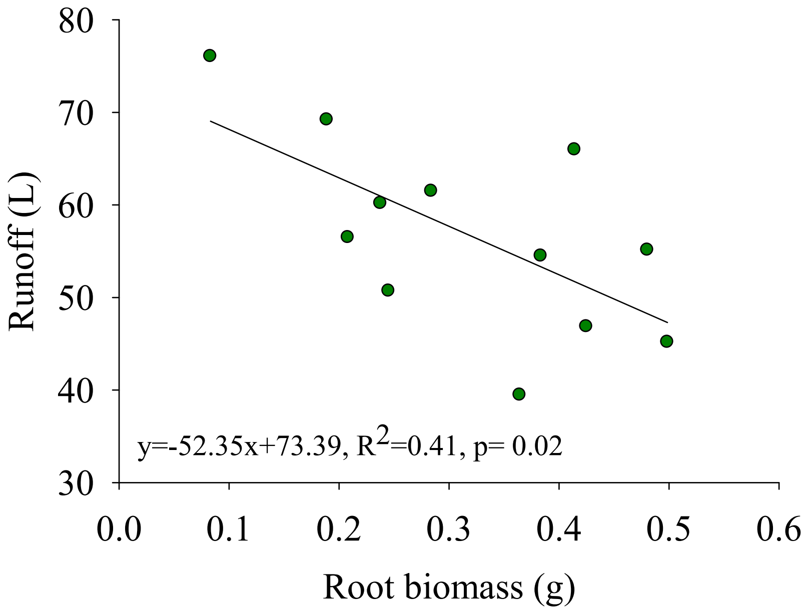


**Figure 3.13** Relationship between runoff averaged by season (large storms removed) and average seasonal root biomass for S. kamtschaticum during 2012.



### 3.4 Discussion

***Plant effects on runoff.*** The influence of any treatment effect is difficult to assess for yearly runoff data, due to the overwhelming influence of storm size on green roof runoff. If this effect were linear, ANCOVA analysis could be employed. If not, in order to truly evaluate treatment effects on greenroof stormwater retention efficiency, the influence of storm size on runoff must be accounted for either by grouping the data by storm size or analyzing a different response variable such as evapotranspiration.

Compared to the other species, runoff from platforms planted in *S. album* was not different from that of the unplanted platforms, in most cases. It is likely that the reduced stormwater retention by *S. album* was due to reduced $E_T$ (i.e. conservation of water) when this species transitions from C3 (under well-watered conditions) to the more water efficient CAM metabolism (as demonstrated in Chapter 2). The CAM status of the other two species in this study has been questioned in the literature. The common name for *S. sexangulare* is 'tasteless' stonecrop (Stephenson 1994), presumably because it lacks the malic acid accumulation typical of species known to strongly exhibit CAM. Greater water use by *S. sexangulare* and *S. kamptschaticum* appears to be related to their growth rates and physiology.

Even though *S. kamtschaticum* and *S. sexangulare* have similar annual $E_T$ rates, *S. kamtschaticum* outperformed *S. sexangulare* in terms of overall water use, and differences in runoff from platforms planted in the two species were greatest in the fall.

This difference is most likely related to the summer dieback of aboveground biomass by *S. sexangulare* (Figure 3.8), and corresponding effects on leaf area and $E_T$ (Table 3.8). Nevertheless, *S. kamtschaticum* did have among the lowest measures of field capacity in our study, and it was the only species for which bulk density was significantly lower in the second year. It is possible that in our climate with frequent rain, having a low water holding capacity is advantageous for the level of $E_T$ that the plants in this study exhibit.

It is tempting to conclude that different runoff patterns seen from year one compared to year two are related to changes associated with plant age. This may be the case, but variable rainfall and weather (light and temperature) differences between years could well have had a significant influence on overall retention and runoff. More research that separates the influence of abiotic conditions on green roof performance from the biotic influences is needed.

***Rates of $E_T$ and relationships with aboveground plant characteristics.*** The range of annual $E_T$ totals, divided by the 275 days I report on each year, amounts to rates between 0.5 to 0.6 mm water per day. This is within the range of 0.12 to 2.91 mm/day (Chapter 1), and the 0.5 to 3.6 mm/day (Voyde 2011) reported for drought-tolerant succulent species elsewhere. Our low daily averages indicate that maximum rates of $E_T$, typical of well watered conditions, were less common during our study. Outside of the positive relationship between leaf area and $E_T$ for *S. sexangulare* (Figure 3.9), few relationships were found between $E_T$ rates and changes in average above-ground biomass, leaf area, and coverage. This data indicates that plant physiological controls on $E_T$ may be more important. Still, even though between 80 and 86% coverage was achieved by the beginning of 2012 for *S. album* and *S. sexangulare*, it is also possible that growth patterns and processes had not stabilized for the plants in this study, and so relationships between $E_T$ and morphological characteristics might grow to be significant on more mature roofs. This is most likely true for *S. kamtschaticum* plants, which were 6-months younger than the other platforms, and for which the most bare area due to winter leaf loss added variability to our measurements.

***Average WHC and relationship to below-ground biomass***. Although there were no overall treatment effects on WHC, the unplanted control was the only treatment for which seasonal effects were not significant (Table 3.9). Thus, it may be possible that root effects on WHC may become significantly positive as the plants grow larger; root production was significantly higher in 2012 compared to 2011 (Table 3.9). Alternatively the roots may be binding substrate particles similar to soil ped-like structures, thus creating pathways for preferential water flow and thus reducing overall WHC (She 2010). Support for this idea comes from the large reduction in both bulk density and water-holding capacity during summer 2012 (Figure 3.12, Table 3.9) for *S. kamtschaticum*, the species with the largest root diameter in this study. It could also be due to the fact that drought conditions were experienced during summer and fall 2012, which may have hastened root turnover, and thus influenced WHC. Finally, plant influences on WHC may be confounded by a variety of other factors inherent in the composition of the substrate, such as particle size differences, and so more research is needed on this topic.

***Additional relevancy of results to green roof research***. Due to the high potential of storm size effects for masking real treatment effects, it is clear that comparison of different plant treatment effects should include multiple treatment responses. These may include runoff for different storm size categories as well as species-specific rates of evapotranspiration. Taking this into account, our data confirms industry observations (Michael Furbish, Furbish Company, Baltimore, MD; *pers. comm.*) that *S. kamtschaticum* is possibly a better choice to optimize stormwater retention in the mid-Atlantic climate, especially compared to *S. album* in this study.

What was apparent from these results was that *Sedum* species, despite their relatively low water use, *do* provide a measurable stormwater benefit compared to unplanted roofs in the mid-Atlantic region, as evidenced by the year 2 results in 2012. This was despite lower-than average rainfall totals in spring and summer, which probably impacted plant performance in these non-irrigated treatments. Even though there was variation in the seasonal performance and annual water use by the different species, these data provide a baseline for comparison with other species, especially natives, for which there is a growing interest (MacIvor et al. 2011).

Those interested in using Sedum species as nurse plants on green roofs (Butler and Orians 2012) could use this information to match different natives to Sedum species that are most compatible. For example, *S. album* might make a better nurse plant because it uses less water than *S. kamtschaticum*. More research is necessary to determine whether species-rich green roofs could maximize stormwater retention or whether selecting a few high-performing species would be better to achieve single targeted benefits (Cook-Patton and Bauerle 2012).

Data from this work, especially regarding WHC, may contribute to the further development green roof models, since I did not explore how these data might have affected the water balance of different substrates of differing composition. Others have also noted reduced WHC in the summer months (Sherrard and Jacobs 2012). Care should be taken to incorporate this seasonal and perhaps other longer term temporal variability into green roof models.

## 3.5 Conclusions

Interestingly, our research hypotheses were only partially supported by our results. Firstly, it appeared that substrate WHC is not significantly related to sampled root biomass, and planted green roofs did not have significantly higher WHC. I suspect this may have been because root biomass is not as relevant as other root properties such as root structure, especially with very fine rooted species such as *S. sexangulare*. Our second set of predictions had some support; rates of $E_T$ were positively related to measures of leaf area, but only for *S. sexangulare*. Planted platforms did have higher rates of $E_T$, excluding *S. album*. The reason for this is that the CAM physiology exhibited by *S. album* would have contributed to a lower stormwater retention performance. Finally, our hypothesis that plants would have a significant overall effect on stormwater retention by green roof platforms is only partially supported by findings for *S. kamtschaticum*. I learned however, that overall (annual) retention rates are not the best response variable to analyze, in order to understand the potential treatment effects with varying storm size. Other approaches to determining a treatment effect demonstrated here include assessing rates of evapotranspiration as well as reporting plant treatment effects on retention as a percentage of the retention totals from unplanted controls.

This study provides insight into different morphological characteristics of three *Sedum* species and their water use in green roof environments during the first two years of establishment. These results demonstrate that there are significant plant species-specific and seasonal effects that can influence stormwater runoff, which are often not considered in other green roof studies, especially those of less than a year in duration, or in newly planted environments. The two species with the greatest stormwater retention efficiencies, *S. kamtschaticum* and *S. sexangulare*, also had the highest rates of evapotranspiration, and higher $E_T$ rates resulted in lower rates of runoff. Since total runoff from platforms planted with *S. album* was only 10% less than runoff from unplanted platforms for both years, it is unlikely that this species has any significant stormwater benefit for the mid-Atlantic region; nevertheless, it is a hardy species which can survive significant periods of drought, which may be important for other greenroof design intents. Future work should address the complex relationships between plant physiology and environmental characteristics to further elucidate water use by additional green roof species, which show suitable hardiness characteristics.

# **Chapter 4.** The application of the FAO56 Penman-Monteith equation to predict plant water use and stormwater runoff from green roofs.

## 4.1. Introduction

Mechanistic models can be used to understand how functional aspects of green roof and their structure relate to important ecosystem services, such as stormwater retention. Because rates of evapotranspiration ($E_T$) have been directly linked to stormwater retention efficiency (Voyde et al. 2010, Chapter 2), investigating and calibrating $E_T$ equations used in predictive models is vital to the precision and accuracy of the model outputs.

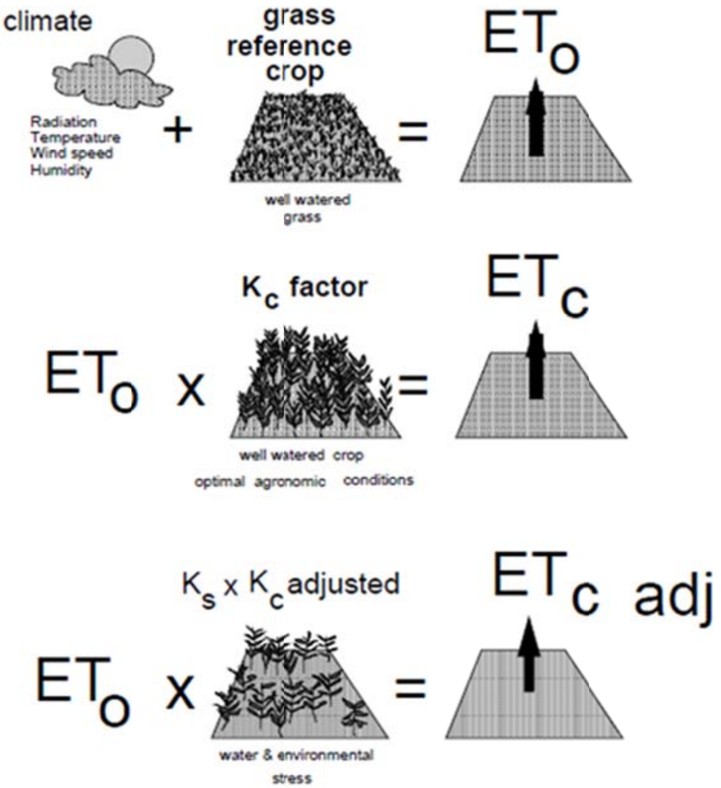
A growing body of research is establishing that standard $E_T$ equations can be adapted with some success to predict $E_T$ from green roofs, which is a major component of any water balance model, and the hardest to measure with any precision. Rezaei and Jarrett (2006) tested a number of different predictive $E_T$ equations for green roof applications and found certain equations worked better under different environmental conditions, in greenhouse studies of *Sedum album* and *Delosperma nubigem*. Of the various equations tested (Rezaei and Jarrett 2006), four have also been used and verified by others to predict $E_T$ from experimental mixed-species green roof modules: (a) the Penman and Penman Monteith equation (Feller 2011); (b) the FAO version of the Penman-Monteith equation (Hilten 2004, Prowell 2006, Schneider 2011); (c) the Hargreaves-Samani equation (Hilten 2004; Prowell 2006), and (d) the Thornwaite equation (Kasmin et al. 2010). These models were also included in a study by Voyde (2011) who tested several additional equations and found the FAO56 version of the Penman-Monteith to one of the most robust tools (the FAO24 was preferred) for predicting total $E_T$ for green roof experiments using *D. australe* and *S. mexicanum*.

The FAO56 equations basically modify the standard Penman-Monteith equations used to predict $E_T$ by assuming the stomatal conductance and albedo of a reference grass crop. These calculations are further modified by a ks coefficient to account for drought stress and a kc coefficient to account for physiological attributes of different plant species (Figure 4.1). A key focus of research on adapting $E_T$ equations (originally designed for agricultural use) for green roofs has been to adjust the calculations for less than well-watered conditions. One recent study has found that the Thornwaite adjustment (Thornwaite and Mather 1955) works well with the ASCE version of the FAO56 Penman-Monteith equation (DiGiovanni et al. 2012). Another study (Sherrard and Jacobs 2012) successfully used a different adjustment (based on Guswa 2002). The FAO manual has recommended a similar equation (see below).

Less is known about how to adjust this equation, using crop coefficients, to account for physiological adaptations by CAM plant species to drought stress. It is because of these adaptations that Sedums are predominantly used for green roofs worldwide. Some unpublished work (DiGiovanni 2012, Voyde 2011) has suggested an overall green roof $k_c$ value is near 1 for well-watered conditions, indicating little difference in $E_T$ rates between Sedum plants and cool season grasses on which the unadjusted

FAO56 equation equations are based (see below). Other studies have used a single $k_c$ value (0.53, Sherrard and Jacobs 2012) for the whole year. The mid-season crop coefficients for the only CAM species (pineapple) in the FAO manual (Figure 4.1) is referenced as 0.3, but is estimated to increase up to 0.5 later in the season (Allen et al. 1998).

**Figure 4.1** The FAO 56 adjusts ETo for crop specific characteristics and less than well watered conditions with ks and kc factors (from Allen et al., 1998).



Voyde (2011) references a number of reported k-values from different studies globally, which we summarize in Table 4.1. Reported values range from 0.25 to 3.25.

**Table 4.1** Summary of different kc-values reported in the literature

| Kc Value | Reference | Notes |
|---|---|---|
| **0.25-0.35** | City of Riverside 1994 | |
| **0.52** | Lazzarin 2005 | Energy balance study in Italy |
| **0.53** | Sherrard and Jacobs 2011 | Based on best model fit on New Hampshire roof |
| **0.85-1.01** | Voyde 2011 | FAO-24 method used in New Zealand |
| **1-1.8** | Schneider 2011 | Uses a dual approach in Pennsylvania |
| **0.24-3.25** | Rezai and Jarrett 2005 | Greenhouse study |

The objective of this study was to determine whether species-specific differences in $E_T$ rates for three green roof species merit the use of different crop coefficients in the FAO56 equation for predicting evapotranspiration. Furthermore, I sought to determine whether these $k_c$ values varied by species and season, and whether there were any additional variables which could be used to increase the precision and accuracy of the FAO56 Penman-Monteith equation, to predict daily water use from green roofs. The equations were calibrated using 2011 data and coefficients were verified against for 2012 using regression analysis. Lastly, these predicted crop coefficients were used to validate the species-specific outputs from a water balance model using data collected in 2012 (from Chapter 2).

## 4.2. Materials and Methods.

### 4.2.1 Using the FAO56 Penman Monteith equations to estimate green roof $E_T$

The FAO56 equation is derived from the Penman Monteith equation (Chapter 1). This equation assumes some constant parameters for a clipped grass reference crop, i.e., a surface resistance of 70s $m^{-1}$ and an albedo value of 0.23 and is defined as:

$$ET_0 = \frac{0.408(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad \text{... } \textbf{Equation 1}$$

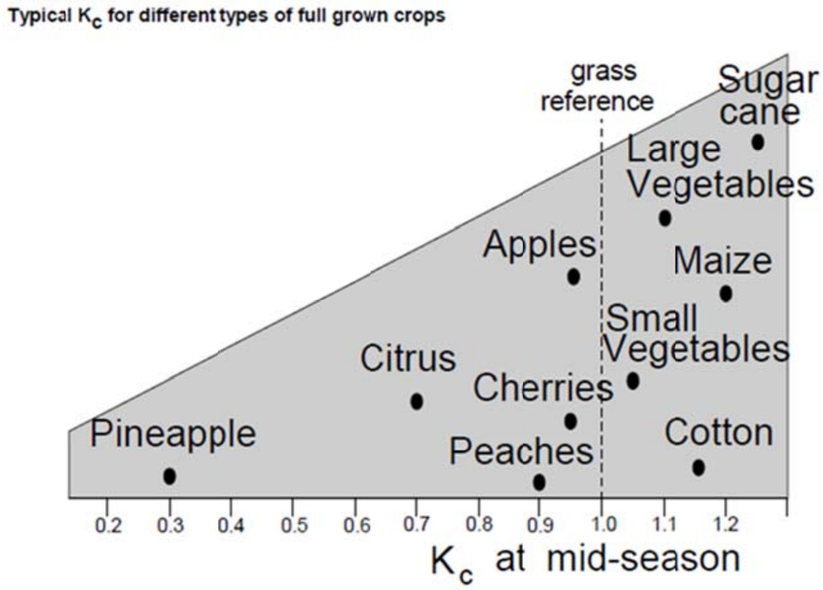
where $ET_o$ is reference evapotranspiration, $R_n$ is net radiation at the crop surface, G is soil heat flux density, $e_s$ is saturation vapor pressure, $e_a$ is actual vapor pressure, $r_s$ is the canopy surface resistance, $r_a$ is the bulk surface aerodynamic resistance, Δ is the slope of the vapor pressure curve, γ is the psychometric constant, T is the average daily temperature and $u_2$ is average daily wind speed. The equation can be adjusted for different crops by a "crop coefficient" multiplier (Figure 4.2; $k_c$ value) to account for species-specific differences in $E_T$. $K_c$ is calculated as the ratio of $E_{To}$ to actual $E_T$.

For seasonal crops, different values are typically assigned throughout the year for changes in growth (leaf canopy). A further adjustment is made to account for less than well-watered conditions, by introducing a water stress coefficient, $k_s$ (Allen et al. 1998). This equation is described as:

$$k_s = \frac{TAW - D_r}{TAW - RAW} \quad \text{......} \textbf{Equation 2}$$

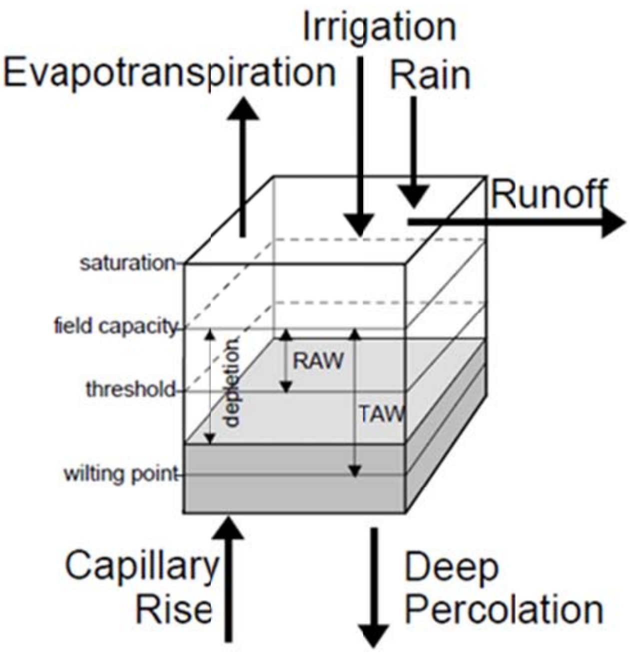
where TAW is total available water, $D_r$ is root zone depletion (mm), i.e., water deficit relative to field capacity, and RAW is water that is readily available to the plant (Figure 4.3). The coefficient ($k_s < 1$) is then used in conjunction with $k_c$.

**Figure 4.2** Recommended crop coefficients for different species (Allen 1998)



Data from previous chapters was used to parameterize this equation (Figure 4.4, Figure 2.8; Table 1). Wilting point, needed to estimate TAW (Figure 4.3), for both species was determined based on the results from Chapter 1 (Figures 2.8 and 2.4). A value of 0.06 $m^3m^{-3}$ was suggested for *S. kamtschaticum* because this is the point at which daily carbon gain became negative for this species. A value of 0.04 $m^3m^{-3}$ was suggested for *S. album* even though daily carbon gain never became negative for this species; this was also related to the lowest recorded volumetric water content (VWC) measured in the growth chamber studies (Chapter 1) and at this point $E_T$ by *S. album* was minimal. A value of 0.05 $m^3 m^{-3}$ was therefore used as the “wilting point” in the FAO56 equations for all species.

**Figure 4.3** Factors determining ks (from Allen et al., 1998).



Total available water is defined as the difference between field capacity and wilting point (Eq. 3, Figure 4.3). In this chapter, I use the terms field capacity and water holding capacity interchangeably (See glossary). Since field capacity did not vary greatly among or between species in 2011 (Chapter 2; Table 4.1), I felt justified in using seasonal averages to estimate field capacity. Thus, seasonal TAW values used were 0.179, 0.132 and 0.182 mm for spring, summer, and fall, respectively for 2011. I set the value of readily available water at zero (0) in equation 3. The justification for doing this is that since green roof substrates typically drain very rapidly, there are very few instances once field capacity is achieved, where one might expect $E_T$ would not be influenced by VWC.

**Figure 4.4** Wilting point was determined as 0.05m3m$^{-3}$ based on Chapter 1.

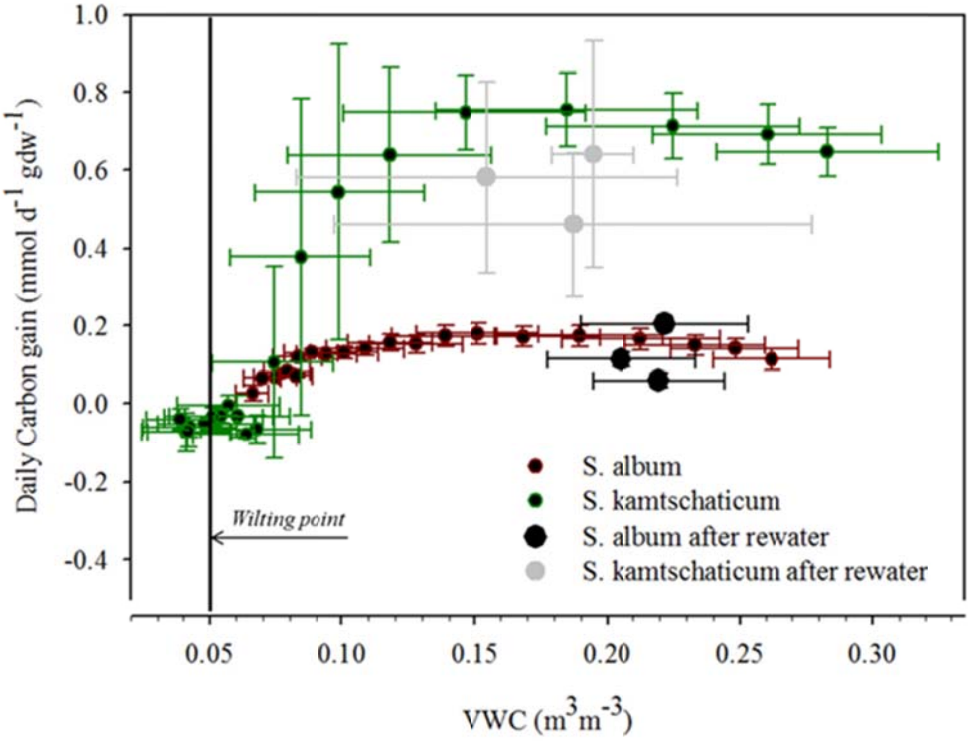


**Table 4.2** Average field capacity by season and species as determined in Chapter 2.

| Treatment | Spring,11 | Summer,11 | Fall,11 |
|---|---|---|---|
| *S. album* | $0.189^{a}$ | $0.131^{b}$ | $0.185^{a}$ |
| *S. kamtschaticum* | $0.186^{a}$ | $0.135^{bc}$ | $0.179^{ab}$ |
| *S. sexangulare* | $0.157^{ab}$ | $0.122^{b}$ | $0.191^{ab}$ |
| Unplanted | 0.183 | 0.138 | 0.173 |
| **Seasonal Averages** | **$0.179^{a}$** | **$0.132^{b}$** | **$0.182^{a,}$** |
| **SE** | **0.007** | **0.004** | **0.004** |

### 4.2.2 Model parameterization and data collection

Environmental data and collection. All environmental and soil moisture data were logged and transmitted using EM50R radio loggers (wireless sensor nodes; Decagon Devices Inc., Pullman WA). Air temperature and relative humidity (VP-3 sensor), wind speed (Davis cup anemometer), solar radiation (PYR, total radiation pyranometer), photosynthetic flux density (PPF, QSO-S PAR sensor) and rainfall (ECRN-100 tipping rain gauge) were continuously collected at the study site during 2011 and 2012 (Appendix E; Figs E1-E5). Sensor data was measured every minute and the 5-min averages logged by the EM50R nodes for the environmental (weather) data and the substrate moisture data (see below) from experimental green roof platforms Data were transmitted and downloaded via a Decagon (RM-1) radio base station in the University of Maryland, College Park (UMCP) greenhouse complex, which was connected to a dedicated computer. Data was downloaded and viewed whenever necessary using DataTrac software v.3.2 (Decagon Devices, Inc.), and from anywhere on the web, using Logmein (Woburn, MA) software, as described previously in Chapter 2.

Experimental platforms for ET, VWC, and runoff verification: Eighteen experimental green roof platforms (1.31 m$^2$ along the interior margins) were constructed and instrumented at the University of Maryland, College Park campus from May – July, 2010 (Chapter 2). Platforms were constructed and maintained according to FLL standards (FLL, 2008). Two platforms were constructed and left as roofing membrane-only controls; these platforms were used to ensure that equipment measuring water inputs and outputs were functioning correctly and to provide some data on how standard flat roofs might perform under the conditions of this study. The remaining sixteen experimental platforms were planted with either *S. album*, *S. kamtschaticum*, or *S. sexangulare,* or left unplanted.

Four replicates of each planting treatment were monitored. All platforms drained into a gutter that was fitted with a 40mL double-tipping rain gauge (TB-4, Hydrological Services, Lake Worth, FL). Runoff data these rain gauges was collected at 1-minute resolution using a CR-10 data logger and two SW8A multiplexers (Campbell Scientific, Logan, UT). The logger program included a calibration to account for water loss at high intensity. Four substrate moisture sensors (Decagon 5TM) were deployed in the center of four quadrants, in each of the 16 experimental platforms. The sensors were positioned so that the prongs were facing upslope, and were oriented vertically to minimize interference with rainfall. Sensors were calibrated at various times throughout the study, to ascertain variations in sensor performance (Appendix B). Evapotranspiration was calculated as the difference in average substrate moisture content each day and assumed to be negligible during rain events.

Simple water balance model: Once $E_T$ can be correctly predicted, these calculations can be incorporated into a water balance model to predict runoff by setting precipitation (P) equal to $E_T$ plus change in storage, or substrate VWC, plus runoff (R) plus interception (I), which we set at 1mm for all species since no known records of interception for Sedum species have been reported.

### 4.2.3 Model validation and verification

Estimates of $k_c$ were averaged by season for each species whereby spring was defined as March-May, summer as June-August, and fall as September through November. The equations were calibrated using 2011 data and coefficients were verified against for 2012 using regression analysis.

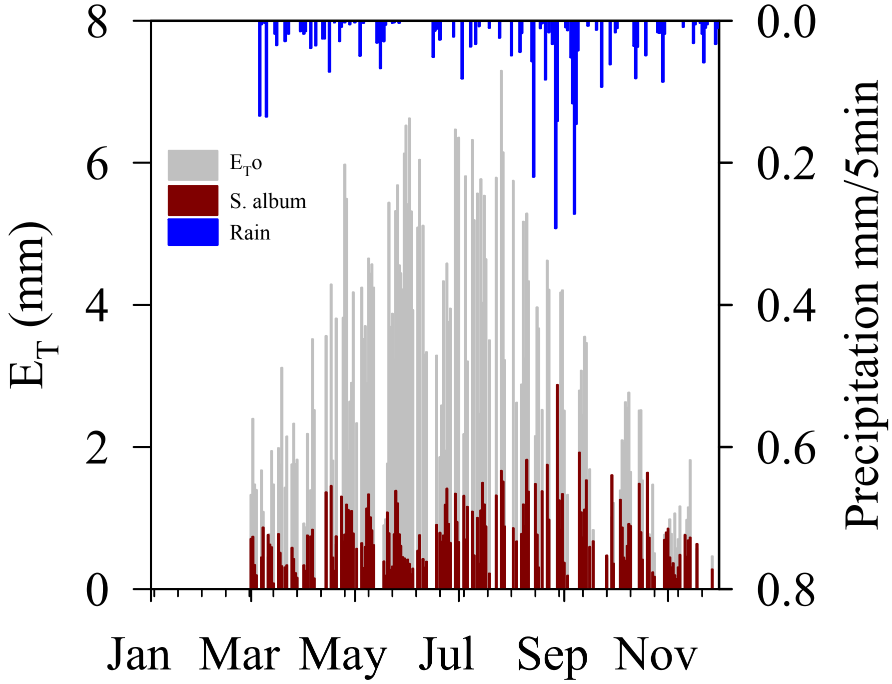
## 4.3. Results and Discussion

### 4.3.1 Actual vs. Estimated Evapotranspiration (ETo).

Figures 4.5 a-c illustrate the relationship between actual $E_T$ and estimated $E_To$ for the three species in 2011. The FAO56 equation consistently over-predicted rates of evapotranspiration. This disparity was greatest during the summer months, when predicted daily $E_T$ rates were nearly double measured rates. Differences between species were also evident. As reported in Chapter 2, *S. sexangulare* had higher $E_T$ rates than the other species during spring, though this difference was not statistically significant, due to high variability among replicates. Total annual evapotranspiration was 147mm for *S. album* , compared to 162mm and 183mm for *S. kamtschaticum* and *S. sexangulare*, respectively.

**Figure 4.5a-c** Calculated ETo and actual measured ET in 2011 for experimental green roof platforms planted with (a) *Sedum album* and (b) *Sedum kamtschaticum*, and (c) *Sedum sexangulare.*

**a.**



**b.**

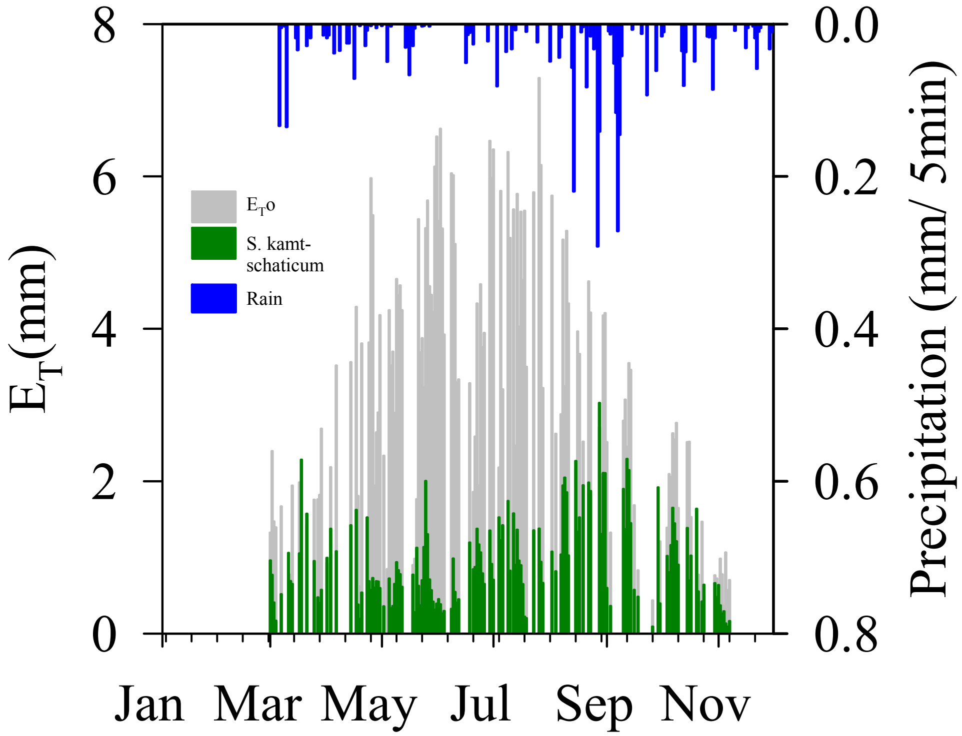


**Figure 4.5c** Calculated ETo and actual measured ET in 2011 for experimental green roof platforms planted with *Sedum sexangulare*.

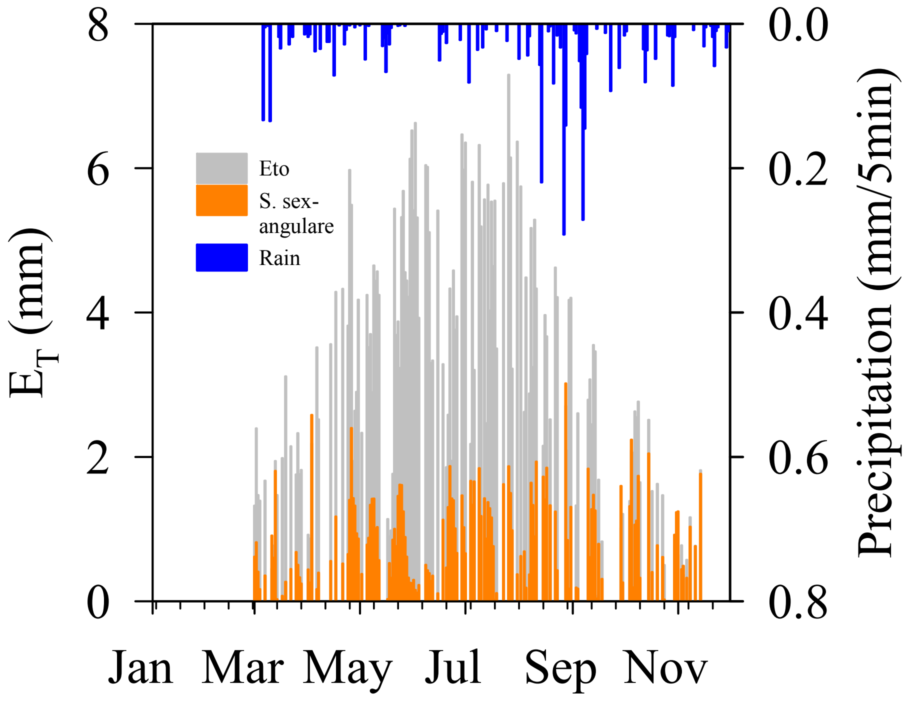
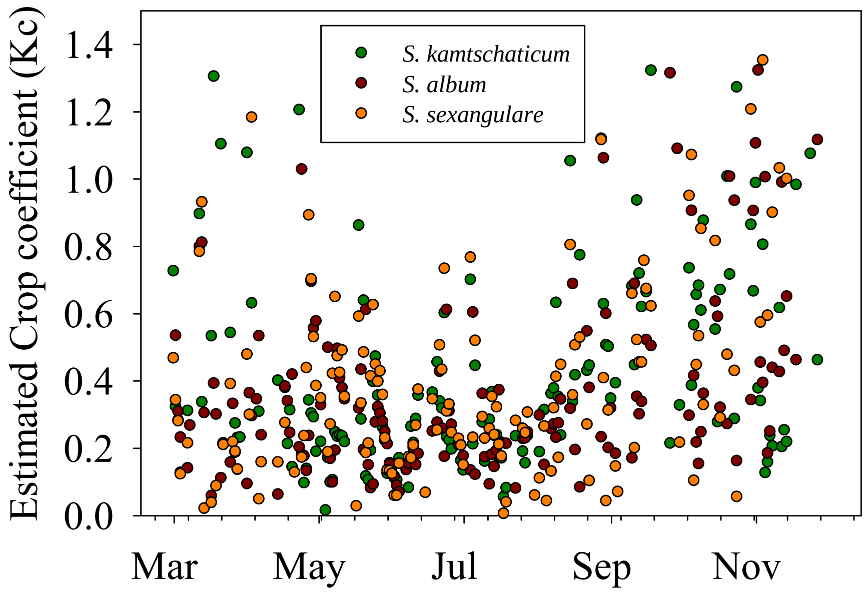


**Figure 4.6** Estimated kc values for each species in 2011



### 4.3.2 Calculating crop coefficients

Since $k_c$ values are not well-defined for green roof species, I chose to estimate them after estimating $k_s$, not before as recommended in the FAO56 manual (Figure 4.1). This was done to eliminate variation due to known relationships between $k_s$ and VWC before attempting to explain unknown variation. After correcting for the influence of having less than well-watered conditions ($k_s$), a large difference between $E_T$ predicted by FAO56 and actual $E_T$ was still evident (Figures 4.5 and 4.6). Figure 4.6 shows the $k_c$ estimates in 2011 and also the relatively large variation in these estimates, especially for values in fall. As can be seen, species-specific differences in $k_c$ values were not easily discernible when viewed on a daily basis (Figure 4.6).

The closer the value of $k_c$ is to 1, the more accurate the FAO56 prediction; notably $k_c$ values for *S. kamtschaticum* were higher compared to the other two species, perhaps reflecting a higher level of C3 metabolic activity. As might be expected due to the smaller differences between actual and predicted $E_T$ in the fall (Figure 4.5) the $k_c$ values were highest for all species (Table 4.2). This could be an indication that green roof plants are more physiologically similar to cool season grasses during this time.

**Table 4.3** Average kc values for three different Sedum species, by season in 2011.

| **Species** | **Spring** | **Summer** | **Fall** |
|---|---|---|---|
| *S. album* | 0.27 | 0.31 | 0.59 |
| *S. kamtschaticum* | 0.36 | 0.33 | 0.58 |
| *S. sexangulare* | 0.35 | 0.29 | 0.62 |

Figures 4.7a-f show $E_T$ fits before and after crop coefficient corrections for 2011. Even after $k_s$ adjustments (Figures 4.7a-c), the FAO56 over-predicts $E_T$ by approximately a factor of two. The slopes of the lines relating predicted $E_T$ to measured $E_T$ after $k_c$ adjustment ranged from 0.47 for *S. album*, to 0.58 for *S. sexangulare*. Although the adjusted ($E_{T\ adj}$) still over-predicts measured $E_T$, the data are much closer to a 1:1 line after adjustment (Figures 4.7d-f).

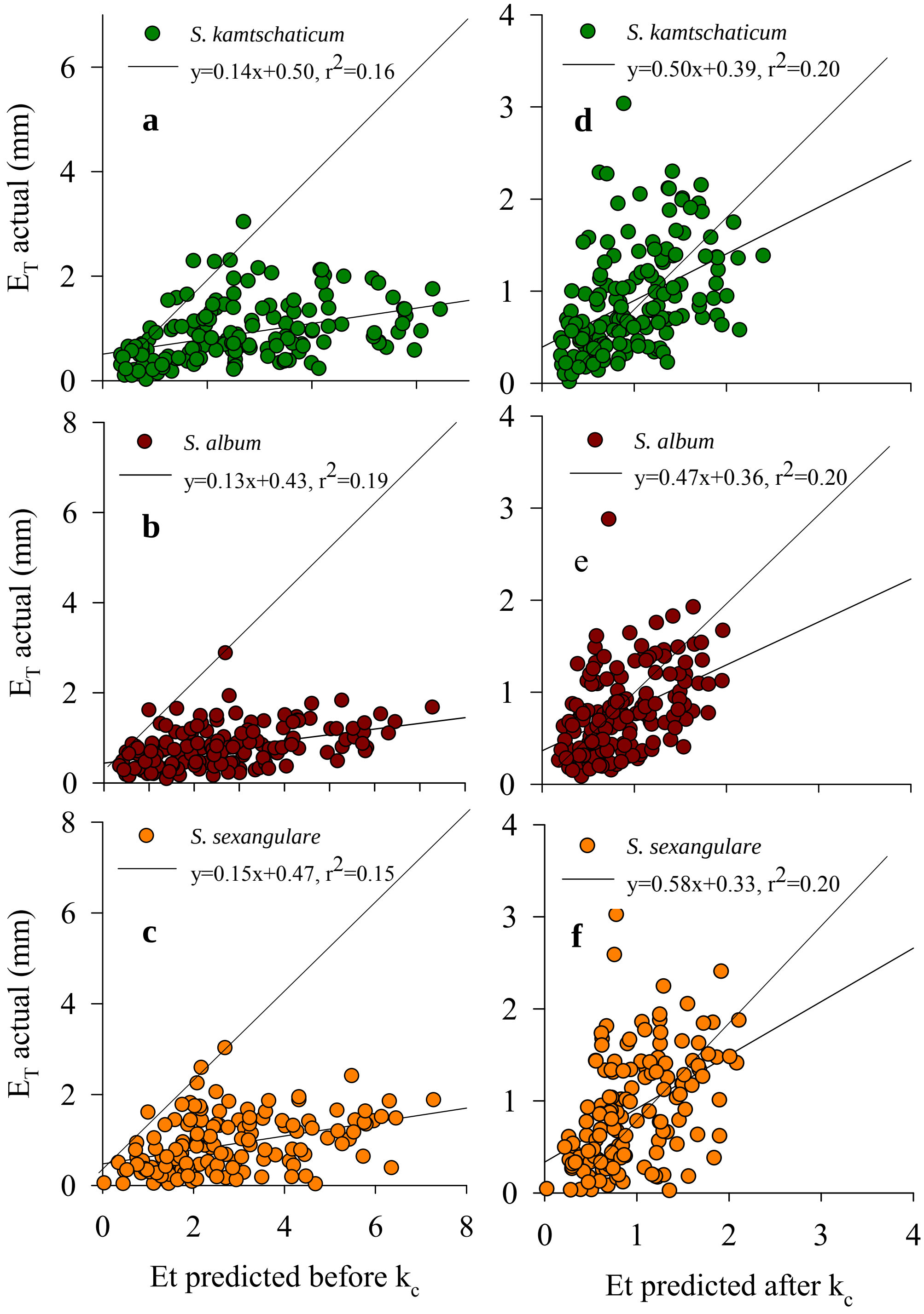
### 4.3.3 Calculating different $k_c$ values for 2012

Estimates of $k_c$ were higher for 2012 compared to 2011. This indicates increased rates of $E_T$ for 2012 and agrees with measurements made in the field studies (Chapter 3). Different seasonal trends in $k_c$ were observed for *S. album* and *S. sexangulare*. Spring values were higher compared to the values for other seasons for *S. sexangulare*, and the reverse was true in 2011. Fall values were lower for *S album* compared to the other two seasons, and the reverse was true for 2011. The same overall trend in $k_c$ value was observed for *S. kamtschaticum* for 2011 and 2012, but the values were higher in 2012.

**Table 4.4** Estimated kc values for three different Sedum species, by season in 2012.

| Species | Spring | Summer | Fall |
|---|---|---|---|
| *S. album* | 0.38 | 0.38 | 0.67 |
| *S. kamtschaticum* | 0.62 | 0.85 | 0.79 |
| *S. sexangulare* | 0.69 | 0.45 | 0.59 |

**Figure 4.7** Regressions of predicted against actual measured values of $E_T$ for (a) *S. kamtschaticum*,(b) *S. album* and (c) *S. sexangulare*, before (a-c) and after kc adjustment (d-f), in 2011. 1:1 lines are also provided



### 4.3.4 Validating 2011 equations with 2012 data:

Models predictions of 2012 data based on 2011 crop coefficients (Figures 4.8a-c) were poor, most likely to some of the issues discussed in Chapter 3. Interestingly, for *S. kamtschaticum*, the adjustment resulted in an under-estimation of $E_T$. We attribute this lack of fit due to differences in plant development and physiology from year to year (Chapters 1 and 2), resulting in different rates of $E_T$ and substrate moisture content, used to calculate actual and predicted $E_T$ in 2012 (Figures 4.9a-c).

### 4.3.5 Substrate Volumetric Water Content

Substrate volumetric water contents (VWC) were measured on a continuous basis throughout the 2-year period for all species (Figs. 4.9a-c). These data were incorporated in the calculations of predicted $E_T$, but what is very noticeable from an examination of the data are species specific differences the daily water use of water from the platforms especially in 2012. An example of this is evident in spring (Figures 4.9a) where daily water use of *S. kamtschaticum* and *S. sexangulare* was greater than for *S. album* and the unplanted platforms; however, during summer, 2012, the performance of *S. sexangulare* was reduced from July onwards, due to unknown causes (Fig 4.9b). An example of the data for *S. kamtschaticum* is given in Appendix E (Figure E.1) with standard errors, to indicate the precision of the replicated sensor data. This gives us confidence in these data for use in quickly evaluating the differences between species, in terms of daily water use. Further estimates on sensor variance are provided in Appendix F.

### 4.3.6 Relating $k_c$ values to plant characteristics.

In order for the FAO56 Penman Monteith equation to accurately predict plant water use, the $k_c$ value has to as accurate as possible. Since above analysis has shown that $k_c$ values do vary by species and season, one approach may be to identify plant characteristics that can be used to predict $k_c$ from large datasets. For example, I found that $k_c$ is related to plant coverage, though this relationship was not significant, most likely due to the lower plant coverage in 2011 (p=0.13, Figure 4.10).

### 4.3.7 Using $E_T$ equations to estimate VWC :

Once $E_T$ can be correctly predicted, these calculations can be incorporated into a water balance model to predict runoff by setting precipitation (P) equal to $E_T$ plus change in storage, or substrate VWC, plus runoff (R). As an example, Figures 4.11a-c show the predicted runoff for (a) *S. kamtschaticum,* (b) *S. album* and (c) *S. sexangulare* using both 2012 data and 2012 $k_c$ values (from Table 4.3). As it stands, the simple water balance model over-predicts runoff by approximately 40% on average. This disparity may be due our current lack of understanding of hydraulic conductance through substrates, which would introduce this kind of error into a simple water balance. For example on June 12, an 8mm rain only resulted in a 2mm increase in VWC (Fig 4.11a).

**Figure 4.8** The relationship between measured and predicted ET for (a) S. kamtschaticum,(b) *S. album* and (c) *S. sexangulare* in 2012, using kc values established in 2011.

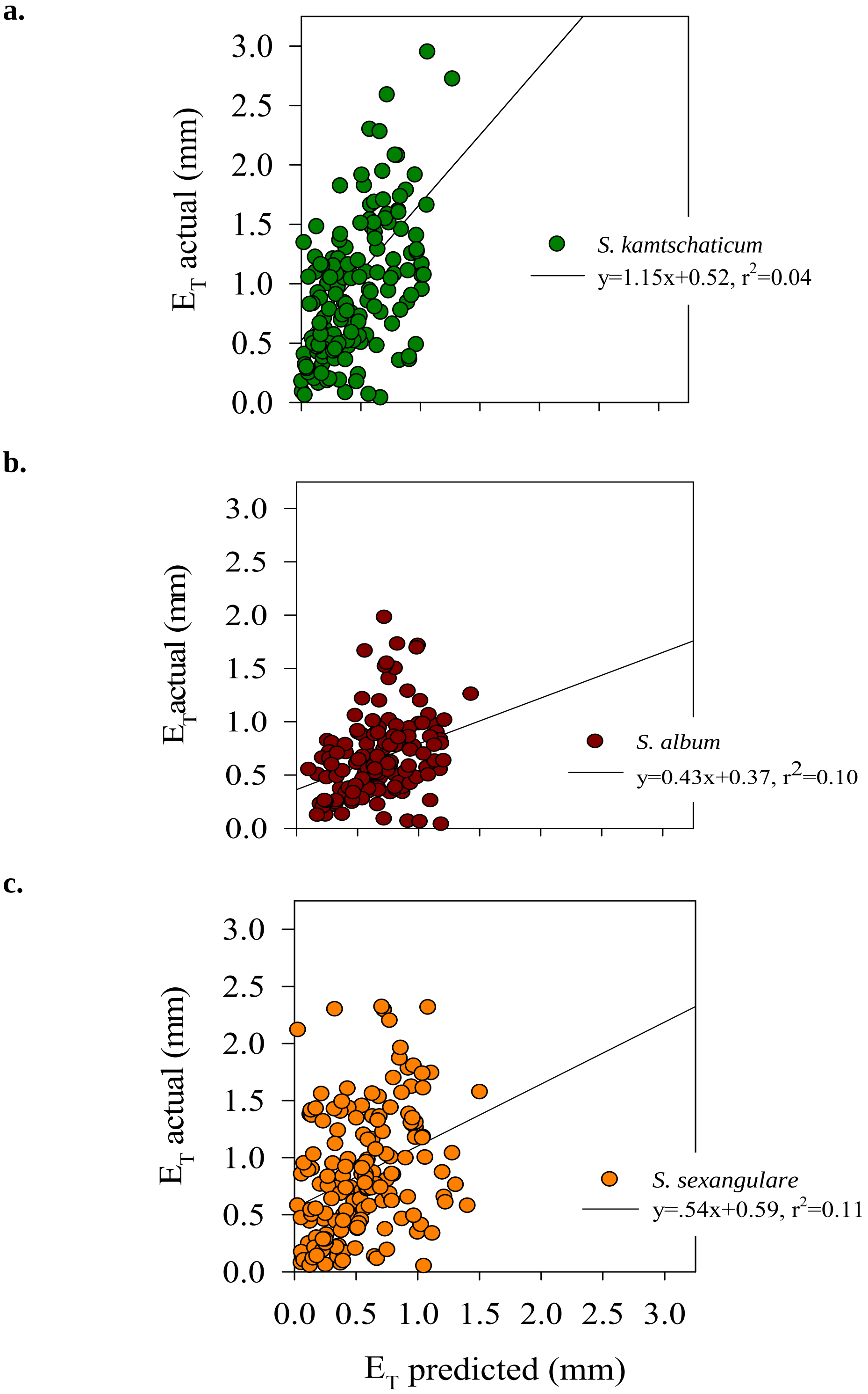
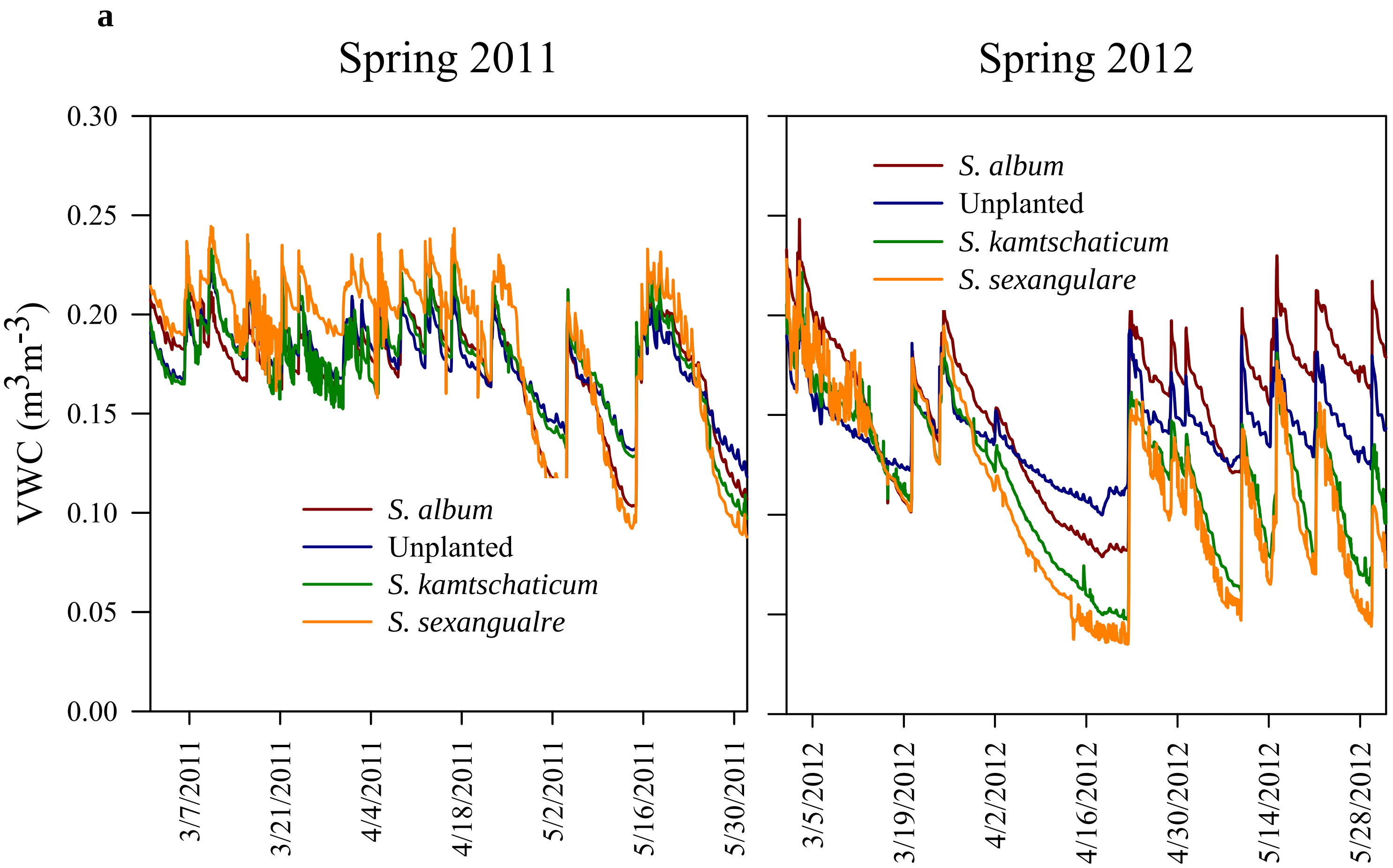
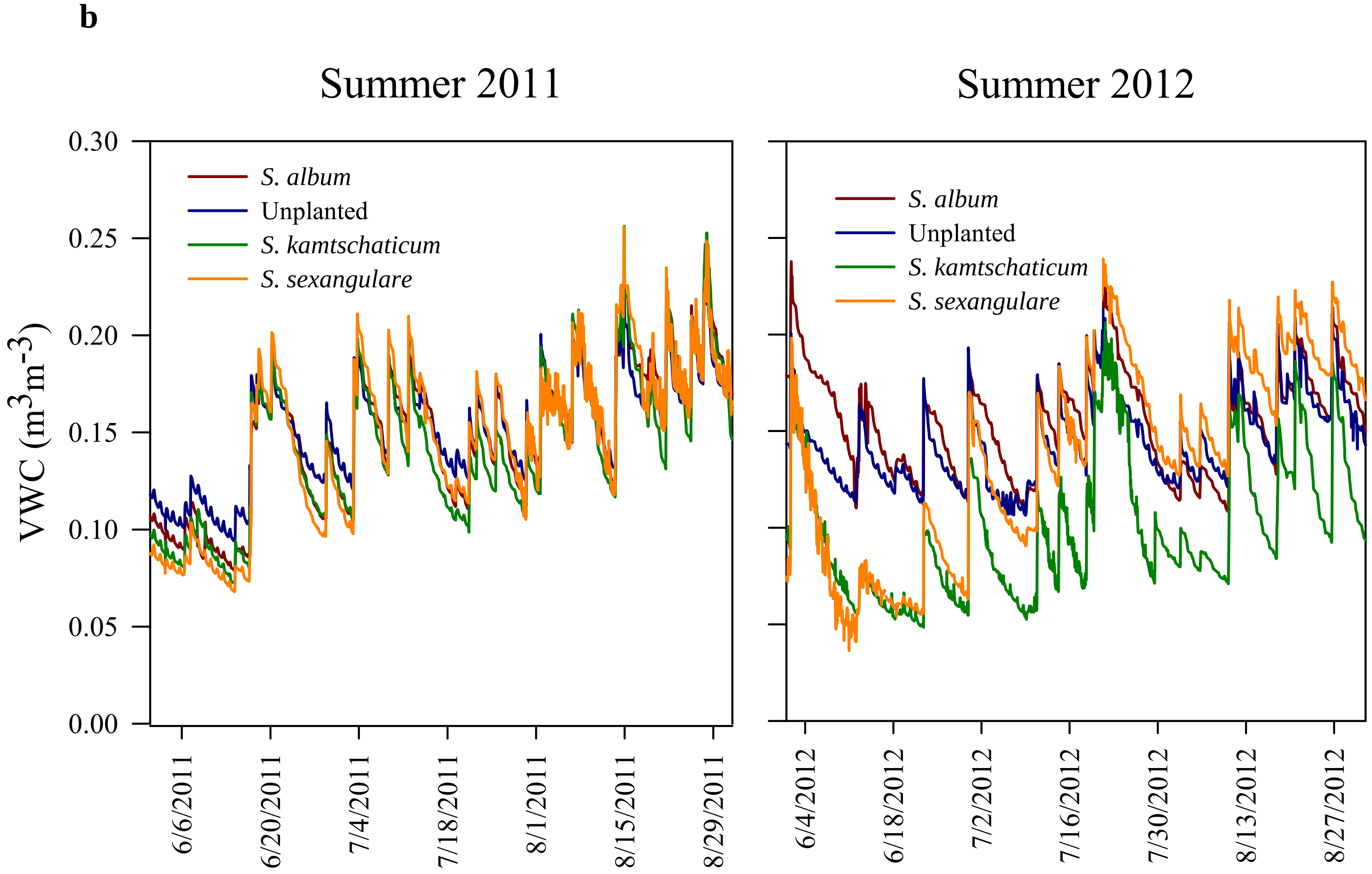


**Figure 4.9a** Species-specific differences in VWC during (a) Spring, (b) Summer and (c) Fall, 2011 and 2012.




b
Summer 2011
Summer 2012
VWC (m3m-3)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
S. album
Unplanted
S. kamtschaticum
S. sexangulare
6/6/2011
6/20/2011
7/4/2011
7/18/2011
8/1/2011
8/15/2011
8/29/2011
6/4/2012
6/18/2012
7/2/2012
7/16/2012
7/30/2012
8/13/2012
8/27/2012

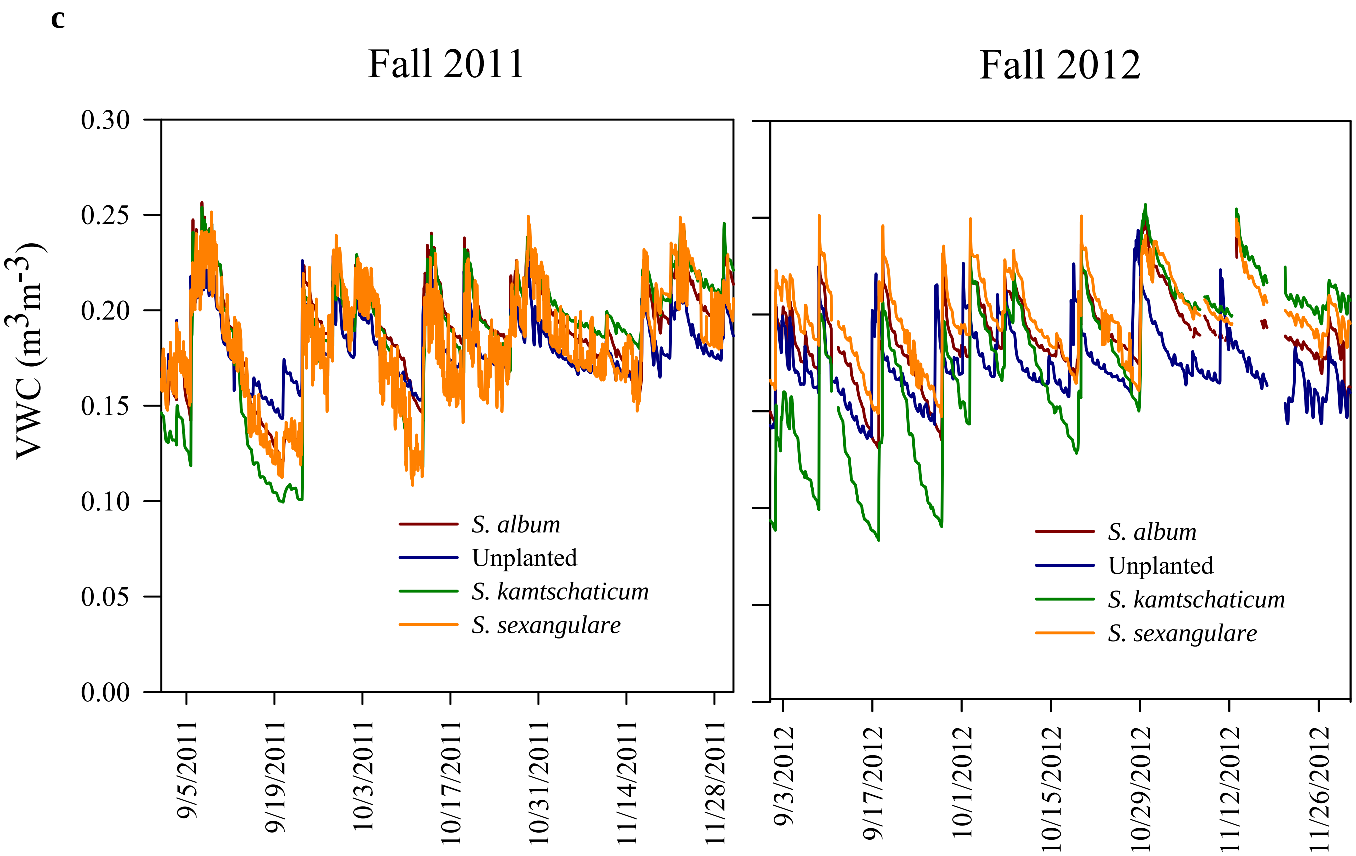

c
Fall 2011
Fall 2012
VWC ($m^3m^{-3}$)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
S. album
Unplanted
S. kamtschaticum
S. sexangulare
9/5/2011
9/19/2011
10/3/2011
10/17/2011
10/31/2011
11/14/2011
11/28/2011
9/3/2012
9/17/2012
10/1/2012
10/15/2012
10/29/2012
11/12/2012
11/26/2012

**Figure 4.10** The relationship between kc values and plant coverage for all seasons during 2011 and 2012.

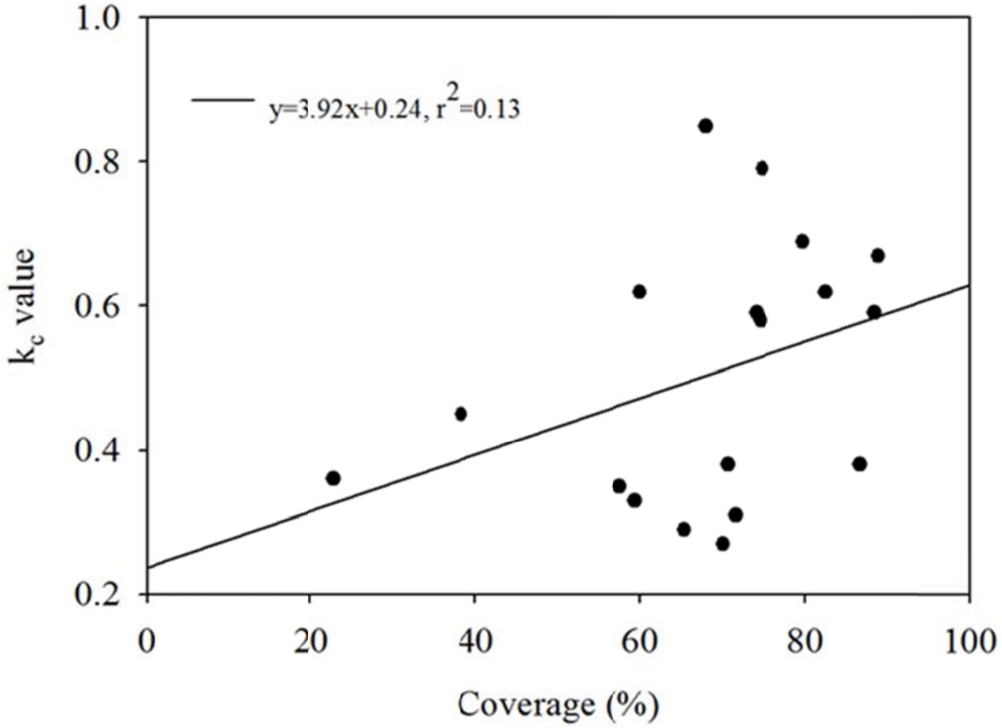
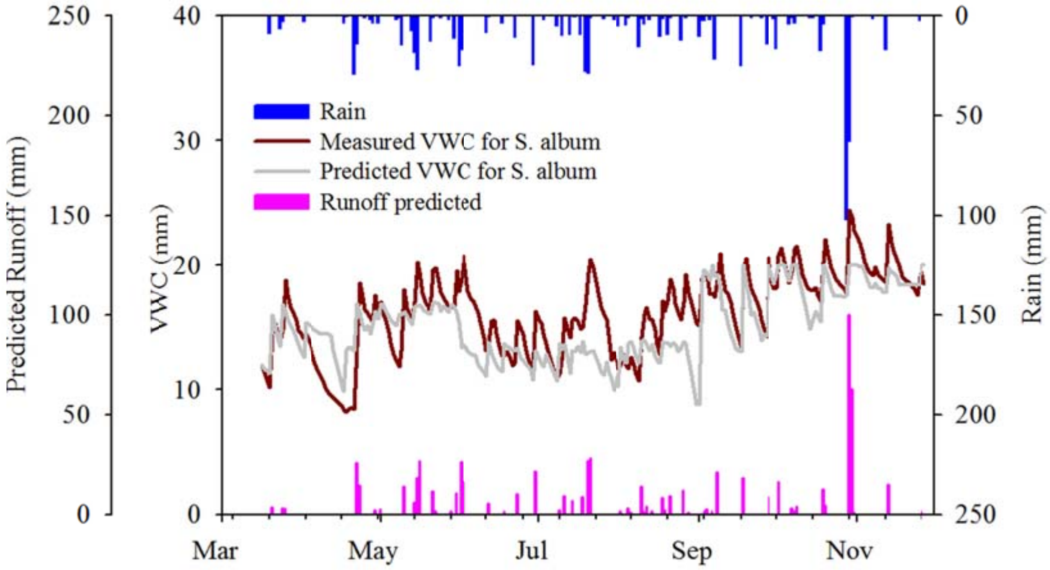


Figure 4.12 depicts other sources of potential error and directions for future research. Another source of model error could be our treatment of interception as 1mm; this is a possible underestimate especially for *Sedum album* (Appendices C and G). Future work will involve refining this model, further scrutinizing rain data against data from other weather stations in the area and re-evaluating runoff measurements. Nevertheless, it is apparent that this simple water balance approach, when combined with good estimates of substrate VWC and plant water use on a daily basis can quickly inform us about the performance of different species and their influence on daily water use from green roof substrates.

**Figure 4.11** Incorporating $E_T$ estimates into the green roof water balance model to predict stormwater runoff for (a) *Sedum album* and (b) *Sedum kamtschaticum* and (c) *Sedum sexangulare*

**a.**



**b.**

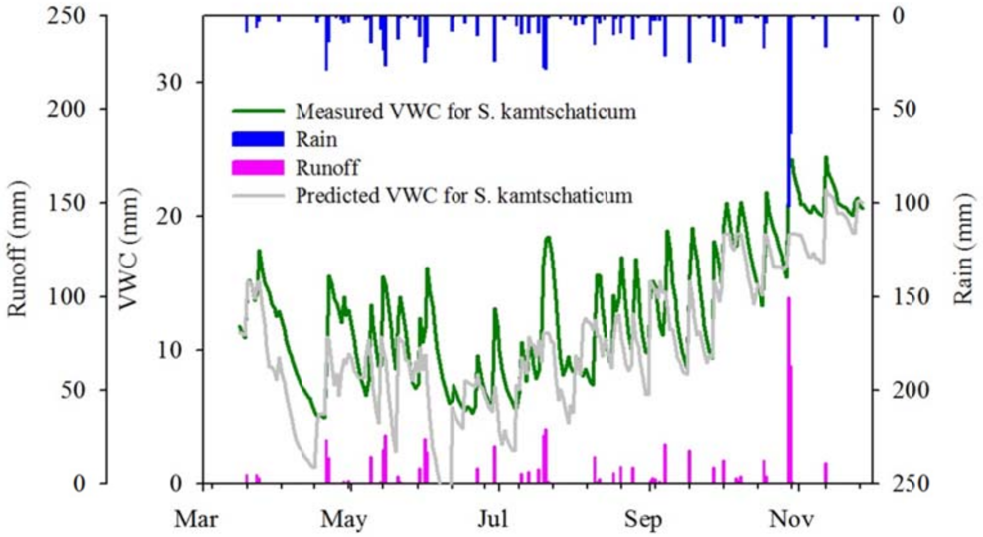


**Figure 4.11c.** Incorporating $E_T$ estimates into the green roof water balance model to predict stormwater runoff for *Sedum sexangulare*.

**c.**

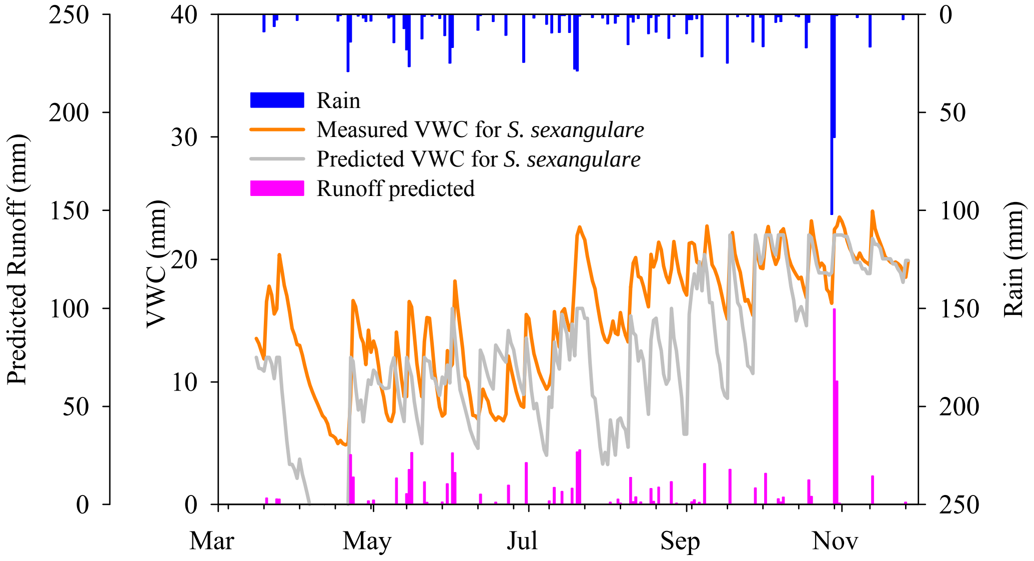
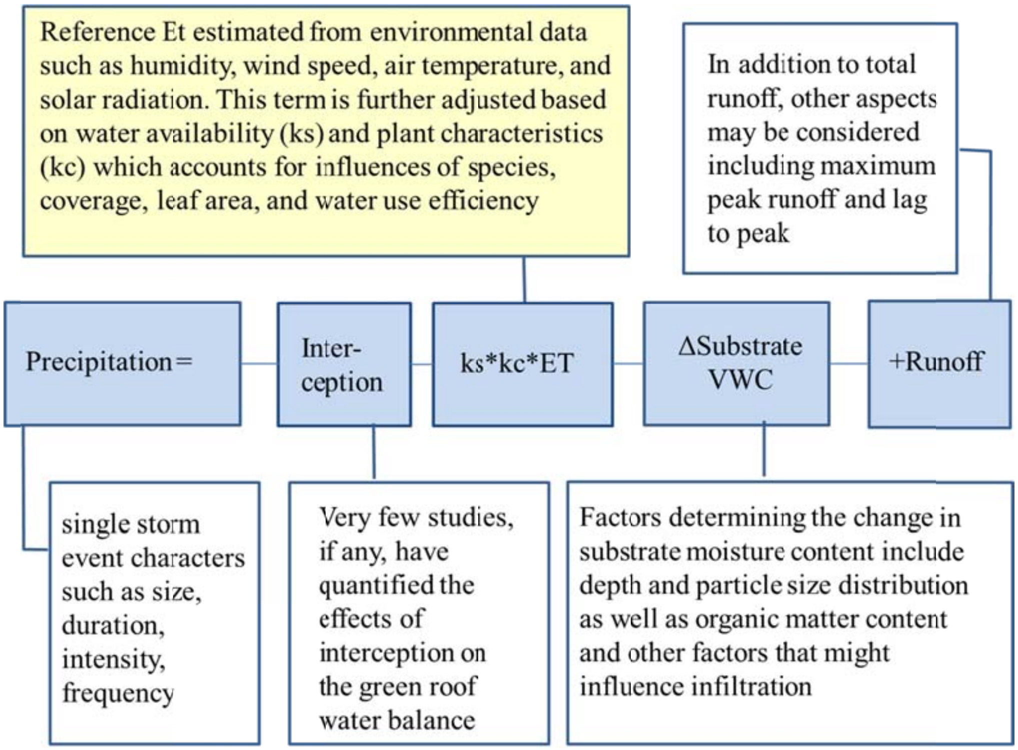


**Figure 4.12** Graphic indicating how the water balance was calculated, potential sources of error, and directions for future research.



Reference Et estimated from environmental data such as humidity, wind speed, air temperature, and solar radiation. This term is further adjusted based on water availability (ks) and plant characteristics (kc) which accounts for influences of species, coverage, leaf area, and water use efficiency

In addition to total runoff, other aspects may be considered including maximum peak runoff and lag to peak

single storm event characters such as size, duration, intensity, frequency

Very few studies, if any, have quantified the effects of interception on the green roof water balance

Factors determining the change in substrate moisture content include depth and particle size distribution as well as organic matter content and other factors that might influence infiltration

## 4.4 Conclusions

In summary, the advantage of using the FAO56 equation to predict $E_T$ is so it can be applied to green roofs for situations where actual rates of $E_T$ are unknown, and where measurement of runoff is difficult (e.g. in retrofit situations). I have identified and provided some insight into how accurate $k_c$-values can be estimated. Nevertheless, it is obvious that more research needs to be done to confirm and further these results. I found that $k_c$-values for the three species were variable between season and species. This variation can be predicted in part by plant characteristics. Long-term estimates of $k_c$ values, accumulated over many years for different green roof plant species may ultimately yield a more generalizable $k_c$-value for use in this equation. Perhaps a better approach may be to use more mechanistic based equations such as the actual Penman-Monteith equation, incorporating measures of resistance and stomatal conductance for Sedum species.

# **Chapter 5.** Summary Discussion and Conclusions

As part of the built environment, green roofs are being planned, accredited, and maintained as such. But how can the ecosystem functions of living green roof ecosystems be optimized by owners and urban planners, as well as quantified by scientists and practitioners? By the same token, how can ecological concepts be applied to these engineered systems? Questions like these are typical in the field of urban ecology (Pickett and Cadenasso 2008) and are probably best answered through interdisciplinary approaches, which weave fundamental ecological research together with engineering principles in order to improve landscape designs (Felson and Pickett 2005). My research in this Dissertation attempts to incorporate elements of this approach, while focusing specifically on the influence of Sedum plants on the water cycle of green roof structures.

The chamber studies address important physiological questions about the influence of CAM physiology on individual species water use while at the same time providing valuable information that can lead to better green roof plant selection. Though Sedum species are often lumped together in discussions about green roof plants, this research demonstrates extremely different physiological responses by *S. album* and *S. kamtschaticum* in response to decreasing water availability. Perhaps the most interesting finding of this study and the field research was the very low efficiency of *S. album*, particularly in comparison to *S. kamtschaticum*. Despite their widespread use on green roofs there is still much to be learned or re-visited regarding the unique ecophysiology of many Sedum species. There is also a wealth of German literature on this topic that needs to be unlocked for the English speaking world (Krupka 1992. Koehler and Poll 2010).

The relevancy of the growth chamber results was illustrated at a larger scale in the field study results, especially during the second year (2012). These results highlighted how green roof plant selection can inform designs for enhanced plant success and stormwater management. Excluding large storms, platforms planted in *S. kamtschaticum* were 30% more efficient compared to the unplanted platforms in 2012. My results demonstrated that there are significant species-specific and seasonal effects that can influence stormwater runoff, but these could only be seen by taking into account the influence of storm size on runoff. The two species with the greatest stormwater retention efficiencies, *S. kamtschaticum* and *S. sexangulare*, also had the highest rates of evapotranspiration, and that higher $E_T$ rates resulted in lower rates of runoff. *S. album* was the more drought tolerant species under the environmental conditions of this experiment. Thus, for geographic areas with extended dry periods, *S. album* may be the preferred species compared to the other two, given its ability to survive.

Now that this baseline information about the plants most typically installed on green roofs exists, future studies can compare the performance of these commonly chosen plants against other plant selections. For example, now that it is clear how these species perform in monoculture, these data could be compared to a study of these three species in community, to see if there was some synergistic effects in stormwater performance that may well have been lost, especially during 2012 which had extended dry periods where *S. sexangulare* appeared to have reduced growth and efficiency. More research to optimize plant selection can be justified now that plant-specific effects on stormwater retention have been shown, especially when ongoing green roof management or renovation costs are considered. Part of the issue with green roofs is the fact that they are biotic systems, and could therefore be expected to improve in performance, if they are well designed and maintained over time.

Of course, the effectiveness of green roof plants, and green roofs in general, at retaining large storms is relatively low for current designs. Nevertheless, treatment of small storms is very important, especially for managing runoff quality (Pitt 1999), especially in dense urban areas with combined sewage /stormwater (CSO) systems. To address stormwater challenges associated with larger storms, green roofs designs can be improved by increasing flow path length. Furthermore, multiple management practices may need to be combined at the watershed scale (Brown et al. 2012). Greenroofs have an advantage over other low-impact design systems in densely built environments, in that they can be more easily retrofitted into the built environment (Dietz 2007).

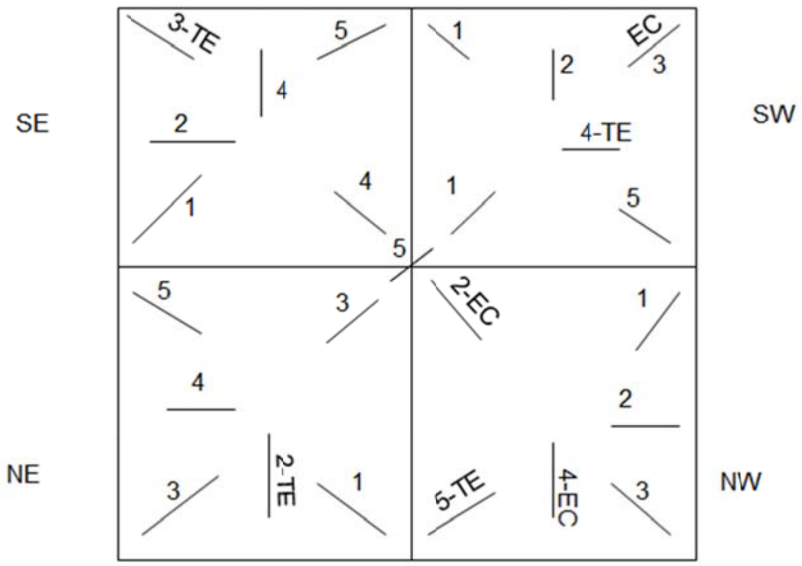
The modeling research results contribute to the growing range of studies regarding the elucidation of crop ($k_c$) and stress ($k_s$) coefficients that are being used to predict $E_T$ rates by green roofs. The importance of accurately predicting species and seasonal $E_T$ rates was identified in Chapter 3 as key for predicting green roof stormwater retention, as illustrated in the modeling results in Chapter 4. This interdisciplinary approach sought to elucidate the key parameters to refine these coefficients, and to provide greater physiological context to the selected coefficients. This work was greatly enhanced through the installation of a soil moisture and environmental sensor network which was able to monitor information at the temporal and spatial precision required, to understand these effects.

The importance of being able to incorporate these fairly simple equations into green roof stormwater models is the ability to relate changes in design elements to system performance, in order to maximize performance for varying climates. Ultimately these smaller scale models could be incorporated into larger scale watershed models that could assist in the management decision-making process. The ability to sense green roofs at the small scale, to understand variability at the large scale, is currently limited only by cost. However, having demonstrated the possibilities of this approach with a relatively dense sensor network that cost less than $25,000 illustrates that this cost is now within the bounds of some building managers. Having models that can predict green roof efficiency and performance combined with cost-effective monitoring systems will become more important as communities become more committed to stormwater management. For example, in Maryland the newly passed House Bill 987, assessing a stormwater fee, will raise awareness about stormwater challenges and should lead to incentive driven monitoring (CleanWaterBaltimore 2012).

In summary, the research described here demonstrates a few strategies that will help contribute to quantifying the benefits of green roofs, to move us towards more sustainable urban design. The incorporation of ecological experiments into green roof designs coupled with advanced new tools for data collection and assimilation can lead to solutions for efficient management of resources in urban environments.

## **Appendix A:** Placement of moisture sensors in trial study (2010)

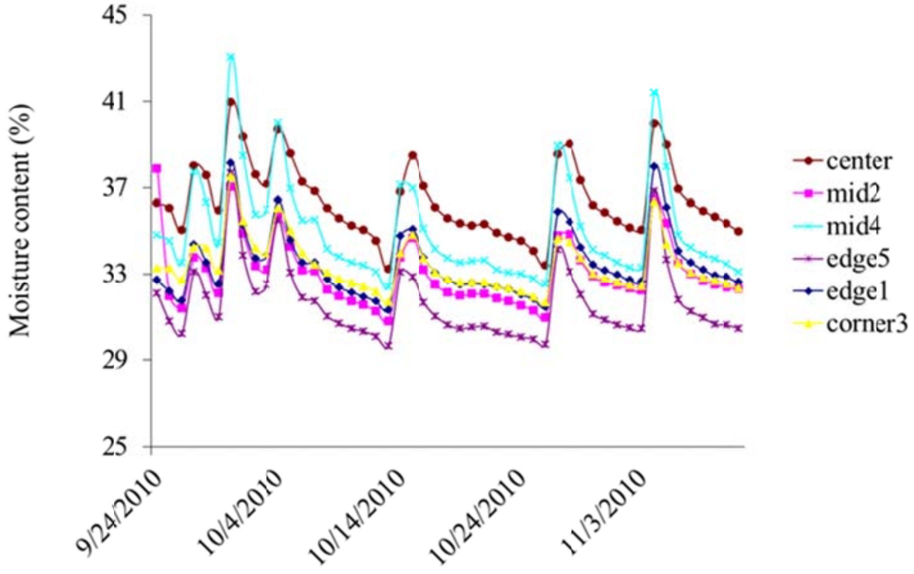
**Figure 0.1** Placement of the intensive study sensors.



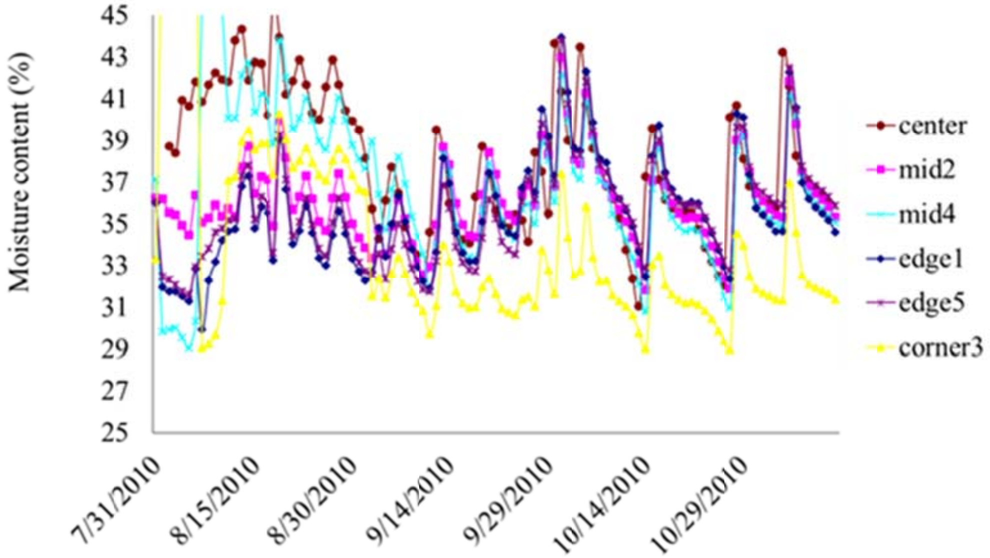
Dashes indicate sensor placement. The numbers, 1-5, dictate whether the sensor is considered and "edge" sensor (1,5), a middle sensor (2,4), or a corner sensor (3). The only exception to this numbering scheme is that 5 sensors in the center which are also labeled 1-5. The letters EC or TE indicate that instead of a 5TM, a different sensor type (Echo-5TE or EC-5, Decagon Devices, Pullman WA) was used.

**Figure 0.2**. Volumetric water content at locations above for three different experimental platforms planted in (a) *S. album* (b) *S. spurium*, or (c) left unplanted. Numbers correspond to locations described in Figure 1.

**a.**



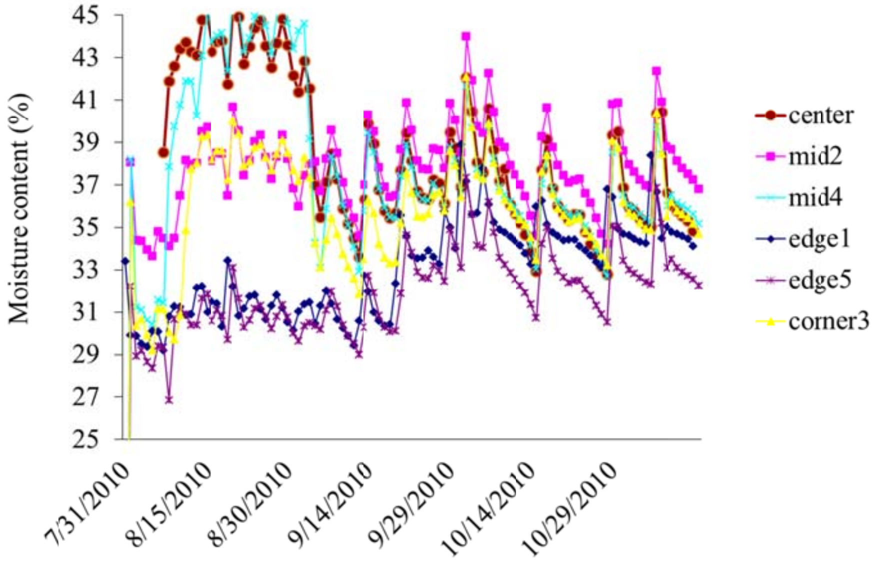
**b.**



*note an alternate sensor calibration was used compared to the rest of the dissertation

**Figure A.2.c** Volumetric water content at locations above for (c) experimental platforms left unplanted. Numbers correspond to locations described in Figure 1.

**c.**



*note an alternate sensor calibration was used compared to the rest of the dissertation

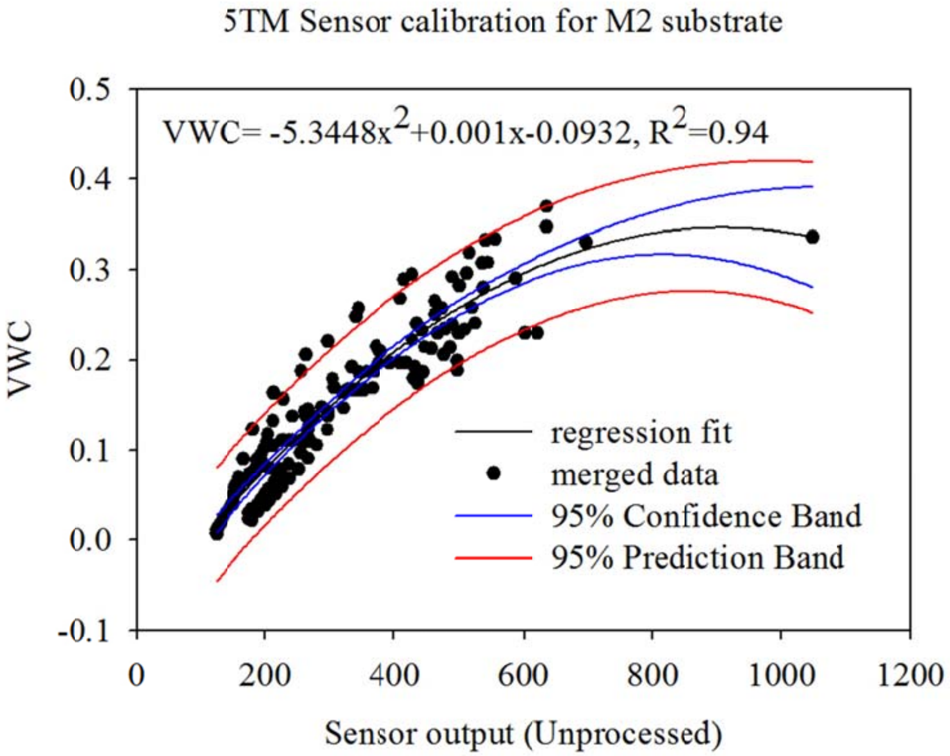
## **Appendix B:** Sensor calibration

Sensors were calibrated according to standards protocol (Cobos and Chambers 2010). Five containers were filled with 760mL of substrate and moisture sensors were inserted, spanning the depth of the containers. These were watered until water began to drain out the bottom (Figure 1). An initial reading sensor reading and container weight was taken once drainage ceased. Then, containers were placed in a drying over at 40º C. Periodically container weights and sensor readings were taken. Then, at the end of the experiment, the containers were left in the oven until the weight was no longer changing. This final weight was substracted from the all the other weights in the data. Finally, changes in water loss, measured as weight, but expressed as volume of water per volume of substrate, were compared to sensor readings for the calibration.

**Figure 0.1** Preparing the greenroof substrate for calibration

This run was replicated in our lab twice. For a third calibration, we sent samples to decagon for outside verification. During this calibration, an additional calibration point for times during which water is still draining from the substrate, above water holding capacity. All data from these three calibrations were merged to obtain the final sensor calibration curve (Figure B.2).

**Figure B.2** Calibration of 5TM sensors to the M2 greenroof substrate.



## **Appendix C:** Calculation of leaf area:

Due to the cylindrical shape of the *S. album* and *S. sexangulare* leaves, leaf area per $cm^2$ of platform surface area was determined using 1) leaf volume 2) average leaf height, and 3) equations for the surface area and volume of a prolate ellipsoid and a cylinder for *S. album* and *S. sexangulare*, respectively:

Volume of a prolate ellipsoid: $4/3\pi abc$, where $a=b=$radius, and $c=$height

Eq. 1a

Approximate surface area of a prolate ellipsoid:
$4\pi\ (a^p b^p a^p c^p b^p c^p/3)^{1/p}$, where $p=1.061$

**Eq. 1b**

Volume of a cylinder: $\pi * \text{radius}^2 * \text{height}$

**Eq.2a**

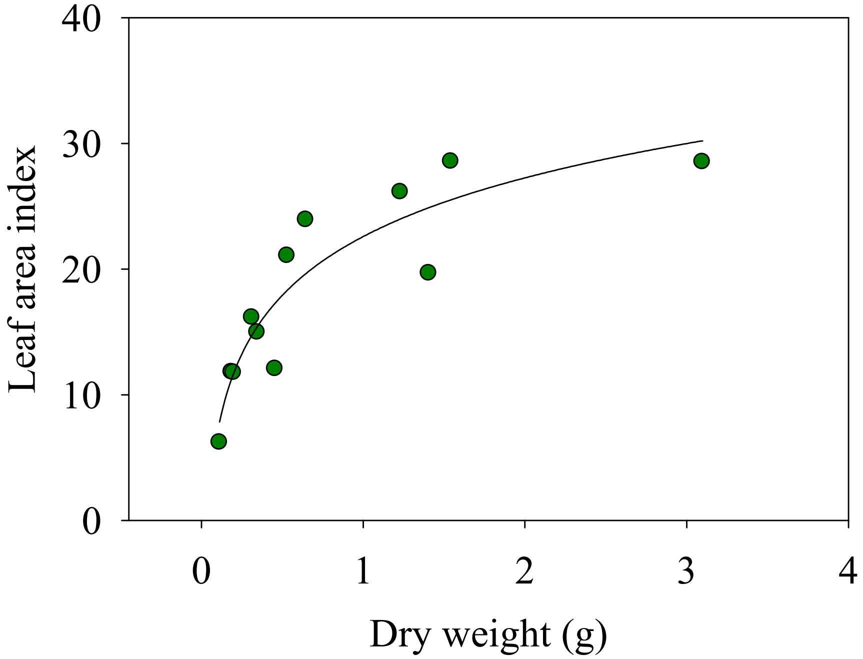
Surface area of a cylinder: $2\ \pi\ \text{radius}\ (\ \text{radius} + \text{height}\ )$

**Eq.2b**

Leaf volume was determined by inserting all leaves from each sample, into a small volume syringe, and then dividing the measured volume by leaf number. Average leaf height was measured for 3-12 leaves per sample. These values were inserted into equations 1 and 2 above in order to derive leaf radius in equation a and solve for surface area in equation b. The dry weight : leaf area ratio was then determined by regression analysis (Figures C. 1a-c). Leaf area was divided by sample area (6.84 $cm^2$) to determine leaf area index. This value was divided in half as per Chen and Black (1992).

**Figure 0.1a-c.** Equations relating leaf area (cm$^2$) to dry weight (g) for (a) *Sedum kamtschaticum* (b) *S. sexangulare*, and (c) *S. album.* Different numbers of points reflect different numbers of sub-samples.

**a.**



**b.**

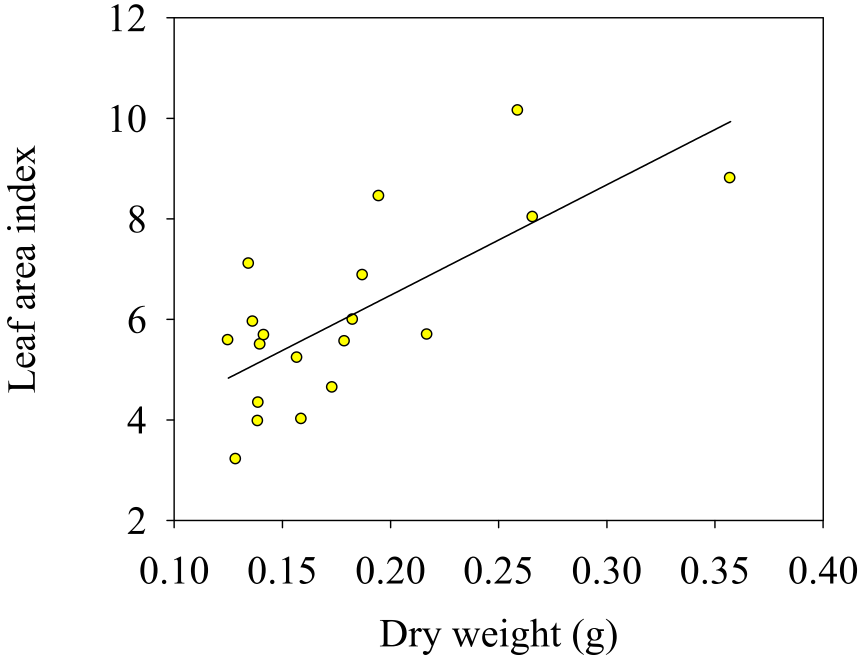
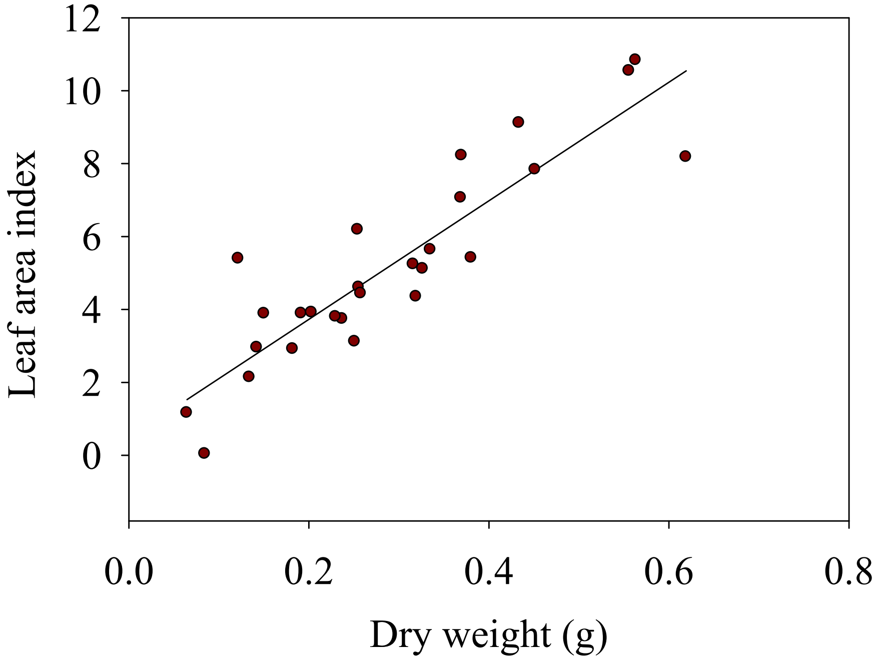


**Figure C.1.c** Equations relating leaf area (cm$^2$) to dry weight (g) for (c) *S. album*. Different numbers of points reflect different numbers of sub-samples.

**c.**



## **Appendix D:** Environmental data (2011-2012).

**Figure 0.1** Photsynthetic Flux density (µmol/m2/s)

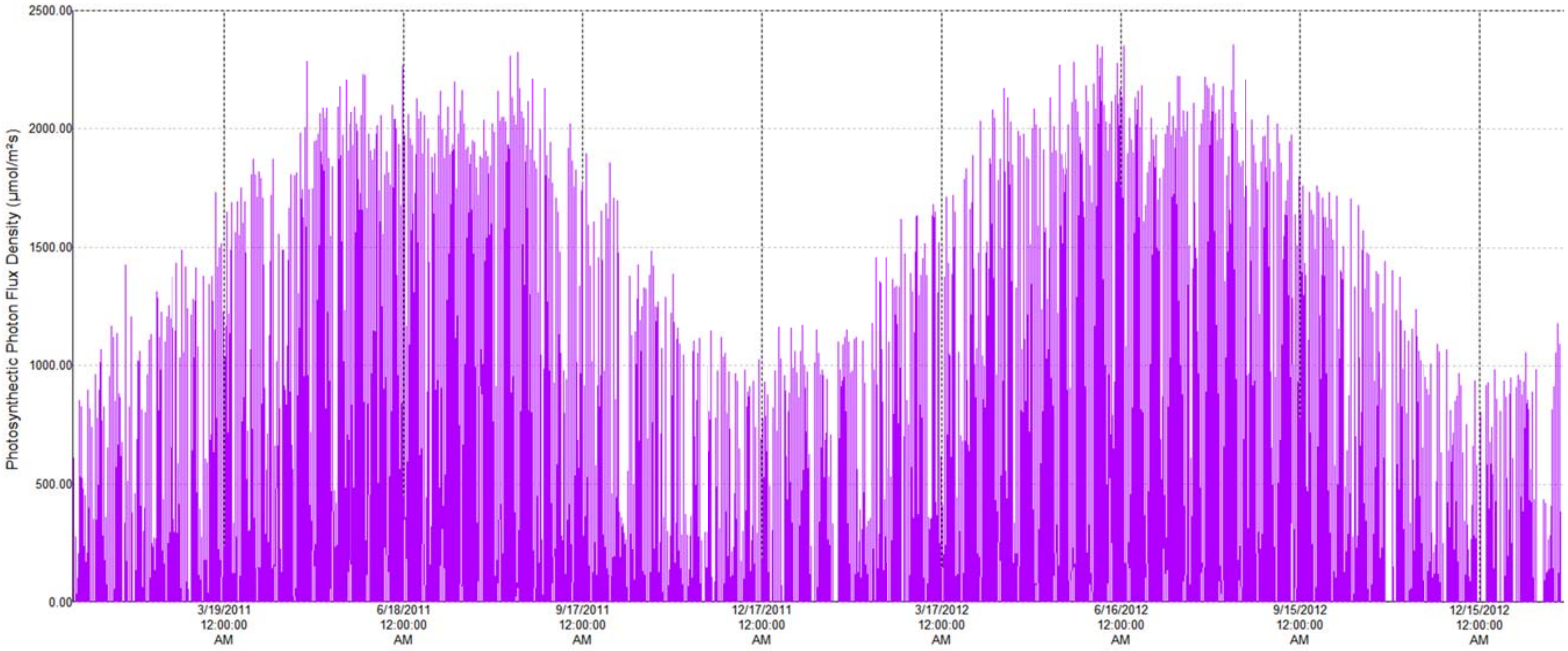


**Figure 0.2** Solar Radiation (W/m$^2$)

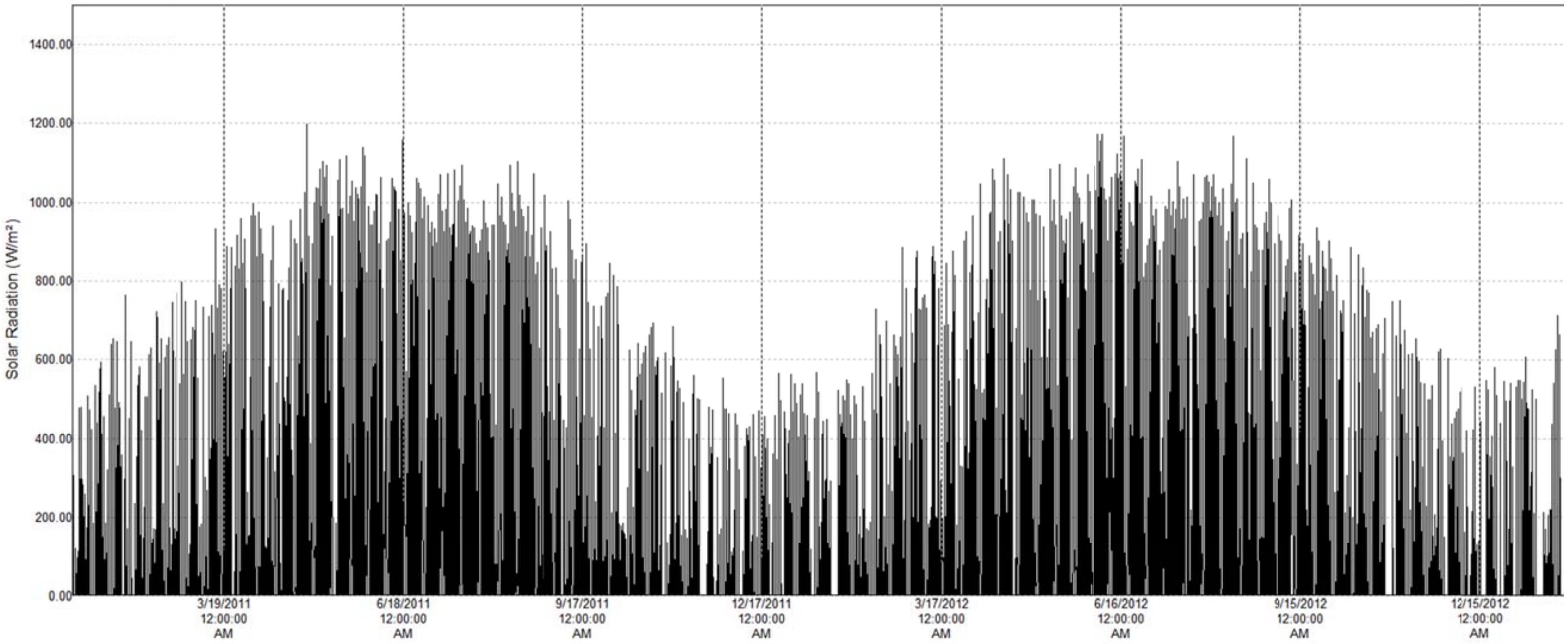


**Figure 0.3** Temperature °C

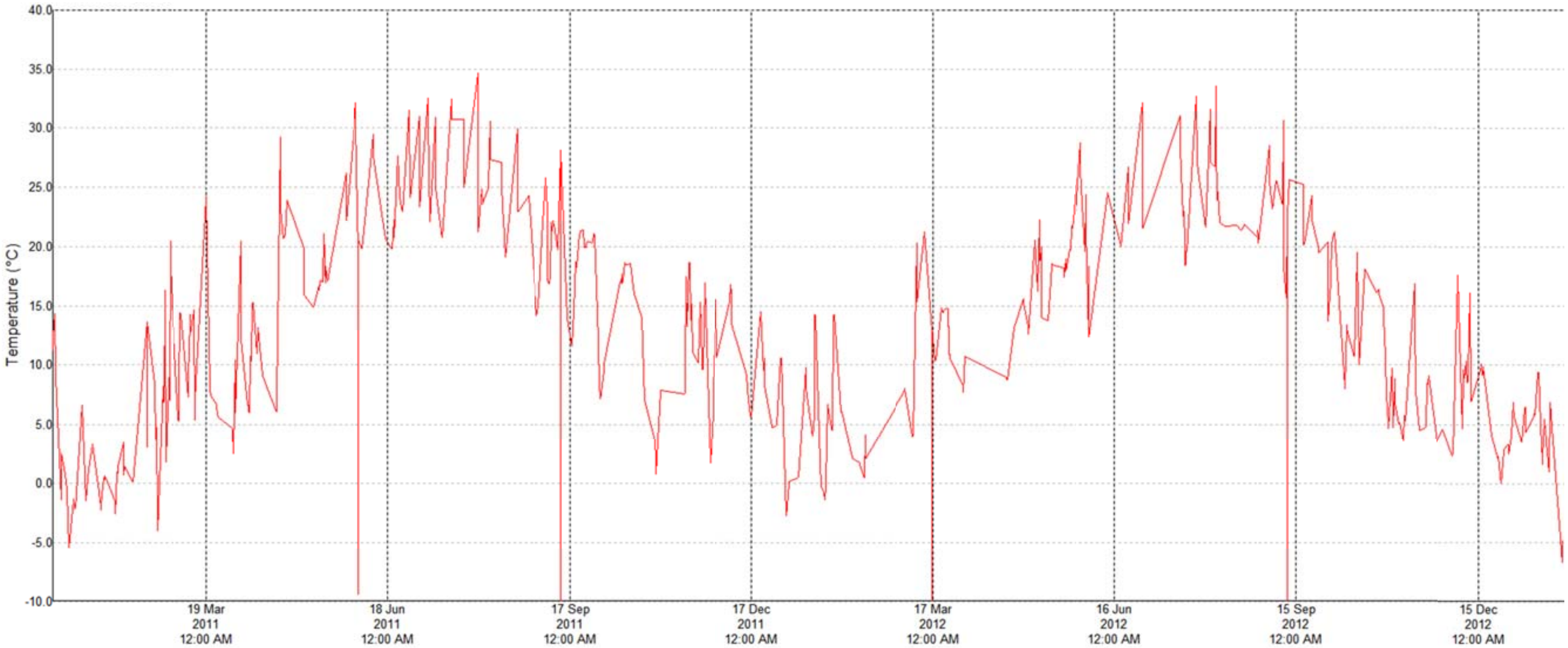


**Figure 0.4** Relative Humidity (%)

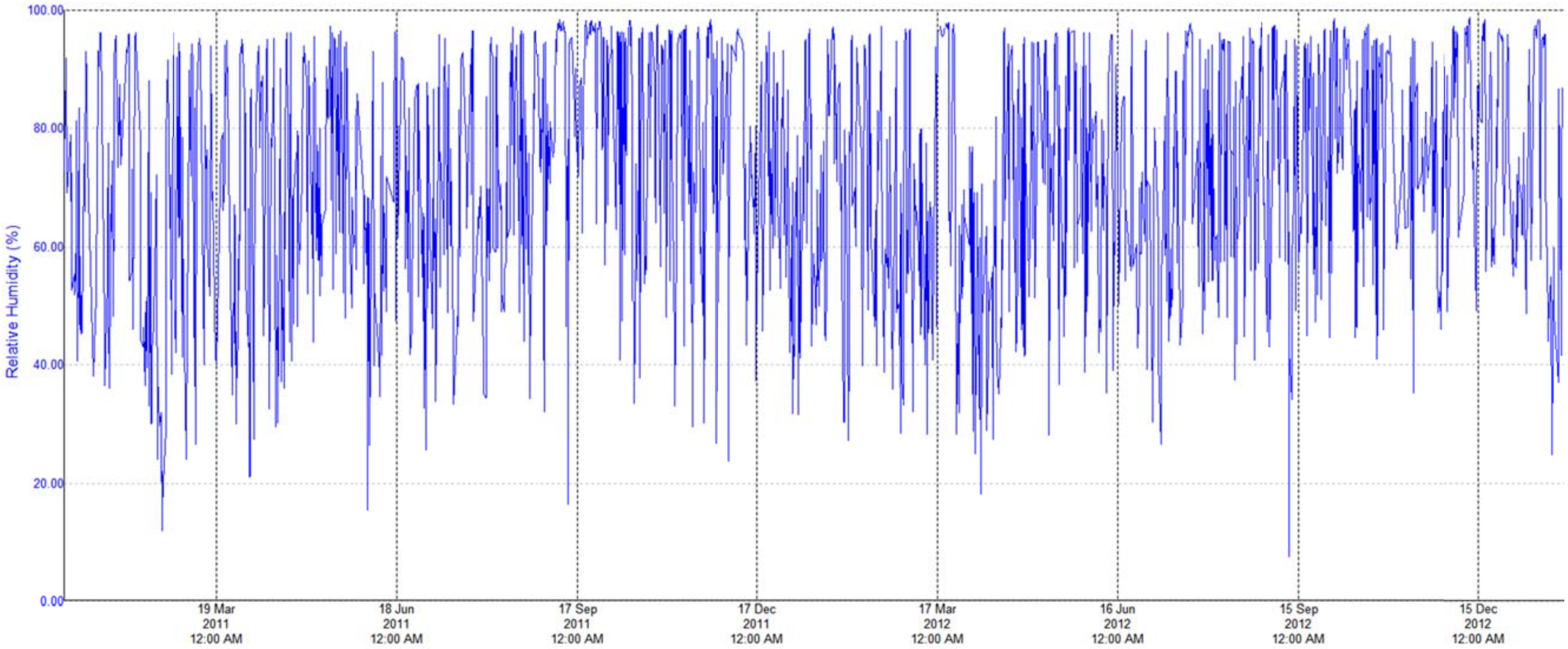


**Figure 0.5** Wind speed (m/s)

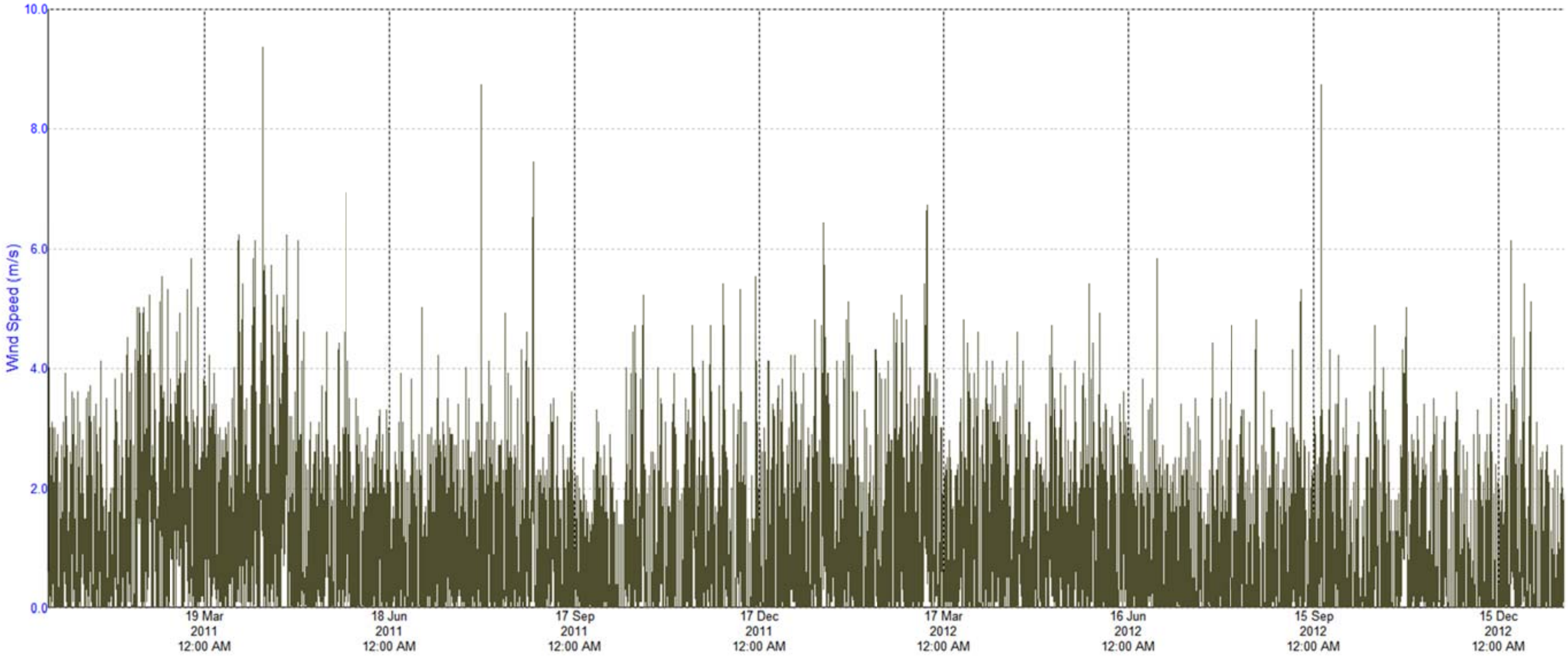


**Figure 0.6** Precipitation (mm)

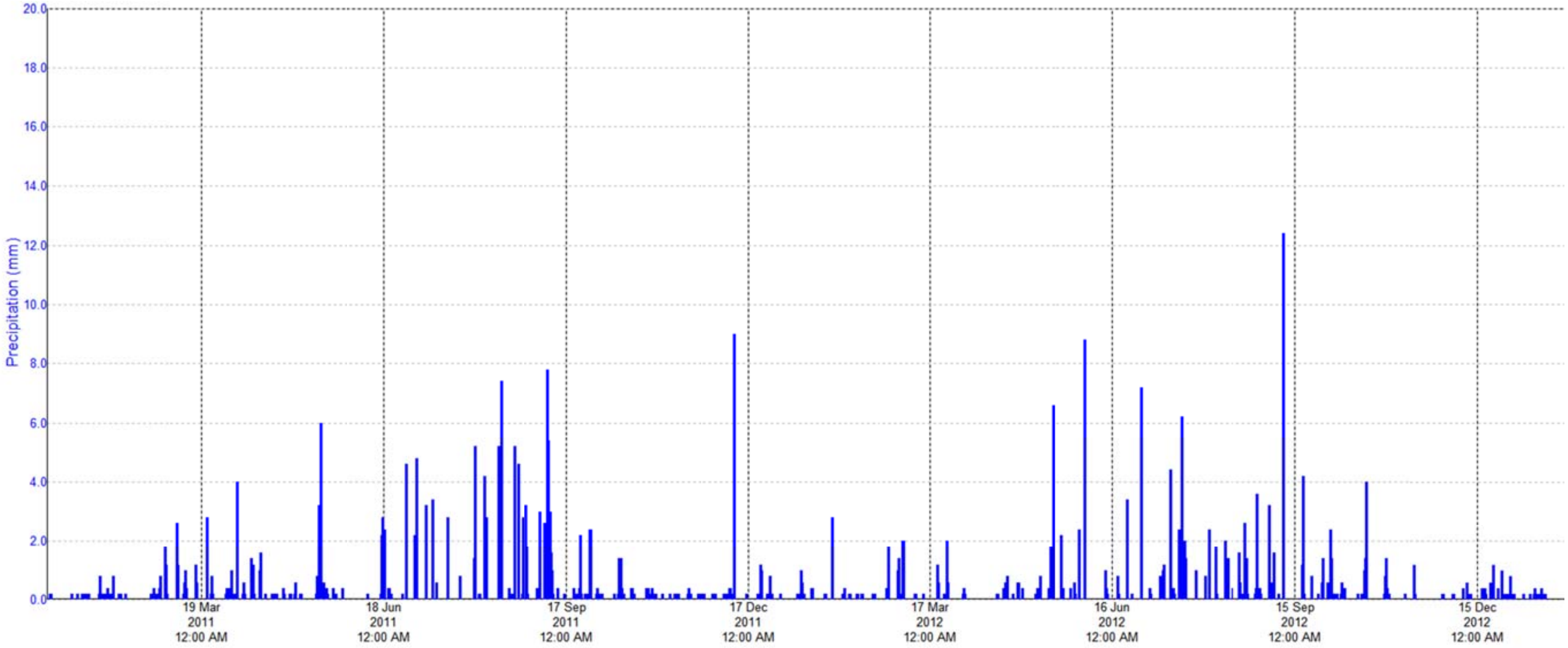
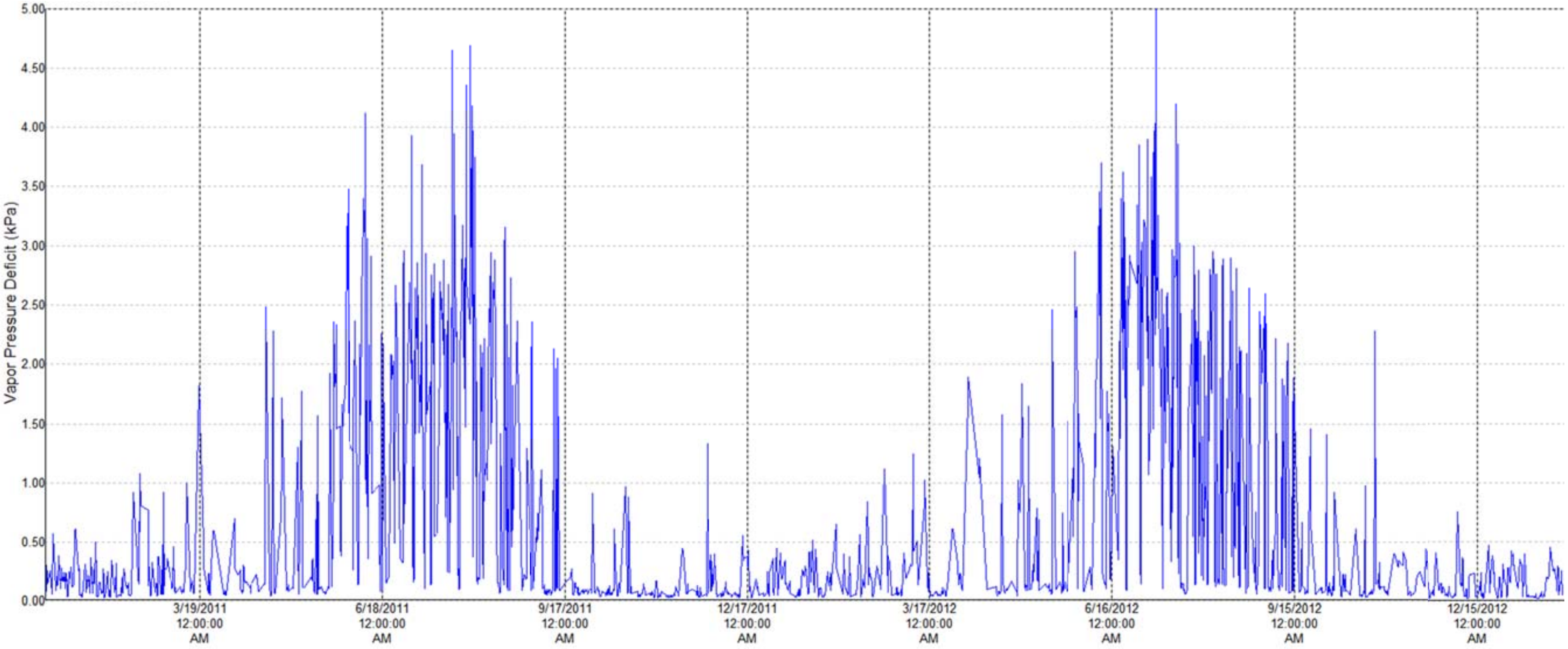
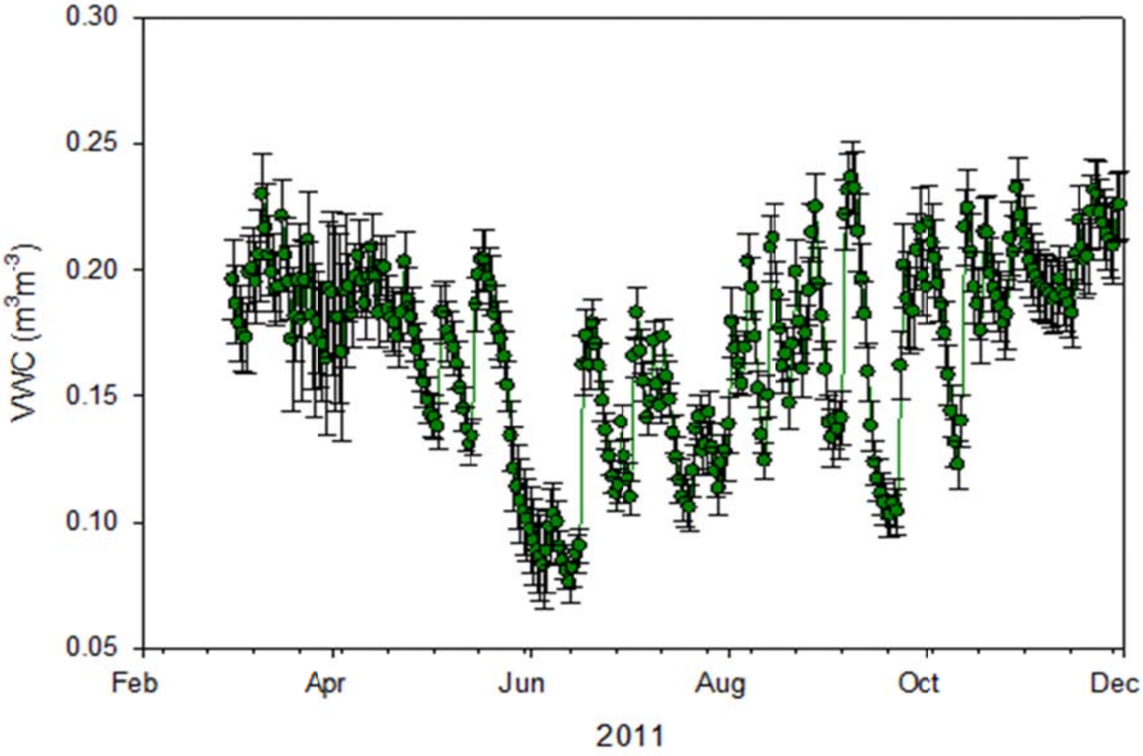


**Figure 0.7** Range in vapor pressure deficit (kPa)



## **Appendix E:** Example demonstrating the small range of sensor variability.

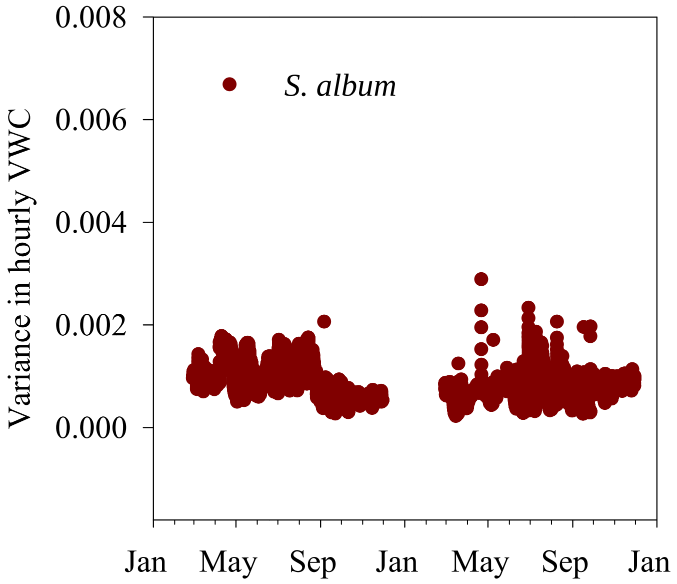
**Figure 0.1** Average of 16 volumetric water content (WVC) values from Echo-5TM sensors placed in four quadrants of four replicate *S. kamtschaticum* platforms during 2011.



## **Appendix F:** Example demonstrating the small range of sensor variability.

**Figure 0.1** Average hourly variance in volumetric water content (VWC) data measured over two years in experimental green roof platform substrate for *S. album* (a), *S. kamtschaticum* (b), *S. sexangulare* (c), and Unplanted treatments (d).

**a.**



**b.**

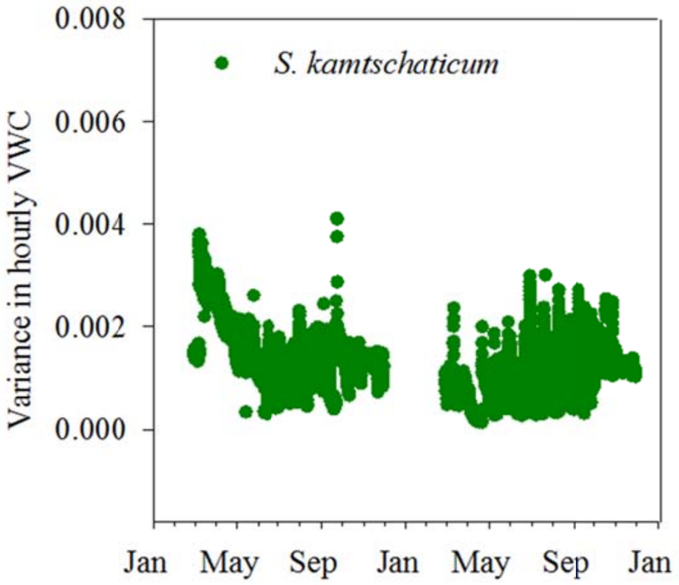
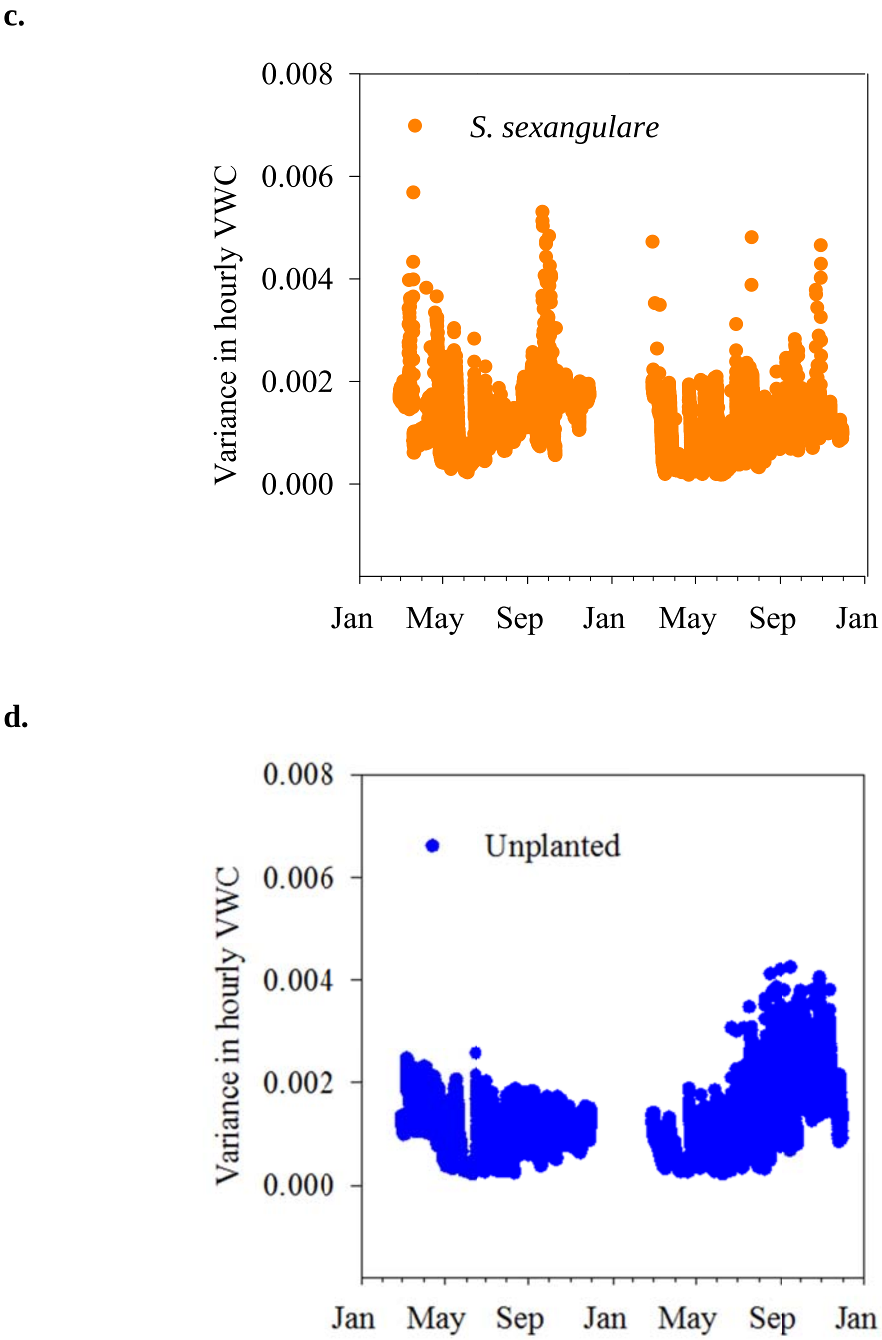


**Figure F.1** Average hourly variance in volumetric water content (VWC) data measured over two years in experimental green roof platform substrate for *S. sexangulare* (c), and Unplanted treatments (d).



# **Appendix G:** Photo demonstrating interception potential by *Sedum album*

**Figure 0.1** Picture of S. album on one of the planted platforms during 2012, illustrating the potential for rainfall interception, which was not measured.

## Glossary

**Daily carbon gain (DCG):** equals $CO_2$ fixed over a 24 hour period. Other studies may limit this calculation to the light period during the day; I define DCG as the net $CO_2$ exchanged over a 24 hour period.

**Evapotranspiration ($E_T$):** the movement of water vapor from the surface of the green roof substrate, either directly (by evaporation), or through plants (by transpiration)

**Growth chamber:** this is a controlled environment chamber in which abiotic parameters such as photoperiod, light level and temperature can be exactly controlled. In Chapter 2 we distinguish this term from "gas exchange chamber" which is a more specialized enclosure (see below)

**Gas exchange chamber:** equivalent to a large cuvette used to measure gas exchange in open environments. In Chapter 2 these were sealed acrylic boxes through which $CO_2$ and water vapor flow were quantified every 10 minutes.

**Leaf area index (LAI):** leaf surface area relative to the corresponding surface area of ground. In Chapter 3, we present LAI results in units of $cm^2$ / $cm^2$. Leaf area for non-flat leaves was divided by 2.

**Rain event:** We defined the start and stop times of rain events based on rain gauge data from the onsite weather station..

**Runoff:** runoff events were defined by the start and stop times of runoff rain gauge data, and considered consecutive unless more than 6 hours passed in between runoff events.

**Storage:** storage and retention (see definition below) are used interchangeably throughout the studies

**Stormwater:** is defined as precipitation that falls on non-soil surfaces and which does not infiltrate as would occur in an agricultural or ecological environment

**Stormwater retention:** the volume of water retained by a green roof, relative to the volume rain water per unit area. I assumed that any water that did not run off from the experimental platforms in this study was either retained or evapotranspired.

**Stormwater retention efficiency:** in this dissertation I use the term efficiency to quantify the amount of water retained; it could also refer to the effectiveness relative to some other variable such as green roof cost.

**Stormwater removal:** this term is used interchangeably with evapotranspiration

**Stormwater intensity:** this refers to the rate of precipitation falling on area over time. This was typically measured on a 1-minute basis, averaged and plotted every 5 minutes.

**Water holding capacity:** the amount of water held in the green roof substrate after it had drained. For soils, is typically defined as the volume of water held by a soil at a potential of -33J/kg. This is not relevant for green roof substrates due to their high porosity. In Chapter 3, water-holding capacity is defined as the substrate moisture content one hour after rainfall ended.

**Water use efficiency (WUE):** The amount of CO2 fixed relative to water used. In Chapter 2, WUE is calculated as the DCG / daily $E_T$. See above for definition of DCG and $E_T$.

**Wilting point:** For soils, wilting point is defined as the amount of water held at -1500J/kg. Since this approach is not applicable to green roofs because they drain so rapidly and because Sedum typically show few signs of wilting, we propose numbers for wilting point for two species in this dissertation based on physiological experiments in Chapter 2.

# Bibliography

Allen, R. G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration-Guidelines for computing crop water requirements. FAO, Rome.

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

Berghage, R., A. Jarrett, D.J. Beattie, K. Kelley, S. Husain, F. Rezaei, B. Long, A. Nagassi, R. Cameron, and W. Hunt. 2007. Green roofs and green roof media capacity for neutralizing acid rain. A report on the National Decentralized Water Resources Capacity Development Project.

Booth, D., and C.R. Jackson. 1997. Urbanization of Aquatic Systems-- Degradation Thresholds, Stormwater Detention, and the Limits of Mitigation. Journal of the American Water Resources Association 22:1-20.

Bousselot. 2011. Moisture content of extensive green roof substrate and growth response of 15 temperate plant species during drydown. HortScience 43:518-522.

Borland, A., and. H. Grifiiths. 1990. The regulation of CAM and respiratory recycling by water supply and light regime in the C3-CAM intermediate Sedum telephium. Functional Ecology 4:33-39.

Brown, R.A., D.E. Line, and W.F. Hunt. 2012. LID treatment train: pervious concrete with subsurface storage in series with bioretention and care with seasonal high water tables. J. Environ. Eng. 138:689-697.

Brulfert J., M. Kluge, S. Gluclu, and O. Queiroz. 1988. Interaction of photoperiod and drought as CAM inducing factors in Kalanchoe¨ blossfeldiana Poelln. cv. Tom Thumb. Journal of Plant Physiology 133:222-227.

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

Campbell, G.S., and J. M. Norman. 1998. An introduction to environmental biophysics. 2nd Edition. New York, N.Y.: Springer.

Carter, T., and A. Keeler. 2008. Life-cycle cost-benefit analysis of extensive vegetated roof systems. J Environ Manage 87:350-363.

Carter, T., and R.C. Rasmussen. 2006. Hydrologic behavior of vegetated greenroofs. Journal of the American Water Resources Association October:1261-1274.

Chen, J.M., and T.A. Black. 1992. Defining leaf area index for non-flat leaves. Plant, cell, and environment. 15: 421-429.

City of Riverside Planning Department 1994. Water Efficient Landscaping and Irrigation.

Ordinance Summary and Design Manual (2nd Edition).CleanWaterBaltimore. 2012. Stormwater remediation fee factsheet. http://www.cleanwaterbaltimore.org/flyers/Stormwater%20Remediation%20Fee%20fact%20sheet.pdf

Cobos, D., and C. Chambers. 2012. Calibrating ECH2O Soil Moisture Sensors. http://www.decagon.com/education/calibrating-ech2o-soil-moisture-sensors-13393-04-an/.

Cook-Patton, S. C., and T. L. Bauerle. 2012. Potential benefits of plant diversity on vegetated roofs: a literature review. J Environ Manage 106:85-92.

Dietz, M. 2007. Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. Water Air Soil Pollut.186:351-383.

DiGiovanni, K., F. Montalto, S. Gaffin, and C. Rosenzweig. 2013. Applicability of Classical Predictive Equations for the Estimation of Evapotranspiration from Urban Green Spaces: Green Roof Results. Journal of Hydrologic Engineering 18:99-107.

Dodd, A., A.M. Borland, R.P. Haslam, H. Griffiths and K. Maxwell. 2002. Crassalucean acid metabolism: plastic fantastic. Journal of Experimental Botany 53:569-580.

Dvorak, B., and Carroll, K. (2008). “Chicago City Hall Green Roof: Its Evolving Form and Care.” The Sixth Annual International Rooftops for sustainable Communities Conference, Cardinal Group, Toronto, Baltimore, MD, 10.

Dvorak, B. and A. Volder. 2010. Green roof vegetation for North American ecoregions: A literature review. Landscape and Urban Planning 96:197-213.

Dunne, T., and L.Leopold. 1978. Chapters 8-10. Water in Environmental Planning. W.H. Freeman and Company, San Fransisco, CA.

Dunnett, N., A. Nagase, and A. Hallam. 2008b. The dynamics of planted and colonising species on a green roof over six growing seasons 2001–2006: influence of substrate depth. Urban Ecosystems 11:373-384.

Dunnett, N., A. Nagase, R. Booth, and P. Grime. 2008a. Influence of vegetation composition on runoff in two simulated green roof experiments. Urban Ecosystems 11:385-398.

Durhman, A., D.B. Rowe, and C.L. Rugh. 2006. Effect of watering regimen on chlorophyll fluorescence and growth of selected green roof plant taxa. HortScience 41:1623-1628.

Feller, M. 2011. Quantifying evapotranspiration in green infrastructure: a green roof case study. MS Thesis. Villanova University, Villanova PA.

Felson A.J., and S.T.A. Pickett. 2005. Designed experiments: new approaches to studying urban ecosystems. Frontiers in Ecology and the Environment 3: 549-556.

FLL. 2008. Forschungsgesellschaft fuer Landschaftsentwicklung und Landschaftsbau. *Richtlinie für die Planung, Ausführung und Pflege von Dachbegrünungen*. Bonn, Eigenverlag.

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

Grant, J. W. Suitability of Canadian-bred and Native Plant Speciesfor Extensive Green Roofs in Northern Nova Scotia. MS Thesis. Dalhousie University Halifax, Nova Scotia

Gravatt, D., and C. Martin. 1992. Comparative ecophysiology of five species of Sedum (Crassulaceae) under well-watered and drought-stressed conditions. Oecologia 92:532-541.

Guswa, A. J., M. A. Celia, and I. Rodriguez-Iturbe. 2002. Models of soil moisture dynamics in ecohydrology: A comparative study. Water Resources Research 38:5-1-5-15.

Herrera, A. 2009. Crassulacean acid metabolism and fitness under water deficit stress: if not for carbon gain, what is facultative CAM good for? Ann Bot 103:645-653.

Hilten, R. 2002. An analysis of the energetics and stormwater mediation potential of greenroofs. MS Thesis. University of Georgia, Athens GA.

Hudson, B. 1994. Soil organic matter and available water capacity. Journal of Soil and Water Conservation 49:189-194.

Huntington, T. 2006. Available Water Capacity and Soil Organic Matter. Page 1959 Encyclopedia of soil science. CRC Press.

Kasmin, H., V.R. Stovin, and E.A. Hathaway. 2010. Towards a generic rainfall runoff model for greenroofs. Water Sci. and Technology. 62.4. 898-905.

Kim, K., S. W. Kang, C. H. Pak, and M. Kim. 2012. Changes in leaf variegation and coloration of English Ivy and Polka Dot Plant under various indoor light intensities. HortTechnology 22:49-55.

Kim, J., and M. W. VanIersel. 2011. Slowly developing drought stress increases photosynthetic acclimation of Catharanthus roseus. Physiol Plant 143:166-177.

Kim, T.J., and Y.S. Choo. 2007. Photosynthetic Patterns of 3 Crassulacean Plants under Drought Conditions. J. Ecol. Field Biology 30:187-193.

Kluge, M. 1977. Is *Sedum acre* L. a CAM plant? Oecologia 29:77-83.

Koehler, M. and P. Poll. 2010. Long-term performance of selected old Berlin greenroofs in comparison to younger extensive greenroofs in Berlin. Ecological Engineering. 36: 722-729

Koehler, M. and A.M. Clements. 2012. "Green Roofs, Ecological Functions." In Robert A. Meyers (ed.) Encyclopedia of Sustainability Science and Technology. Springer Verlag, Vol. 7, pp. 4730 -- 4754

Konrad, C., and D.B. Booth. 2002. Hydrologic Trends Associated with Urban Development for Selected Streams in the Puget Sound Basin, Western Washington USGS Water-Resources Investigations Report. United States Geological Survey. 40p.

Krupka, B. 1992. Dachbegrünung. Pflanzen- und Vegetationsanwendung an Bauwerken. Eugen Verlag.

Lazzarin, R.M., F. Castellotti, and F. Busato. 2005. Experimental measurements andnumerical modelling of a green roof. Energy and Buildings, 37: 1260-1267.

Lee, K., and J. Kim. 1994. Changes in CAM of Sedum plants with special reference to soil moisture conditions. Journal of Plant Biology 37:9-15.

Livingston, E.H., Miller, C., Lohr, M., 2004. Green roof design and implementationin Florida. In: Paper presented at the The Second Annual Greening Rooftops for Sustainable Communities Conference.

Lundholm, J. T., and A. Marlin. 2006. Habitat origins and microhabitat preferences of urban plant species. Urban Ecosystems 9:139-159.

Luttge, U. 2004. Ecophysiology of Crassulacean Acid Metabolism (CAM). Ann Bot 93:629-652.

MacIvor, J. S., M. A. Ranalli, and J. T. Lundholm. 2011. Performance of dryland and wetland plant species on extensive green roofs. Ann Bot **107**:671-679.

Martin, C., Higley, M., and W.Z. Wang. 1988. Ecophysiological Significance of $C0_2$-Recycling via Crassulacean Acid Metabolism in Talinum calycinum Engelm. (Portulacaceae). Plant Physiol. 86:562-568.

Maryland Department of the Environment (MDE) 2009. Stormwater design manual. http://www.mde.state.md.us/Programs/WaterPrograms/SedimentandStormwater/stormwater_design/index.asp

Mentens, J., D. Raes, and M. Hermy. 2003. Greenroofs as a part of urban water management. Pages 35-44 *in* C. Brebia, editor. Water Resources Management II. WIT Press, Southhampton, UK.

Mentens, J., D. Raes, and M. Hermy. 2006. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landscape and Urban Planning 77:217-226.

Mollering, H. 1974. *in* H. Bergmeyer, editor. Methods of enzymatic analysis. Verlag chemie, Weinheim, Academic Press, New York, NY.Pages 1589-1593.

Nobel, P. 1983. Nutrient levels in Cacti: Relation to nocturnal acid accumulation and growth. American Journal of Botany 70:1244-1253.

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R., Doshi, H., Dunnett, N., Gaffin, S., Koehler, M., Liu, K., and B. Rowe. 2007. Green Roofs as urban ecosystems: ecological structures, functins, and services. BioScience 57(10)823-832.

Osmund, B., W.W. Adams III, and S.D. Smith. 1989. Crassalucean Acid Metabolism Pages 255-279 *in* R. Pearcy, J.R. Ehleringer, H.A.Mooney, and P.W. Rundel, eds. Plant physiological ecology field methods and instrumentation. Chapman Hall, New York, NY.

Palla, A., I. Gnecco, and L. G. Lanza. 2010. Hydrologic Restoration in the Urban Environment Using Green Roofs. Water 2:140-154.

Paul, M., and J.L. Meyer. 2001. Stream in the urban landscape. Annual Review of Ecology, Evolution, and Systematics 32:333-365.

Pickett, S.T.A., and M.L. Cadenasso. 2008. Linking ecological and built components of urban mosaics: an open cycle of ecological design. Journal of Ecology 96: 8-12.

Pilon-Smits, E., H. Hart, and J.V. Brederode. 1991. Seasonal variation in phosphoenolpyruvate carboxylase specific activity in fifteen species exhibiting facultative or obligate crassulacean acid metabolism. J. Plant Physiology 138:581-586.

Pitt, R. 1999. Small storm hydrology and why it is important for the design of stormwater control practices in. Advances in Modeling the Management of Stormwater Impacts, Volume 7. (Edited by W. James). Computational Hydraulics International, Guelph, Ontario and Lewis Publishers/CRC Press. 1999.

Prowell, E. 2006. An analysis of stormwater retention and detention of modular green roof blocks. MS Thesis. The University of Georgia, Athens, Ga.

Rezaei, F., and A.R. Jarrett. 2005. Measure and predict evapotranspiration rate from green roof plant species. *in* Penn State College of Engineering Research Symposium, University Park, Pennsylvania.

Rowe, B., Getter, K.L., and A.K. Durhman 2012. Effect of green roof media depth on Crassulacean plant succession over seven years. Landscape and Urban Planning 104:310-319.

Roy, A., A.D Rosemond, M.J. Paul, D.S. Leigh, and J.B. Wallace. 2003. Stream macroinvertebrate response to catchment urbanization. Freshwater biology 48:329-346.

Ryerson University. 2005. Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto.

Saxton, A. 1998. A macro for converting mean separation output to letter groupings in Proc Mixed. . Pages 1243-1246 In Proc. 23rd SAS Users Group Intl. SAS Institute, Cary, NC.

Sayed, O. 2001. Crassulacean acid metabolism 1975-2000, a checklist. Photosynthetica 39:339-352.

Sayed, O., M.J. Earnshaw, and M. Cooper. 1994. Growth, water relations, and CAM induction in Sedum album in response to water stress. Biologia Plantarum 36:383-388.

Schneider, D. 2011. Quantifying evapotranspiration from a green roof analytically. MS Thesis. Villanova University, Villanova PA.

Schroll, E., J. Lambrinos, T. Righetti, and D. Sandrock. 2011. The role of vegetation in regulating stormwater runoff from green roofs in a winter rainfall climate. Ecological Engineering 37:595-600.

Schuber, M. and M. Kluge. 1981. In Situ Studies on Crassulacean Acid Metabolism in *Sedum acre* L. and *Sedum mite* Gil. Oecologia 50(1):82-87.

She, N., and M. Pang. 2010. Physically based greenroof model. Journal of hydrologic engineering. 15(6):458-464.

Sherrard, J. A. and J. M. Jacobs. 2012. Vegetated Roof Water-Balance Model: Experimental and Model Results. Journal of Hydrologic Engineering 17:858-868.

Smith, J.A.C, and K. Winter. 1996. Taxonomic distribution of crassulacean acid metabolism. Pages 427-436 in Crassulacean Acid Metabolism: Biochemistry, Ecophysiology and Evolution. Springer Verlag, Berlin.

Snodgrass, E., and L.L. Snodgrass. 2006. Green roof plants. Timber Press Inc.

Stephenson, R. 1994. Sedum cultivated stonecrops. Timber Press Inc.

Stovin, V., G. Vesuviano, and H. Kasmin. 2012. The hydrological performance of a green roof test bed under UK climatic conditions. Journal of Hydrology 414-415:148-161.

Susca, T., S. R. Gaffin, and G. R. Dell'osso. 2011. Positive effects of vegetation: urban heat island and green roofs. Environ Pollut 159:2119-2126.

Thornthwaite, C. W., and Mather, J. R. 1955. The Water Balance. Publications in Climatology, Drexel Institute of Technology, NJ.

VanIersel, M., and B Bugbee. 2000. A multiple chamber, semicontinuous, crop carbon dioxide exchange system: design, calibration, and data interpretation. Journal of the American Society for Horticultural Science 125:86-92.

VanWoert, N. D., D. B. Rowe, J. A. Andresen, C. L. Rugh, R. T. Fernandez, and L. Xiao. 2005. Green roof stormwater retention: effects of roof surface, slope, and media depth. J Environ Qual 34:1036-1044.

Voyde, E. 2011. Quantifying the complete hydrologic budget for an extensive living roof. Dissertation. The University of Auckland, Auckland, New Zealnd.

Voyde, E., Fassman, E, Simcock, R, and Wells, J. 2010. Quantifying Evapotranspiration rates for New Zealand green roofs. Journal of Hydrologic Engineering 15:395-403.

Walsh, C., Roy, A.H., J. W. Feminella, P. D. Cottingham, P.M. Groffman, R.P. Morgan, II. 2005. The urban stream syndrome: current knowledge and the search for a cure. J. N. Am. Benthol. soc. 24:706-723.

Winter, K. and J. A. Holtum. 2005. The effects of salinity, crassulacean acid metabolism and plant age on the carbon isotope composition of Mesembryanthemum crystallinum L., a halophytic C(3)-CAM species. Planta 222:201-209.

Wolf, D., and J.T. Lundhom. 2008. Water uptake in green roof microcosms: effects of plant species and water availability. Ecological Engineering 33:179-186.

Wolf, J. 1960. Der diurnale Säurerhythmus. Pages 809-889 *in* R. W, editor. Encyclopedia of plant physiology. Spring Verlag, Berlin, Heidelberg.