ABSTRACT

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The evaluation of plant species for use in green roof systems is an important step in providing recommendations to the industry. In this study we investigated the ability of five species to grow and survive on a green roof in the Mid-Atlantic, and how they contributed to the performance of a green roof system. One species, *Tradescantia ohiensis* was found to retain more storm water than other species and an unplanted control. Three of the plants evaluated were found to reduce substrate temperatures when compared to unplanted controls during the summer months. One species, *Chielanthes lanosa,* was unable to survive the summer. While another, *Asclepias verticillata,* lost biomass over the study. Indicating both are unsuitable for use on green roofs in the Mid-Atlantic. The other species: *Sedum album*, *Sedum kamtschaticum* and *Tradescantia ohiensis* all survived and exhibited a positive growth rate.

EVALUATION OF FIVE PLANT SPECIES FOR SURVIVAL, GROWTH AND CONTRIBUTION TO GREEN ROOF FUNCTION

By

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Chapter 1: Introduction

1.1 Background and Literature Review

Green roofs are engineered systems designed primarily to capture storm water and reduce temperature extremes experienced by roofs of buildings (Obendorfer et al., 2007), enhancing the environmental and aesthetic benefits of these impervious surfaces. They are composed of a series of layers set on top of a waterproof membrane. These layers can take a variety of forms however they can be narrowed down to four basic categories: a drainage layer, a root barrier, a mineral-based substrate and plant material. Green roofs fall into two classes based on the depth of the substrate layer. Extensive green roofs are those with a substrate depth generally less than 15 cm. Green roof systems with a depth greater than this threshold are generally considered intensive green roofs. Extensive green roofs are more common due to lower installation and maintenance costs (Peck et al., 1999).

The environmental conditions that plants must endure to survive on an extensive green roof can be vastly different than that of the prevailing regional environment in which the green roof is present. Modern extensive green roofs are, in general, xeric environments, meaning they experience very low levels of plant available water (Obendorfer et al., 2007) often for lengthy periods of time between rain events. This is in part due to the light-weight substrates used to construct green roofs. These are engineered media that generally have high porosity and lower bulk density when compared with natural soils. In general they also are low in organic material. These substrate properties, combined with the shallow substrate depth of extensive green roof systems, limits the amount of plant-available moisture at any one time; this, in turn, also affects the water retention capacity of the green roof. These factors combine to make drought conditions common on green roofs; thus, plants must be able to tolerate very low water availbility in order to be considered viable candidates for use in these systems. The morphological and physiological characteristics of species vary considerably within the plant kingdom. There are numerous factors and interactions between environmental variables and physiological traits that influence the growth for any given species. Two of the greatest limiting factors on plant growth are typically water availability and seasonal temperatures.

1.1.1. Temperature

Temperatures experienced on green roofs are generally very high during summer months (Obendorfer et al., 2007) but interestingly, very few substrate / root temperature data are available for green roofs in the mid-Atlantic or from other regions of the US. Plants selected for use on green roofs should therefore be capable of surviving extended drought periods and actively growing during periods where water is available..

There have been a number of studies that have investigated the contribution of plants to the storm water and insulation functions of green roofs (McIvor and Lundholm 2011, Gaffin et al. 2010, Lundholm et al. 2010, Monterusso et al. 2005). The ability of green roofs to insulate buildings from solar heating is one possible benefit that has been investigated in the literature. Green roofs do reduce summer roof temperatures over conventional black tar roofs (Gaffin et al. 2010), but the effect of specific plant species on green roof temperature has been less thoroughly investigated. McIvor and Lundholm (2011) measured surface and within substrate temperatures at five times during the course of their study, concluding that increased plant cover tended to lower roof temperatures. However their data was not replicated over time or across a broad range of environmental conditions. Monterusso et al. (2005) measured substrate temperature during a single day, and found no differences in substrate temperature based on species planted in their experimental units. Lundholm et al. (2010) found that unplanted controls had higher temperatures than most planted treatments, and that unplanted controls also had greater water loss rates when measured as total water loss 24 hours after a controlled irrigation event and with gravimetric water loss accounted for. They also went on to state that the interaction between evapotranspiration, temperature and water relations is still unclear and needs to be further investigated.

McIvor et al (2011) and Luldholm et al (2010) found that increasing canopy cover correlated with lower substrate temperatures on the surface of green roof modules. While these results provide some preliminary temperature data, it is unclear if different plant species provide consistent temperature reductions on green roofs across daily or seasonal time intervals. Nardini et al. (2012) collected continuous data from using thermocouples and found no significant effect of vegetation type on temperature of an intensive green roof system in a Mediterranean climate. They also found that the thermal properties of the roof were significantly affected by the substrate water content. Temperatures were measured at the base of the custom built experimental modular system beneath the substrate just above the waterproofing membrane. This masks the effects that species may have on substrate temperatures within the root zone, which is also where the influence of temperature on plant physiological processes and survival is greatest. Additionally, there was no replication of experimental units in this study, which should be taken into account when interpreting their results. Thus, it appears that the effect of plant species on green roof substrate temperature has not been thoroughly investigated in the literature. A species effect on substrate temperatures is likely to not only have effects on long-term green roof performance, but could be a factor in plant survival and health, especially during the critical establishment phase.

It is well documented that low soil temperatures inhibit root growth, depending on species (Lahti et al 2004). Substrate temperature affects a variety of root processes such as root initiation, direction of growth and turnover (Kasper and Bland, 1992). The use of USDA cold hardiness zones throughout the horticulture field indicates the importance of low winter temperatures in horticultural plant selection and survival.

Both low and high temperatures affect root growth and development. Root turnover and production rates were found to be highest when soil temperatures and moisture levels were high in semi-arid conditions (Kitajima et al. 2010). High soil temperatures correlated with greater transpiration rates and stomatal conductance rates both during the day and at night in *Vitis* (C3 species), independent of air temperature and vapor pressure deficit (Rogiers and Clarke, 2012). This indicates that water use may increase in at least C3 species, as temperature increases, This becomes significant for plant health particularly where high night-time soil temperatures occur. Plants experiencing high soil temperatures at night use up carbohydrate reserves faster due to higher respiration rates. For this reason high night-time temperatures have been attributed to a decline in the in some agricultural crops (Brenchley and Singh, 2008, Robison and Massengale, 1969).

Plants have the ability to modify their immediate surroundings over time, by increasing the amount of organic matter in soils as they grow, cooling air temperatures through evapotranspiration and shading the soil surface below their canopies.

Shading by plant canopies has a powerful effect on environment. A study on shade trees in Taiwan found that species intercepted different amounts of solar radiation and that foliage density had the greatest effect on cooling soil surface temperatures (Lin and Lin, 2010). Increasing canopy cover in urban areas on a macro-scale results in lower air temperatures (Ellis, 2009). At smaller scales, epiphytes were found to lower microsite temperatures in the canopy of tropical forests. (Stuntz et al. 2002).

Plant canopies not only affect the immediate environment by intercepting solar radiation; they also affect the substrate and root zone profile through evapotranspiration. The effect of evapotranspiration on soil temperature is multifold. Evapotranspiration lowers the ambient air temperature (Osman 2012) removes water from the soil and increases relative humidity. Continuous temperature data collected by substrate moisture and temperature probes may to reveal some of the complex interactions between plant species, substrate temperature and water content. The relationship is likely a complex one with numerous interactions between physiological and morphological traits of the plant species and the physical and chemical properties of the substrate.

As a plant removes water from the soil in which it is growing, it changes a number of soil properties: thermal conductivity and potential heat storage capacity. Decreasing soil moisture also decreases the potential heat storage capacity and at the same time has a logarithmic relationship with thermal conductivity (Oke, 1987). Water requires greater energy to increase its temperature than other soil components; thus wet soils tend to heat up more slowly than dry soils (Osman 2012).   Thus, given the same amount of daily solar radiation, a drier soil will tend to be hotter than a wetter soil or substrate. When a plant is actively removing water from the soil, it theoretically should increase the rate at which a soil can retain heat.

Plants also increase the amount of organic matter in green roof substrates over time (Getter et al. 2009). Organic matter is a poor conductor of heat (Osman 2012), so it seems logical that as a roof ages and accumulates organic matter content, it should become a better insulator. Increasing substrate organic matter content correlated with greater soil moisture contents and greater rainfall retention amounts (Speak et al. 2013). Thus as organic matter content increases it directly affects the insulating capacity of the substrate and also indirectly effects it by altering the water holding capacity (Bouyoucos 1939). As discussed previously wetter substrates require more energy to heat, increasing the ability to retain water may mean the substrate is in general cooler. Green roof studies have not focused on the effect of increased substrate organic matter on temperatures experienced on them. The argument outlined above is largely conjecture and needs to be investigated in a targeted study.

1.1.2. Substrate Water Content and Retention

One of the reasons for the installation of green roofs in urban areas is to mitigate the effects of storm water runoff from impervious surfaces. Variable rates of storm water retention by green roof systems have been reported in the literature. A review paper by Obendorfer et al. (2007) found that studies reported variable storm water retention rates by green roofs, between 25% of rainfall and 100% depending on storm size and system design. Retention rates of 100% were reported for small storms in substrates greater than 10 cm in depth. Kohler et al. (2002) reported that installing a green roof can reduce rainfall runoff between 60% and 79% on a yearly basis.

Several studies have shown that plants increase water retention rates by green roofs as discussed by Oberndorfer et al. (2007). However there is still controversy, as other studies show small or no differences in water capture between planted treatments and unplanted treatments (Lundholm et al., 2010, Carter and Butler, 2008, VanWoret et al., 2005). Despite these discrepancies recent work has focused on how measurable performance variables may differ between roofs planted with different species (Starry 2013, Maclvor et al.2011, Lundholm et al., 2010, Wolf and Lundholm , 2008, Dunnett et al. 2008, Prowell 2006, VanWoert et al., 2005).

Plants may affect green roof water holding capacity, both through physical modification of the roof substrate (Berghage et al. 2007) and through evapotranspiration. Plants modify the environment in which they grow; the degree to which they do so depends in part to the amount of root and leaf tissue that is present and accumulated over time. Previous green roof studies have used a variety of methods to quantify plant size, growth and other characteristics.

Dunnett et al. (2008) found that increasing root biomass had a negative relationship with storm water runoff. This result came from an experiment comparing experimental green roof modules with sixteen different treatments. Green roof modules were grown for a single growing season and only controlled volumes of simulated rainfall were applied over the course of the study. The analysis did not remove the effect of treatment before the regression was preformed. Mean root biomasses for each species were plotted against mean runoff for the same treatment and then the regression was plotted using these treatment specific values. While the effect of biomass was found to be significant it is not clear from this study what the effect of biomass was on retention since any qualitative effect of species was not accounted for. The species used Dunnett et al. (2008) were a mixture of traditional green roof species and natives from the study region.

Lundholm et al. (2010) applied controlled volumes of water for comparison of storm water capture for 35 different treatments, a combination of different plant species and combinations of species. No treatments in this study were found to capture more storm water than the unplanted control, though some were found to capture significantly less. The water capture data generated in this study was based on a single simulated 5mm rainfall event during the study period. It is difficult to produce any general conclusions about species performance from the results of this study since there was no replication of simulated rainfall events and no variability in simulated rainfall amount or intensity.

Starry (2013) compared three *Sedum* species in experimental green roof platforms for their contribution to green roof water retention. Runoff from each experimental unit was measured over the course of the two-year study. Significant differences in runoff were found between treatments in the second year for storms less than 12.5 mm and between 12.5 mm and 62.5 mm. Two Sedum species, *S. album* and *S. kamtschatium* were found to reduce storm water runoff when compared to unplanted modules and a third *Sedum* species, *S. sexangulare*. There was a significant reduction in runoff from treatments from the first year to the second. This effect was attributed to increased levels of biomass as the plants grew and established over the course of the study. Reliable continuous monitoring sensor systems were used to acquire the data in Starry (2013).

These methods have the benefit of providing accurate replicated data under real environmental conditions. Real runoff was measured during natural rainfalls with variable volumes and intensities. This makes the data from this study more applicable to commercial green roof systems.

Despite the fact that this recent study by Starry (2013) showed that differences in stormwater runoff exist between species and unplanted modules, it is unclear if similar differences exist between species not in the genus *Sedum* when real time data is acquired during natural rainfalls and environmental conditions.

1.1.3. Plant Species

Quantifying the establishment, survival and growth under realistic edaphic and environmental conditions is important to determine the suitability of a plant species for use in green roofs for various regions in the US (Monterusso et al., 2005).

It has been established that many *Sedum* species survive well on green roofs throughout many regions of North America (Butler and Orians 2011, Duhrman et al. 2006, Monterusso et al., 2005). Additionally, some native species from diverse genera have also been found to survive (, Maclvor et al.2011, Lundholm et al., 2010, Wolf and Lundholm, 2008, Monterusso et al., 2005). *Sedum* species are, in general, highly drought-tolerant succulents, many of which are capable of Crassulacean Acid Metabolism (CAM). This physiological adaptation limits evapotranspiration during the day (Ranson and Thomas, 1960), and enhances the capability of these species to withstand drought periods which are not uncommon on green roofs. This photosynthetic pathway that many *Sedum* species have are not absolutely necessary for survival on green roofs; however, species selected for this study exhibited a variety of drought tolerance adaptations, for several reasons. Two species that are commonly planted on green roofs in the Mid-Atlantic region were selected, i.e., *Sedum album* (L.) and *Sedum kamtschaticum* (Fisher). These are both well-investigated in the literature and some data is available about their contribution to green roof systems and physiological responses to low water availability (Starry, 2013). Two other species were selected that have been found capable of surviving on green roofs in other studies (Butler and Orians 2011, Monterusso et al., 2005). These two species, *Asclepias verticillata* (L) and *Tradescantia ohiensis* (L) have radically different morphologies, both from each other and from *Sedum*, The final species in this study was *Chielanthes lanosa* (Michx), which was selected because it also differs greatly in morphology and response to drought from all others in the study; also it has not been previously researched for suitability as a green roof species.

T. ohiensis is a monocot in the family Commelinaceae. It is iteroparous, reproducing many times during its life cycle. Both vegetative and sexual propagation occur in this species. Clonal propagation can take two forms, simple division of bulbs in the basal rosette or occasional formation of adventitious bulbs in the axils of the flowering stems after flowering. Leaves arise from the basal stem within the bulb and are v-shaped, convex side upwards. This leaf shape may serve to funnel rainfall directly to the basal rosette; this morphologic feature is shared by many monocots. Leaves can also increase or decrease their convexity based on the water content of their tissue.

T. ohiensis is a species of open sunny ecosystems, appearing quite widespread and adaptable. It is native from Texas to Florida and north to Maine and portions of Ontario. It is known to occur on granite outcrops in the southeastern US (Shure, 1999), dry oak savannas near the Great Lakes and in deep soil savannas and barrens of the Midwestern US (Anderson and Bowles, 1999). All these environments are classified as xeric, which would require adaptation by a native plant species to drought. *T. ohiensis* is known to hybridize with nine other closely related species in the wild (Faden 2006) indicating the genotypic plasticity of the genus.

Asclepias verticillata L is a dicot in the family Apocynaceae. It is native from Arizona to Florida and north to Vermont and west to Saskatchewan. It is known to occur in dry environments such as serpentine barrens (Tyndall and Hull 1999), deep soil savannas and barrens of the Midwestern US (Anderson and Bowles, 1999), cedar glades of the southeastern US (Baskin and Baskin 1999) and in the alvars of the Great Lakes region (Catling and Brownell, 1999).

Cheilanthes lanosa Michx is a pteridophyte in the family Pteridaceae. It is native from Texas to Florida, north to New York and west to Illinois, with populations also in Minnesota and Wisconsin. It is known to occur on shale and limestone outcrops (Brown and Brown, 1984). It exhibits a drought tolerance strategy common to many resurrection type ferns. When water is scarce its foliage desiccates and curls, appearing to senesce. When water does become available, it then rehydrates leaf tissue and returns to normal function (Cobb 1984, Lellinger 1985)

There is no published literature identifying precisely which photosynthetic pathway that the three species discussed above utilize, be it C3, C4 or CAM (Crassulacean Acid Metabolism), though it is likely that they are C3 plants. The designation of photosynthetic pathway actually refers to the chemical mechanism by which carbon dioxide is fixed from the atmosphere into a usable form by plants (Waller and Lewis 1979). The photosynthetic pathway that a species utilizes is a species level adaptation (Waller and Lewis 1979). In general, C4 and CAM are considered to be metabolic adaptations to low water availability in terrestrial plant species and low CO_2 availability in aquatic plant species. Terrestrial CAM species open their stomates for gas exchange at night in order to reduce water loss. They then store CO_2 using malic acid for use by the photosynthetic process during the day (Ranson and Thomas, 1960). C3 and C4 plants keep their stomates open during the day and at night. Night-time transpiration rates are generally low in C3 and C4 plants, between 10-15% of daytime values (Snyder et al. 2003). Daytime transpiration serves several functions, one of which is to reduce leaf temperatures, such that temperatures suitable for photosynthesis are maintained. This prevents temperature related slowing of the photosynthetic process (photoinhibition).

Two of the species evaluated in this study use the CAM photosynthetic pathway, *Sedum kamschaticum* and *Sedum album* (Starry 2013). *Sedum kamtschaticum* (Fisher) is a dicotyledonous species within the family Crassulaceae. It is native to eastern Asia from Siberia to the Kamchatka peninsula, northern Japan, and Korea south through eastern China (Clausen, 1975). *S. kamtschaticum* has been shown to be capable of CAM metabolism but typically only after a significant drought period (Starry 2013). Propagation is mainly from seed, however vegetative propagation is possible. It can produce large thickened roots as the crown matures.

Sedum album (L.) is native to Europe, Asia and northern Africa. *Sedum album* appears to be an obligate CAM species (Starry, 2013), growing more slowly than *S. kamtschaticum* at similar soil moisture levels (Starry, 2013). *S. album* has small ellipsoid leaves that when separated from the rest of the plant, form potential propagules. In addition to this very effective form of vegetative propagation, self-sown seed is also likely to be pronounced under green roof conditions. The ease of self-propagation makes *S. album,* and other similar species, able to colonize a favorable habitat relatively rapidly. It is a staple on green roofs and is extremely tolerant of drought conditions (Snodgrass and Snodgrass 2006).

Measuring plant survival and growth are important components of a species evaluation. Many studies have only used non-destructive means to estimate above ground biomass and growth (MacIvor et al., 2011, MacIvor and Lundholm 2010, Monterusso et al., 2005). Other studies incorporated destructive harvest techniques, but only for partial plant samples. Wolf and Lundholm (2008) for example used above ground biomass as a covariate in their analysis, but did not attempt to measure below ground root tissue. Dunnett et al. (2008) conducted a final whole plant destructive harvest at the conclusion of a controlled indoor experiment to relate plant characteristics to storm water retention. Increasing dry root mass showed a negative correlation with water runoff in their study. In a study aimed at quantifying carbon sequestration on green roofs, Getter et al. (2009) harvested plants seven times during the growing season, but did not attempt to determine if there was a correlation between biomass and green roof function. Standardized methods for relating species contributions to green roof performance have not been established. The studies cited have highly variable methods and experimental designs.

Two measurable values from green roofs after a rainfall event are runoff, defined as water lost from the experimental unit, and storm water captured/ retained in the experimental unit. The measure of either can allow for an approximate calculation of the other, as long as the total amount of storm water applied is known. A variety of techniques have been used to measure both depending on the study (Dvorak and Volder, 2010). The robustness of various methods have not been investigated, and it is difficult to draw comparisons between studies without this information.

Long-term data collection techniques using automated sensors and dataloggers may provide clear results on the small scale effect of species on temperature and interactions of green roofs with storm water. Starry (2013) is the first study of its kind to report replicated precision soil-moisture and runoff data, in addition to other long-term environmental monitoring data, to investigate differences between plant species. Volumetric water content was found to differ between species on a seasonal basis, but this research did not report any substrate temperature data.

The degree of the effect that plant species can have on green roof functions has not been fully investigated. There is no established methodology for evaluating the performance of various plant species, and it is unclear if there is value in examining new candidates not only for their ability to survive under green roof conditions, but also for the degree to which they may contribute to the performance of the system.

1.2 Objectives and Hypotheses:

The purpose of this research study was to develop an experimental design that would improve the ability to detect differences in species-specific performance, while also determining their ability to survive and persist in a green roof system in the first year after establishment. This study utilized both whole-plant destructive harvests and continuous recording of soil moisture and temperature during a full growing season. The best of the techniques from previous research were combined and replication was maximized to achieve a robust experimental design that would increase the likelihood of detecting species performance differences in this outdoor study. Three primary hypotheses were proposed:

1. Species evaluated over the course of the study would exhibit different growth and survival rates based on their suitability for planting on green roofs within the Mid-Atlantic region and they partition biomass to above ground and below ground portions differently.
2. Significant differences in temperatures experienced within the substrate would be found beneath planted and unplanted experimental units.
3. Significant differences in storm water retention and substrate water loss would be found between treatments, and that these could be attributed to traits such as root biomass and leaf area.

Chapter 2. Materials and Methods

2.1 Species Selection

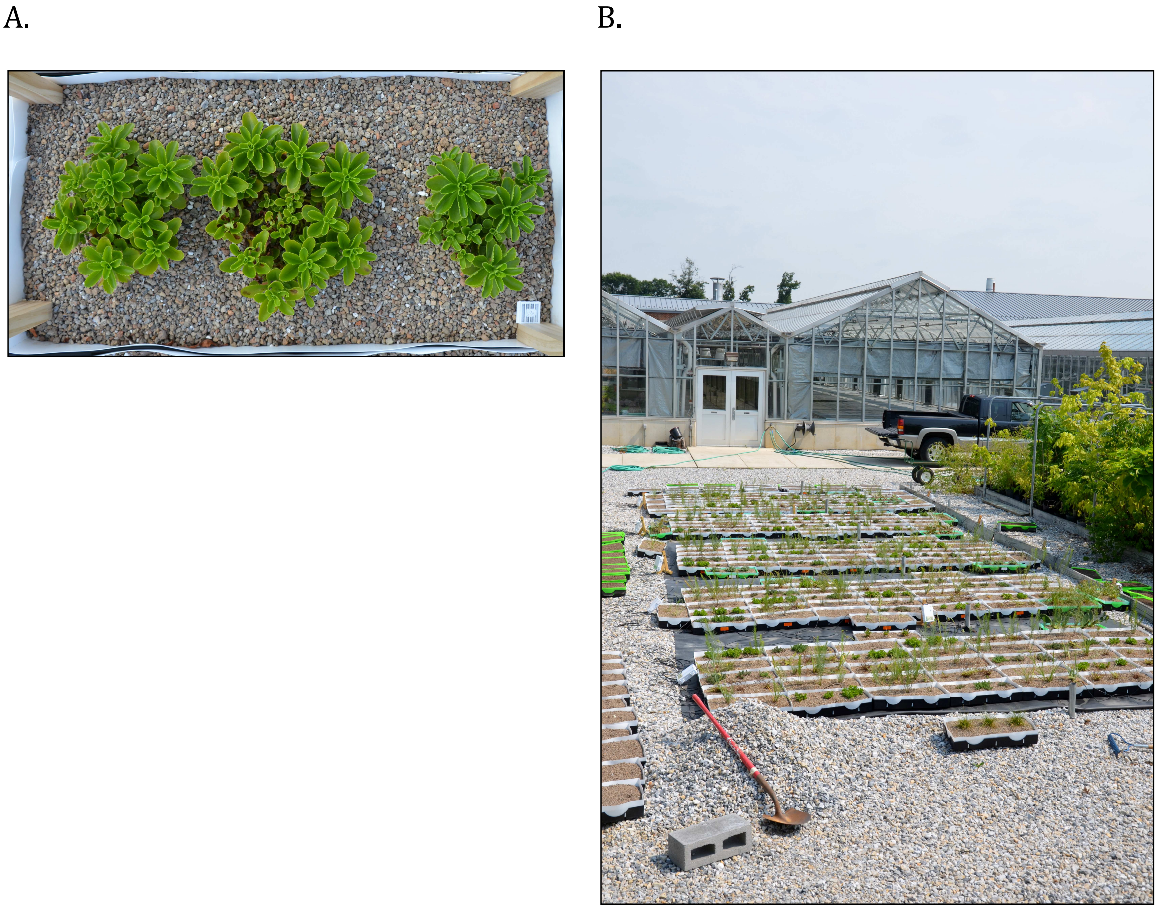
Five plant species were selected for evaluation. Species were selected from those used in prior green roof research studies, with the addition of a new un-trialed species. The two traditional green roof species were *Sedum kamtschaticum* (Starry 2013, Monterusso et. al. 2005). and *Sedum album* (Starry 2013, Monterusso et. al. 2005). Two plant species were also used which are native to the Mid-Atlantic region and were researched in other studies; *Tradescantia ohiensis* (Monterusso et. al. 2005) and *Asclepias verticillata* (Butler and Orians, 2011). The final species was a un-trialed native with radically different morphology; *Cheilanthes lanosa*.

2.2 Experimental Design

Green roof modules were used as independent experimental units. Note that the terms ‘module’ and ‘experimental unit’ will be used interchangeably as they are synonymous in this study. The green roof modules measured 30 cm by 61 cm with a depth of 10 cm. The manufacturer requested their brand not be disclosed. This brand was chosen for the thin sidewalls that allowed for an independent hydrology between experimental units and a built-in drainage layer, allowing for ease of installation. Modules were installed outdoors on a 15-20 cm gravel bed at the University of Maryland research greenhouse, on top of a Firestone 45 mil rubber pond/ roof liner at ground level. The gravel bed was graded to a 2% slope, east to west.

Thirty modules (Fig 2.1a) were assigned to each planted treatment; ten were assigned to the unplanted control. Twenty of the experimental units designated for each planted treatment were specifically for destructive harvests of the plants within each module. These were unnecessary for the unplanted modules as no plant material was harvested. The 160 modules were then divided evenly between 5 blocks, measuring 4 m in width by 1.5 m in length (Fig 2.1b). A randomized mix of both planted and unplanted non-experimental modules where then added surrounding the periphery of each block as guard rows, to buffer any edge effects to the experimental units. There were an additional 110 modules used in the guard rows, 22 per block. Blocks were oriented lengthwise north-south, and parallel to each other (Fig. 2.1b).

Fig 2.1. (A). Image of a planted green roof module from directly above. The three plants shown are within a single module and were treated as sub-samples during all destructive harvest measurements. (B) is a photograph of the green roof modules at the start of the experiment, in the block arrangement described in 2.2.



2.3 Soil Moisture and Temperature Sensing

Ten experimental units from each of the six treatments had a Echo-TM soil moisture and temperature sensor (Decagon Devices, Inc., Pullman, WA) placed at the center of each module. The sensors were connected to EM50R wireless radio data loggers (Decagon Devices, Inc.). These loggers measure sensor data every minute; the loggers were set to average the data and record it at 15-minute intervals. Each record included the time, date, soil temperature and soil volumetric water content (VWC). A total of sixty sensors were installed; all were placed diagonally (facing southeast) in the exact center of the experimental unit, with the blade of the sensor orientated vertically (i.e. thinnest side upwards). Sensor installation occurred on 12 June, 2012 when the modules were moved to their outdoor location, after a three-month greenhouse establishment period. The sensor was placed within the substrate by first digging a small hole roughly 10-15 cm from the module’s center point. The prongs of the sensor were then inserted into the undisturbed substrate beneath the center plant. All modules where then thoroughly watered to settle the substrate around the sensors. This method allowed for minimum disturbance of the established plants and removed this potential source of error. Experimental units which received sensors were randomly assigned within treatment and block by random number selection.

A suite of environmental (weather) sensors were installed immediately adjacent to the green roof modules. These included ECRN-100 high resolution rain gauge, a QSO-S photosynthetically-active radiation Sensor, a Davis cup anemometer and temperature / relative humidity sensor (Decagon Devices Inc.). The Em50R radio datalogger measured data every 1 minute and averaged that data every 5 min.

2.4 Planting, Establishment and Randomization

Sedum kamtschaticum plants were purchased as standard 72 cell plugs from Emory Knoll Farms, MD. *Tradescantia ohiensis*, *Asclepias verticillata* and *Chielanthes lanosa* where purchased from Northcreek Nurseries of Landenburg, PA. *T. ohiensis* and *A. verticillata* were in LP50 cell trays and *C. lanosa* in LP32's. *Sedum album* was planted as cuttings acquired from plant material already in the possession of the green roof research team at University of Maryland. Purchased plant size was not quantified; plant size was recorded in the first destructive harvest (see section 2.5) after a three month establishment period. All plugs were washed of any potting media provided by the nursery prior to planting in the experimental units. Green roof modules were filled with M2 green roof media (Stancills Inc., Perryville, MD). The bulk density of the M2 substrate was 0.75 g/mL with a pH of 7.2 and 3.8% organic matter content (Starry, 2013). Each module was then filled to a depth of 10 cm. Three individual plants of each species were planted in each module (Fig 2.1a). These were considered sub-samples within the designated experimental unit, module, in all further analyses. They were planted in a straight line down the middle of the module on 15 cm centers, such that each plant was equidistant from others and the edge of the module. The green roof modules were planted in March, 2012, three months prior to installation outdoors. Modules were placed in a greenhouse range at the University of Maryland and watered every three days from March through June 11, 2012, during this establishment period. On 13 June, 2012 the modules were randomly assigned within one of the five blocks, as described in section 2.2.

2.5 Destructive Harvests

Five destructive harvests were conducted during the study period from 13 June, 2012 through 15 May, 2013. At each harvest, five experimental units per species where sampled one from each block. As previously mentioned in section 2.2, three individual plants were planted in each experimental unit. These were treated as sub-samples and while each was measured separately their traits were averaged within experimental unit for all further analysis. This avoided statistical error and pseudo-replication. The height of each sub-sample was recorded for all experimental units prior to the start of the harvest. The stem and foliage were then separated from any below ground tissues of each plant by cutting horizontally at substrate level.

The foliage and stem samples were taken and processed for all treatments within each block, before the next block was sampled. Bagged samples were taken indoors where fresh weight and single sided leaf area were measured. For three of the species (*T. ohiensis*, *S. kamtschaticum* and *A. verticillata*) single-sided leaf area was measured. Leaves were separated from stems and then passed through a single-sided leaf area meter (Li-3100 Area Meter, Li-COR Inc., Lincoln, Nebraska, USA). Leaf fresh weights were measured using a balance (XL3100D, Denver Instrument). Stem mass per sub-sample was also recorded. Each sub-sample was then rebagged and stored at 3.3 °C until the harvesting for all blocks was completed. *Sedum album* was harvested in a slightly different manner, due to the ovoid shape and small size of its leaves. Total above ground fresh mass was measured without separating leaves from shoots. Then leaf area was derived from a regression analysis relating leaf area to fresh and dry weight particular to this species (Starry, 2013).

Once all above-ground biomass data was recorded, below-ground biomass was harvested for all replicates and species. The entire root system and associated below ground biomass was removed by sliding a hand underneath the crown and gradually easing it up through the media, shaking lightly. The dry porous nature of the green roof substrate allowed for the recovery of intact root systems with relative ease. Each sample was then placed in a brown paper bag and labeled using the same system as described for above-ground biomass. Roots were then stored at 3.3 °C until they could be gently washed to remove any remaining substrate particles. The root systems were washed twice in two separate water baths. The first time in order to remove the majority of coarse particles and the bulk of substrate material. The second time to remove fines and complete the cleaning process.

All above- and below-ground samples were then re-bagged and placed in drying ovens. Root and shoot samples were dried in a Thelco Laboratory Oven (Precision Instruments; Winchester, VA) at 54 °C. Samples remained in the oven until uniformly dry, for a minimum of one week. Dry weights were then measured using a balance (XE100, Denver Instrument) and recorded.

2.6 Data Processing and Statistical Analysis

Data was downloaded from the Em50R data loggers using a direct serial connection and the ECHO Utility program (Decagon Devices Inc). Files were saved as an Excel data file. The raw files had the data organized in both processed and unprocessed form. From the raw dielectric permittivity output by the sensor, a substrate-specific calibration curve was applied to convert it to a true percent volumetric water content value (Starry, 2013). The calibration curve was determined using the procedure outlined in Cobos and Chambers (2012).

The M2 substrate VWC data were organized by treatment. The EM50R data loggers each have five sensor ports. Two data loggers were assigned to each block. One sensor from every treatment was connected to each data logger within the block they were placed. Treatments were assigned to the same port in all loggers. The excel files were reorganized so that each treatment was in one data file. Then temperature readings and percent VWC were separated, again by treatment.

In the original percent volumetric water content data there was significant variability due to an error in sensor operation that caused the VWC measured by the sensor to increase as the temperature rose above 35 C, a temperature level regularly exceeded in the substrate during this study. This error was found to increase the VWC read by the sensor as temperature of the substrate increase. It is likely an internal error of the sensor attempts to apply a temperature correction to the VWC data before it is output to the data logger. The internal sensor correction factor appears to not be resilient across temperatures above 35 C, since soil temperatures rarely reach that level and the algorithm was not intended to operate in the range above that threshold. Averaging the VWC data on a daily basis was the most practical and statistically justifiable solution to remove this source of noise. The average function in excel was used to derive daily averages from the 96 cells representative of a single day’s data between 12:00 am and 11:59 pm. This was applied separately to each sensor output from each replicate.

Storm water retention and water loss were derived from the daily averages, by utilizing rainfall event start and stop times. Rainfall durations and volumes were recorded by the weather station sensors, as described in section 2.3. Retention was defined as the substrate VWC 24 hours after rainfall stopped, minus the substrate VWC 24 hours before rainfall began. Starry (2013) and Voyd (2009) considered that active drainage from green roof substrates stopped 6 hours after rainfall ceased. However, in this case, the use of daily average VWC made 24 hours the smallest possible increment upon which retention could be calculated. For this reason, rainfall events that occurred within 24 hours of each other were considered the same event for the sake of retention calculations. Dry-down periods (referred to as water loss periods) were identified as periods without rainfall, again using 24-hour delineators.

Water loss was calculated as a decrease in VWC between 24 hour averages. Any days with water loss that were within 15 days of a harvest date were averaged together within treatment to estimate the rate of water loss from the substrate at that time during the study. Water loss was treated as a proxy for evapotranspiration which was not directly measured in this study.

All statistical analysis was done using SAS statistical software v. 9.3 (SAS Institute, Cary, NC). Comparisons between species and characteristics within and between destructive harvests were done using CONTRAST statements within the PROC GLM routine. Daily average temperature, daily maximum temperature and daily minimum temperature were tested for significant differences between each planted treatment and the unplanted control. All pairwise comparisons were determined to be an ineffective method of comparison, since it was not my intent to determine if all treatments were different from all others. Statistical power would have been lost in a test such as Tukey’s HSD where comparisons that were not of interest would have been made. Correction of the p-value for multiple comparisons would have been applied automatically through the statistical test and reduced the ability to detect real differences between the control and planted treatments. P-values for contrasts were adjusted to account for multiple comparisons using the Bonferroni method . The Bonferroni method divides the alpha value for detection of a significant difference by the actual number of comparisons made. In this case, for each comparison of one treatment against the mean of all others, five comparisons were actually made thus the alpha value of .05 becomes .01. Using an uncorrected p-value would have resulted in an increased chance of type 1 error since multiple comparisons were actually made for each contrast of one treatment mean against all others.

Comparisons between species within retention events and dry-down periods used the Tukey’s HSD tests across all pairwise comparisons. Each event was analyzed separately as they were not replicates.

Chapter 3. Environmental Data

3.1 Temperature

3.1.1 Ambient Air and Substrate Temperatures

Monthly average air temperatures for the study period did not differ significantly from the 1981-2010 average reported by NOAA for the Washington, DC area (Table 3.1). While temperatures in green roof substrates have not been recorded for the same region over any length of time, the fact that air temperatures during this period were similar to the 1981-2010 average may indicate that the average green roof substrate temperatures that were measured are a realistic indicator of what could be expected.

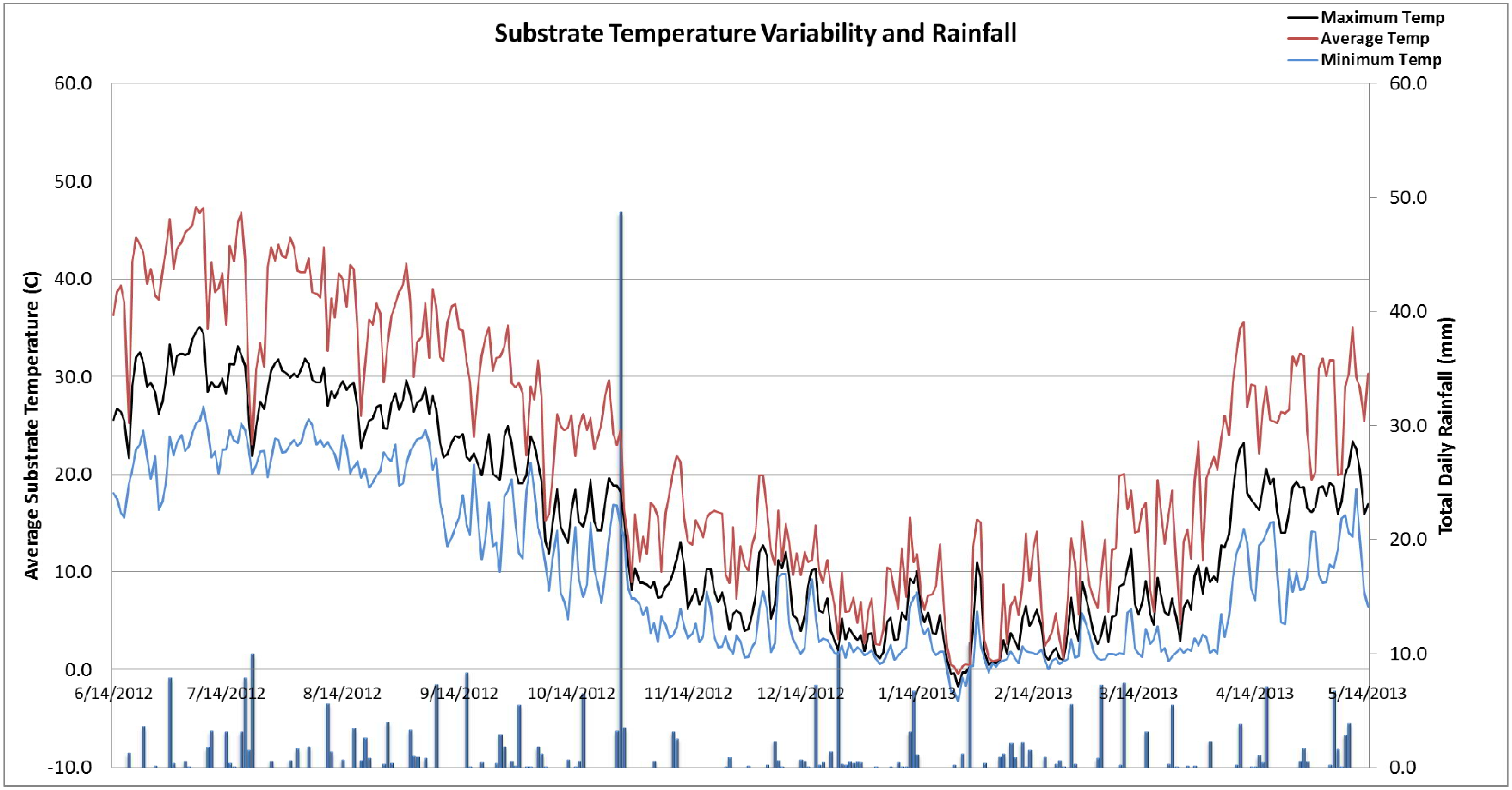
3.1.2 Seasonal Variability of Substrate Temperature

Substrate temperature (Table 3.1; Fig 3.1) varied considerably throughout the growing season. The difference between the minimum and maximum daily temperatures was greatest during periods of warm weather. The temperatures experienced in the substrate during the study period varied from an average maximum of 46 C and a minimum of -3 Celsius (Fig 3.1). From these substrate temperatures, it is not clear what the ideal growing conditions for each species are, since simply monitoring substrate temperature does not provide any information on the ideal growing temperature conditions for each species, and no detailed observations were made during this study.

Table 3.1. Average ambient air temperature by month between 1981 and 2010 as measured by NOAA for the Washington DC. Shown with average monthly air temperature recorded at the study site and average substrate temperature within unplanted experimental units for comparison.

Month	**Average Air Temp. 1981-2010**	**Average Air Temp. (6/12-5/13)**	**Average Sub. Temp (6/12-5/13)**
June	24.0	24.7	29.0 ± 0.9
July	26.6	27.3	30.7 ± 1.0
August	25.6	25.1	28.3 ± 0.7
September	21.7	20.7	23.6 ± 0.9
October	15.3	14.5	16.2 ± 1.2
November	9.78	6.49	7.8 ± 0.7
December	4.28	6.24	6.3 ± 1.0
January	2.22	3.50	4.0 ± 1.0
February	3.89	2.36	3.4 ± 0.7
March	8.22	5.46	6.6 ± 0.8
April	13.8	13.9	16.6 ± 1.3
May	18.9	15.1	19.4 ± 1.0

Figure 3.1 Substrate daily maximum temperature (red line) daily minimum temperature (blue line) and daily average temperature (black line) averaged across all treatments and plotted against time. Total daily rainfall in mm plotted on the secondary y-axis for reference.



3.1.3 Diurnal and Seasonal Substrate Temperatures

Daily average temperature (Table 3.2) was defined as the average of all temperatures measured within a 24-hour period. Unplanted modules were on average warmer than planted modules throughout the summer inter-harvest interval. *Sedum kamtschaticum* was on average cooler than all other planted treatments. No other significant differences were noted between daily average temperatures over the study period.

Daily maximum temperature (Table 3.2) was defined as the highest temperature reached during a 24-hour period. The Echo-TM sensors placed under *Asclepias verticillata* recorded significantly higher (1.51 C) daily maximum temperatures than the overall mean of other treatments during all inter-harvest periods. The unplanted control group experienced significantly greater daily maximum temperatures during summer, early fall and late spring when compared to planted treatments, excluding *A. verticillata*. *Sedum kamtschaticum* had lower maximum temperatures than all other treatments during one inter-harvest period, early fall.

Daily minimum temperature (Table 3.2) was defined as the lowest temperature reached during a 24-hour period. Unplanted modules experienced significantly lower minimum temperatures during late fall, and spring than planted modules. After 1 Nov., *Tradescantia* had higher minimum substrate temperatures than all other treatments for the remainder of the study period. Of all planted treatments *Asclepias* had the lowest average minimum temperatures from late fall through mid-winter; during the first summer it also had the lowest minimum temperatures of all treatments. The unplanted modules experienced the lowest average minimum temperatures during all harvest intervals except from Nov 30th-Jan 14th, where differences to other treatments were not significant.

Table 3.2 Daily average, maximum and minimum temperature averaged within harvest interval and by treatment. Treatments which are significantly different from the unplanted control are indicated by *.

Treatment	Daily Av.	Daily Max.	Daily Min.
	Inter-Harvest Period 6/15-8/8		
Unplanted	30.2±0.12	41.4±0.21	22.1±0.11
Sedum album	29.7±0.12*	40.3±0.25*	22.2±0.11
Asclepias verticillata	29.9±0.12	41.7±0.22	21.9±0.11
Sedum kamtschaticum	29.3±0.12*	38.8±0.21*	22.3±0.11
Tradescantia ohiensis	29.7±0.12*	39.6±0.20*	22.6±0.11*
	Inter-Harvest Period 8/9-10/31		
Unplanted	21.9±0.19	31.2±0.25	15.8±0.19
Sedum album	21.8±0.19	30.0±0.24*	16.1±0.18
Asclepias verticillata	22.2±0.19	32.2±0.27*	15.9±0.19
Sedum kamtschaticum	21.5±0.18	28.6±0.23*	16.6±0.18*
Tradescantia ohiensis	22.2±0.18	30.3±0.24	16.8±0.18*
	Inter-Harvest Period 11/1-1/14		
Unplanted	6.61±0.11	11.7±0.17	3.46±0.08
Sedum album	6.74±0.11	11.6±0.16	3.66±0.09
Asclepias verticillata	6.87±0.11	12.4±0.18*	3.54±0.09
Sedum kamtschaticum	6.80±0.11	11.2±0.16	3.95±0.09*
Tradescantia ohiensis	7.01±0.11	11.7±0.17	4.05±0.09*
	Inter-Harvest Period 1/15-4/7		
Unplanted	5.23±0.12	10.8±0.25	1.80±0.06
Sedum album	5.01±0.12	10.0±0.23	1.81±0.07
Asclepias verticillata	5.32±0.13	11.1±0.25	1.76±0.07
Sedum kamtschaticum	5.17±0.13	10.2±0.24	1.89±0.07
Tradescantia ohiensis	5.29±0.12	10.0±0.22	2.18±0.06*
	Inter-Harvest Period 4/8-5/14		
Unplanted	18.7±0.16	29.8±0.28	10.6±0.2
Sedum album	18.2±0.15	27.7±0.27*	11.3±0.19*
Asclepias verticillata	18.8±0.16	29.9±0.3	10.9±0.2
Sedum kamtschaticum	18.1±0.15	27.0±0.27*	11.4±0.19*
Tradescantia ohiensis	18.3±0.15	27.1±0.26*	11.7±0.18*

3.1.4 Discussion

Plant tissues for the majority of plant species begin to be damaged between 50 and 55 C (Colombo and Timmer 1992, Daubenmire 1943). Lethality for a particularly drought tolerant species, *Pinus ponderosa*, began at 63 C for periods less than 1 minute according to Kolb and Robberecht (1996). They also determined that movement of water through the stem could reduce the temperature of the plants tissues by as much as 30 C. The maximum temperature reached during the study was 61 C for a single 15 minute measurement interval within the substrate of one replicate of *Asclepias verticillata*. This is below the lethality threshold cited from Kolb and Robberecht; however these thresholds likely vary between species. One of the plants treatments in the study– *Chielanthes lanosa* – was removed from the study during the first summer inter-harvest period, due to death of all individuals. It appears likely that high temperatures and perhaps the lack of significant amounts of rainfall (Fig. 3.1) could be attributed as the primary cause.

However it is not possible to assign a lethality threshold for temperatures since the exact time of death for individual plants in the study was not specifically noted. *Chielanthes lanosa* uses tissue desiccation as a drought avoidance strategy and was functionally dormant throughout much of the summer. It was only possible to identify mortality when growing conditions became favorable and no individuals rehydrated. Death could have occurred at any time during the time period between harvests. Mortality was only between 0 and5% for the other species in the study. It therefore appears unlikely that lethal temperatures for these species were reached. Three treatments, including the unplanted treatment never reached 50 C within the substrate during the study period.   This was despite temperatures during summer, 2012 being close to the historic average. Substrate temperatures in both *Asclepias* and *Sedum album* did exceed 50 C on a number of occasions during the first summer period; the amount of immediate damage that may have occurred to roots is unclear, since destructive harvests were not conducted close to when these high temperatures occurred.

All the species grown in this study are apparently capable of surviving to USDA hardiness zone 4 (Snodgrass 2006, Cullina 2000). This value translates to plant species tolerating minimum air temperatures as low as -34.4 C (-30 F). At no point did temperatures reach those extremes during this study, nor was any mortality detected that could be attributed to low winter temperatures for any species.

The increased substrate temperatures noted in *Tradescantia ohiensis* during late fall, winter and spring of the following year was interesting. Although the magnitude of this effect was small (0.4 C from the average of other treatments) during fall and winter, and 0.6 C during the spring, it may it may hint at how root systems can hold greater soil moisture, to modify temperature extremes. *Tradescantia* exhibited greater below-ground dry mass than all other species except for *Sedum kamtschaticum* (see Chapter 4). Greater differences may exist for other as yet untrialed species which could perhaps provide plant community benefits, where marginally hardy ornamentals are desired on a greenroof. It could be speculated that a species that buffered the temperature extremes within the substrate could aid the survival of marginal species planted in close proximity.

Modules planted with *Asclepias verticillata* had the highest maximum daily temperatures across the entire study period. During the first three harvest periods *Asclepias* also had the lowest minimum temperatures, when compared to the within period average. This species therefore experienced a wider temperature range than the other treatments in this study under the same environmental conditions. It is unlikely that some leaf canopy property contributed to these temperature extremes, as the effect occurred both when foliage was present and after dormancy. This species also experienced greater temperature extremes than the unplanted modules throughout the study. This leads one to believe that there may be some other morphological characteristic of this species (possibly tied to roots) that is contributing to greater heat conductance within the substrate.

It is likely that there is an interaction between substrate temperatures and biomass accumulation, if the effects on root respiration are considered. However the nature of the data collected in this study masks the direct testing of this relationship, and we did not measure root respiration data directly at any time. All species started with individuals of the same size and the study period was too short to test long-term effects of temperature on root biomass accumulation. There was no repetition of seasons with plants that were larger and more mature, as would be the case if the study were extended for a second year. Temperature was also measured from one location beneath the crown of one plant within each experimental unit. While the dynamics of biomass of each species were established through whole plant destructive harvests, the distribution and density of that biomass around the sensor is unknown. Without a clear picture of how much of that biomass directly influenced the sensors reading at the measurement point it is unlikely that an accurate relationship could be found without more detailed studies.

3.2 Green Roof Water Relations

3.2.1 Rainfall Compared to Historic Average

Average cumulative monthly rainfall volumes reported from NOAA from 1981 to 2010 are shown in Table 3.3, with cumulative monthly rainfalls as measured by the weather station at the study site and a nearby weather station at the Beltsville agricultural research station (Greenbelt, MD). Rainfall volumes recorded at the study site were more variable than that measured at Beltsville. The reason for this is unclear, however Jan and Dec may be lower due to a failure by the study weather station to properly record the volume of precipitation that fell as snow.

Table 3.3 Average cumulative monthly rainfall as reported by NOAA from 1981-2010 for the Washington DC area, with cumulative monthly rainfall as measured at two locations near the study site all in millimeters of rainfall.

Month	**NOAA, Washington DC**	**USDA-Beltsville, MD**	**University of Maryland Study Site**
June	60.5	88.2	58.4
July	71.4	96.8	124
Aug.	70.6	68.0	87.0
Sept.	109	81.6	25.6
Oct.	148	215	189
Nov.	15.2	20.8	35
Dec.	77.0	77.2	39.4
Jan. 2013	64.3	64.8	24.4
Feb.	42.4	35.6	69.2
March	71.1	72.2	41.4
April	70.1	39.8	60.4
May	71.6	52.2	36.2
Total	**871**	**912**	**790**

3.2.2 Substrate Volumetric Water Content:

The substrate VWC readings from each treatment (plant species) were averaged and compared around date of each destructive plant harvest (Table 3.4). When VWC averages were regressed against biomass values by treatment and harvest date, no significant relationships were found. The substrate VWC of *Tradescantia ohiensis* was significantly greater than all other treatments during Spring 2013 (Table 3.4) During the summer of 2012 *Tradescantia* had greater substrate VWC than all other planted treatments but not the unplanted control. In the fall and early winter for 2012 Tradescantia was significantly different from two treatments *Asclepias* and *S. kamtschaticum*.

Table 3.4: Average volumetric water content by species and harvest date. Tukey's HSD levels shown within harvest date, comparing treatment levels.

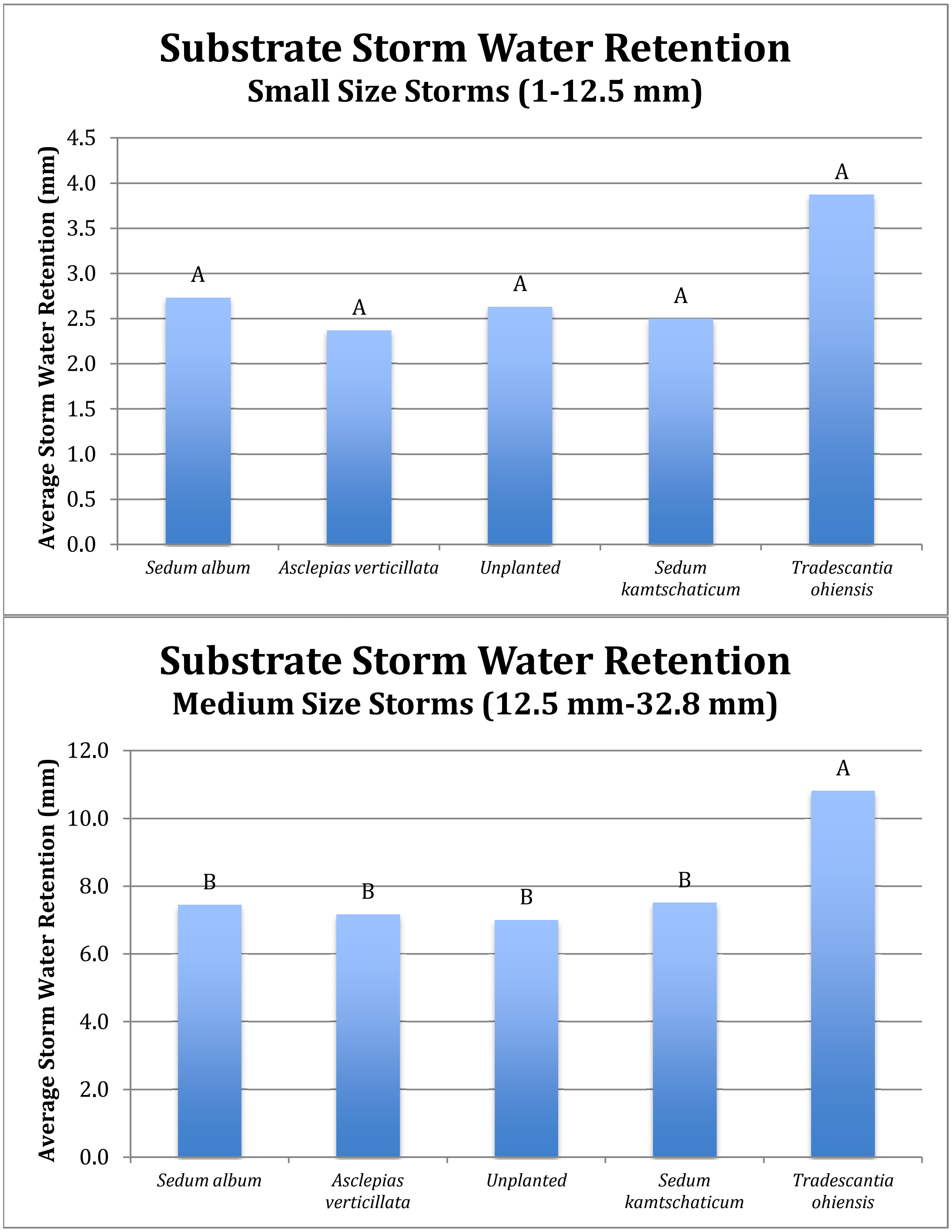
Harvest Date	**6/12/12**	**10/1/12**	**11/30/12**	**3/1/13**	**5/15/13**
Sedum album	0.19^{B}	0.24^{AB}	0.25^{AB}	0.26^{B}	0.19^{AB}
Asclepias v.	0.12^{BC}	0.19^{B}	0.23^{B}	0.24^{B}	0.17^{B}
Unplanted	0.21^{AB}	0.24^{AB}	0.23^{AB}	0.23^{B}	0.18^{B}
Sedum kam.	0.16^{B}	0.20^{B}	0.24^{B}	0.27^{B}	0.20^{AB}
Tradescantia	0.25^{A}	0.27^{A}	0.29^{A}	0.36^{A}	0.27^{A}

3.2.3 Rainfall Retention:

During the course of the study period 42 distinct rainfall events occurred ranging from 1.4 mm to 165mm. The amount of rainfall retained within the substrate after rainfall events was calculated by subtracting the daily average volumetric water content 24 hours after rainfall had stopped from the daily average volumetric water content 24 hours before rainfall began (Table 3.5). This yields an approximate measure of the amount of rainfall that was retained within the substrate of each treatment after drainage had ceased.

Tradescantia ohiensis was the only plant species that showed significantly different substrate water retention over the year. It captured more rainfall on average for medium sized storm events and for a single large storm event (Fig 3.2). Differences were found using Tukey's HSD in SAS. For medium-sized storms *Tradescantia* captured 3.5 mm more than the average of all other treatments, a 49% difference (Fig 3.2b). For the very large 165mm storm event *Tradescantia* retained 6.8 mm more rainfall than the average of all other treatments, a 45% difference (Fig 3.2c). The average size of the 19 storms classed as medium (Fig 3.2b) was 21.9 mm. On average, *Tradescantia* captured 49% of rainfall during medium sized storms while the other treatments captured 33%.

Fig 3.2: Rainfall retention volumes in mm averaged for (a) all small storms, (b) all medium sized storms and (c) for a single large storm event during the study period. Only *Tradescantia ohiensis* was significantly different in both charts, Tukey's HSD levels displayed above each treatment average.



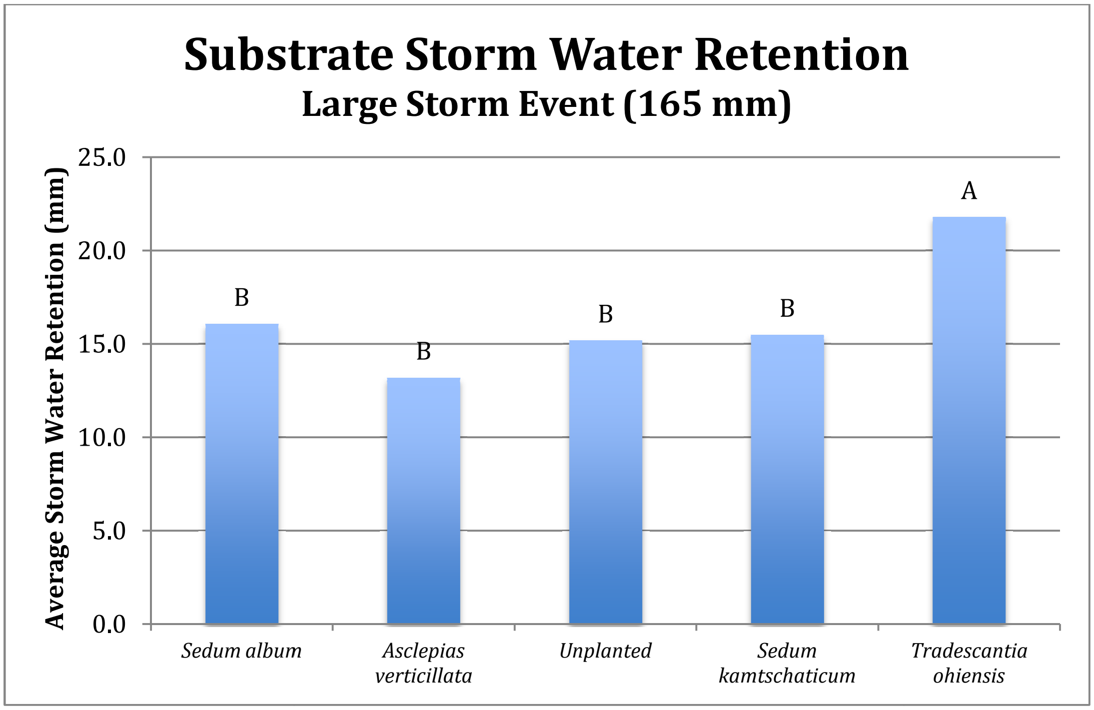


Table 3.5: Rainfall retention amounts for similar sized storms near harvest dates. Retention reported in mm and significant differences showed as Tukey's HSD levels.

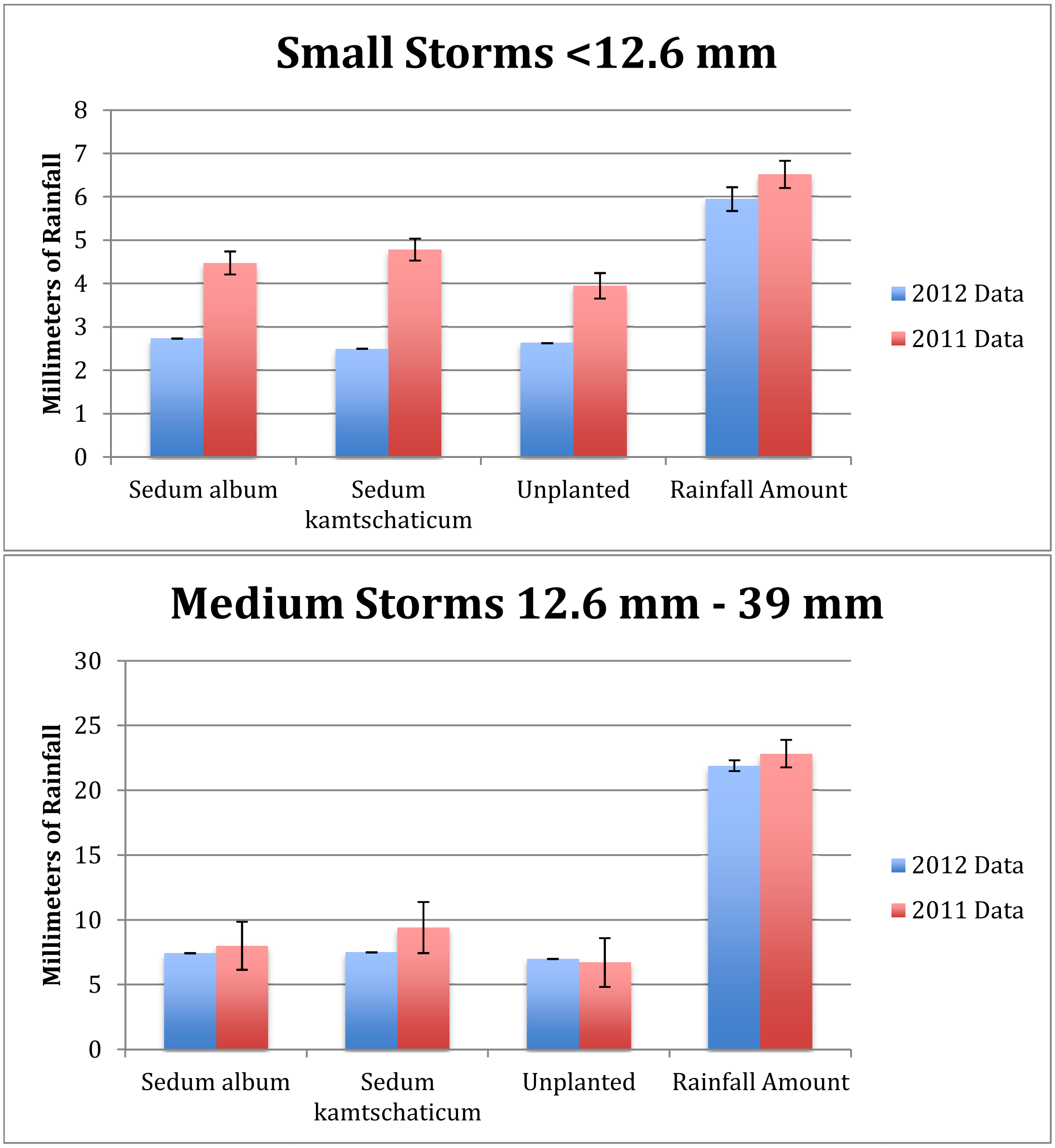
Date	**6/30/12**	**9/19/12**	**12/22/12**	**3/7/13**	**5/9/13**
Rainfall	**23.2 mm**	**25.0 mm**	**22.0 mm**	**23.8 mm**	**24.6 mm**
Sedum album	4.6^{B}	11.0^{B}	3.4^{A}	10.8^{A}	13.0^{B}
Asclepias v.	10.5^{A}	9.6^{B}	2.6^{A}	10.3^{A}	12.5^{B}
Unplanted	8.3^{AB}	12.3^{B}	3.2^{A}	10.6^{A}	8.8^{B}
Sedum kam.	7.2^{AB}	11.6^{B}	3.2^{A}	10.8^{A}	16.7^{AB}
Tradescantia	9.9^{A}	20.7^{A}	3.9^{A}	12.5^{A}	20.1^{A}

The data shown in table 3.5 shows the amount of water retained in mm for storms of about the same size that occurred close to destructive harvests. This data was derived in an attempt to investigate the effect of increasing biomass on rainfall retention. The effect of environmental conditions appears to mask the effect of increasing biomass over the course of the study period retention values are not similar for storms of the same rainfall volume.

3.2.4 Comparison to Previous work:

A comparison of storm water retention results from Starry (2013) are shown with permission of the author (Fig. 3.3). Two of the same species as in this study were investigated by Starry, namely *S. album* and *S. kamtschaticum*. These were grown in experimental green roof platforms with the same M2 media and depth as was used in this research study. Comparison of first year data from Starry was done against the data for this project. Starry measured storm water runoff from her platforms in Liters. This value was converted to mm of retention by multiplying the volume of storm water runoff by the area of the platforms, and subtracting the average of this value for all 2011 storm events from the average storm size for 2011. This approximated the average storm water retention in millimeters. Figure 3.3 compares the data from this study with Starry’s first year (2011) data for *S. kamtschaticum, S. album* and the unplanted controls. Average rainfall size for medium for each year is also shown. Average rainfall sizes for medium and small storms were very similar between the two studies. Rainfall retention amounts for small storms were greater than for all treatments in Starry’s 2011 data than that recorded in this study in 2012. Retention amounts for medium sized storms were similar between both studies.

Figure 3.3 Rainfall retention amounts in millimeters for small storms (A) and medium storms (B) for this research study in 2012 (in blue), compared to Starry's first year data (2011) in (in red).



3.2.5 Substrate water loss:

The rate at which the substrate dries can be calculated value from daily averages of VWC. Periods of time where no rainfall occurred were first identified from the weather data. Subtracting the daily average VWC from the day preceding it, yields the amount of water lost over that time interval. These values were then selected from periods 15 days before and after harvest dates. An analysis of these values using Tukey's HSD show few significant differences between treatments, within harvest dates (Table 5.3). A great deal of variability exists across harvest intervals. This may be due to changing environmental conditions between seasons. Temperature and substrate VWC being foremost as higher temperatures and water contents should yield greater water loss rates than low temperatures and low water contents.

Table 3.6: Average water loss rates from the substrate within 15 days of each harvest date. Tukey's HSD levels displayed for comparisons between treatments, within harvest dates.

Harvest Date	**6/12/12**	**10/1/12**	**11/30/12**	**3/1/13**	**5/15/13**
Sedum album	-0.008^{AB}	-0.020^{AB}	-0.009^{A}	-0.034^{A}	-0.017^{AB}
Asclepias v.	-0.015^{A}	-0.016^{AB}	-0.009^{A}	-0.031^{A}	-0.015^{B}
Unplanted	-0.008^{B}	-0.020^{AB}	-0.013^{A}	-0.031^{A}	-0.012^{B}
Sedum kam.	-0.010^{AB}	-0.017^{B}	-0.007^{A}	-0.033^{A}	-0.016^{B}
Tradescantia	-0.020^{A}	-0.029^{A}	-0.012^{A}	-0.036^{A}	-0.034^{A}

3.2.6 Water relations vs. Biomass values

The series of charts that follow regress biomass values against volumetric water content, water loss and storm water retention. No significant R-squared values are associated with any of the regression lines shown. Regressions were preformed within species and also for all species combined. The combined regression is not plotted on these charts. Within species regressions on each chart are plotted in same color as the data series associated with that treatment. As stated previously no regressions were found statistically significant, graphs with R-squared values and associated p-values are listed in App. B.

3.2.7 Discussion

One fact that became obvious during the analysis of the VWC data set recorded throughout this project is that the seasonal variability of these environmental variables has a great effect on the water content of a green roof substrate. Water contents rose for all treatments as the seasons progressed from fall into winter, and fell again as spring transitioned towards summer.

Comparison of rainfall retention rates for medium sized storms showed that one treatment, *Tradescantia ohiensis* retained significantly more water than all other treatments. On average *Tradescantia* captured 49% of rainfall during medium sized storms while the other treatments captured 33%. This represents a substantial increase in storm water retention based on the use of one species over the others. Unplanted controls did not retain significantly different volumetric water contents from the other species used in the study. This adds more evidence to previous research that showed no differences in performance of planted vs. unplanted green roof systems in the first year after planting (Lundholm et al. 2010, Monterruso et al. 2004).

Daily average volumetric water contents were derived and used for all analysis of substrate water content data, due an interaction between substrate temperature and the water content read by the sensors. Increasing substrate temperatures would correlate with an increase in the VWC reported by the sensor, this made it appear than VWC was increasing during the day as the temperature rose and decreasing again as night approached and temperatures decreased. This posed a problem for the analysis of differences in retention between treatments for small storm events (less than 12.6mm). Retention differences were likely short lived for these small storms, possibly across time intervals under 24 hours. Attempting to detect differences through the use of daily averages was not possible in this data set, due to the inherent lack of precision in using daily averages.

It is interesting to note that during one extreme rainfall event (165mm) *Tradescantia* did appear to retain more substrate water than all other treatments. This is counter to results in other studies that showed large rainfalls did not have any difference in performance between treatments (Starry 2013). This result may be due to the fact that this study measured substrate VWC and calculated retention, whereas Starry (2013) measured water loss directly from her experimental green roof platforms with precision (large tip) rain gauges. Therefore, differences in runoff between treatments may be nonexistent or below the threshold of detection during large storms. However retention amounts calculated from runoff data in Starry 2013 showed that retention amounts were similar between *Sedum kamtschaticum*, *Sedum album* and unplanted modules during the first year of both studies, indicating that these two green roof studies preformed at the same location did have some consistency in storm water retention, despite being measured during different years.

The maximum amount of water that can be held in the substrate is a small percentage of the total storm volume. The average retention for the only significantly different treatment, *Tradescantia*, was 21.8mm. The storm volume during this event was 165 mm, making the percent retention 13%. The average retention for the other treatments was 15 mm or 9% of the 165mm of rainfall. Since this study was not able to measure runoff, it is not known if this retention difference would have been visible in the amount of runoff from the green roof modules. It is unusual also in that the second largest storm during the study period (66mm) did not show any differences between species. These two events occurred at different times of year: the 165 mm storm was on 10/27/2012 and the 66 mm storm was on 7/17/2012. It is possible that either environmental conditions were such that differences between treatments were masked for the 66 mm event or that plant species were not large enough to show a treatment effect at this point. These were the only two storms during the study period classified as large, the next largest storm was 32.8 mm and this represented the upper threshold for those considered medium sized. Thus it is difficult to draw any general conclusions about the performance differences between treatments for large rainfalls based on the data available from this study.

Lundhom et al. (2010) concluded that planting a monoculture on a green roof could lead to lower evapotranspiration rates when compared to unplanted green roof substrates, yielding lower water capture after rainfall. This general conclusion is not supported by this study. Modules planted with *Tradescantia ohinesis* were both wetter throughout several of the harvest periods than unplanted modules, and they also captured more storm water and had greater rates of evapotranspiration at varying times throughout the study.

Rates of water loss were greatest overall during spring and fall, when temperatures were moderate and available water was high. Unplanted controls did not lose significantly more or less water than other planted treatments, excluding *Tradescantia* during late spring/ early summer. The substrate beneath *Tradescantia ohiensis* was wetter than all other treatments throughout the early spring; it also retained more water near the crown during many rainfall events. This may be due, in part, to morphological traits of this species. *Tradescantia* is a monocotyledonous, its leaves are narrow and v-shaped around the mid-vein. The leaves arise from a bulb and spread radially out from the center. The v-shape of the leaf aids in capturing water and causing it to flow downwards directly to the bulb. This may have contributed to the increased volumetric water content readings taken beneath the sensor, as more water was directed there than for the other species in the study. It is not clear how localized this effect was, since sensors were only placed beneath the crown and not throughout the whole root zone of the specimens monitored. At first glance there appears to be no value to redistributing water from throughout a larger area to beneath the crown of a plant. It is possible though that this water capture trait of *Tradescantia* may actually serve to allow it to better survive drought by increasing available water and increasing its growth rate and ability to maintain its biomass.

In addition observations made during root excavations for destructive harvest measurements showed that *Tradescantia* appears to produce a large amount of root exudates relative to the other species evaluated. This was most apparent when roots were washed of fine soil particles. These root exudates could contribute to the greater volumetric water content experienced where this species was planted. as well as aiding in the retention of storm water. However, this is merely conjecture based on an empirical observation. and would need experimental evidence for validation.

A question that could not be answered by this study is whether or not the increased performance for green roof water retention functions beneath *Tradescantia* scales. Would a larger experimental unit planted with *Tradescantia ohiensis* still have detectable performance differences when compared to other treatments? If rainfall is just being redistributed and focused beneath the crown of the plant, then it is quite possible that a larger experimental unit would end up with only a redistribution of the same volume of retained rainfall within the substrate, and not an actual increase in performance of the whole experimental unit. While in the first few years this may not result in any real benefit to the experimental units function it could result in better performance as the system ages. Pockets of greater plant available water could serve to increase the ability of *Tradescantia* and other species adjacent to it to survive and maintain biomass through drought periods. This would then result in increased biomass accumulation over time. More biomass could translate into greater water retention rates and greater evapotranspiration rates.

If future work is done to build on this study several problems should be addressed. The error caused by the interaction between VWC read by the sensors used in this study and temperature of the substrate needs to be addressed if small-scale time periods are to be analyzed for treatment differences. A longer study period would also have allowed for the testing of longer term effects of different species, as well as organic matter accumulation within the substrate and the maturation of the specimens. This study was only conducted over a single growing season, as discussed in the previous section on temperature. It is likely that the effect of species on storm water retention and green roof volumetric water content will increase over time. Green roofs that have been in place for longer than 2 years with greater levels of living and dead organic matter in their substrates have greater water retention capacities (Getter et al. 2007). Different plant species likely accumulate organic matter at different rates and this may result in increased differences in performance of green roof functions over time.

The nature of the data collected by the sensors used in the project masks some of the potential effects of species on green roof function. Sensors read volumetric water content, changes in this value over time were easily quantifiable. While the amount of water retained in the substrate can be calculated easily from the available data, it is unknown where the water that was not retained ended up. For example, canopy interception likely influenced the amount of water that entered the substrate yet it is not possible to what portion of rainfall was captured in this layer. Other studies have used runoff, perhaps better defined as gravimetric water loss, as the measure for determining green roof performance (Starry 2013, Dunnett et al 2008, Monterruso et al. 2004). The advantage to this is it measures total plant effect, not just what is retained within the substrate.

In general the results of this project partially supported my initial hypothesis. Differences were detected between treatments, though only in one species *Tradescantia ohiensis*. No other treatments showed consistent significant differences between the other species or the unplanted control. All were found to perform the same as the unplanted control for storm water retention. There was no detectable trend in storm water retention , water loss or VWC over the course of the study period that could be related to the passing of time and as the plants grew, increasing biomass and leaf area. This is mainly due to the variability of environmental conditions preventing the detection of the species effect over the short study period of only one year. Future work seeking the effect of increased biomass should be designed to take multiple growing seasons to improve the chances of detection.

Chapter 4. Plant Harvest Data

4.1 Destructive Harvest and Survival Results

Harvests were conducted starting at the initiation of the outdoor study on 6/12/12, 3 months after planting. Four additional harvests were conducted at 108 days, 168 days, 259 days and 334 days after the initiation of the study. Throughout the results portion of this chapter, these harvests will also be referred to as harvest 1, 2, 3, 4 or 5 respectively.

4.1.1 Survival

Simple observation of plant survival is a useful measure. It is fairly straight forward; once a plant has died it is deducted from the overall percent survival for that species within the number of replicates in the study. In this study death was not measured solely due the lack of viable aboveground tissue, but required that roots and belowground plant parts also be dead.

All *Chielanthes lanosa* died between the first and second harvest. It was not therefore possible to compare *C. lanosa* to any of the biomass values of other species. *Asclepias veticillata* had the second greatest mortality, at 10% of the total individuals planted. *Tradescantia ohiensis* lost 5 individuals (5.5%) and *Sedum kamtschaticum* lost 4 individuals (4.4%) over the 334 days of the study. *Sedum album* suffered no whole plant mortality during the course of the study.

4.1.2 Total Dry Biomass

Total dry biomass showed few overall differences between species. All species were identical during the second harvest in Oct. *Sedum kamschaticum* had more biomass than all other species by the third harvest on 11/30/12.. The fourth harvest on 3/1/13 again showed no statistically significant differences between species. The final harvest on

May 15th, 2013 with *S. kamtschaticum* and *T. ohiensis* had the greatest overall dry biomasses and were not significantly different from each other. *Sedum album* had the next most dry biomass followed by *Asclepias;* both were significantly less than the other species. All species grew during the course of the study period except *A. verticlliata* which showed a decrease after the first harvest, and then failed to grow over the remaining time.

4.1.3 Aboveground Dry Biomass

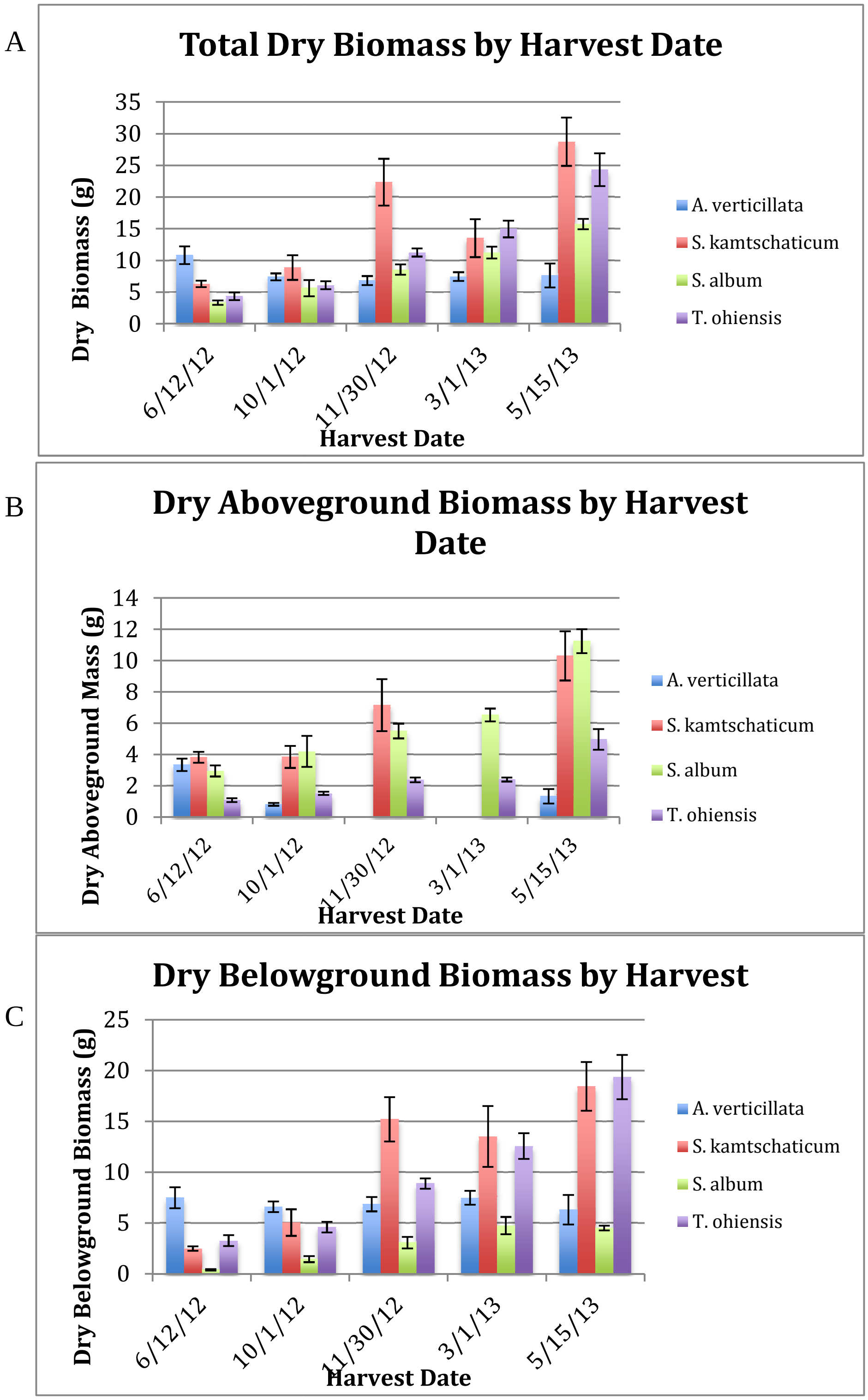
Differences were found between aboveground biomasses for species within harvest times. *T. ohiensis* had the lowest dry shoot mass at the beginning pf the study (Harvest 1; Fig 3.2). The other three species were all statistically identical. Both Sedum species hadgreater shoot dry mass than *A. verticillata* and *T. ohiensis* by harvest 2,which were statistically identical. *Asclepias verticillata* decreased in aboveground mass from harvest one to harvest two and between harvest two and harvest three, when it went dormant. It remained dormant into the fourth harvest then re-sprouted for an increase in aboveground mass by the final harvest (at 5/15/13). *S. kamtschaticum* did not grow during the summer between harvest one and two. It did grow between harvest two and three, then went dormant for harvest four and increased aboveground biomass for the fifth harvest in early summer. *Sedum album* did not grow significantly until between the fourth and fifth harvests. *Tradescantia* added a significant amount of aboveground biomass between the second and third harvests and the fourth and fifth.

4.1.4 Belowground Dry Biomass

Differences were found between belowground biomasses for species within harvest times (Fig. 3.3). The term belowground biomass instead of root biomass since any plant parts that occurred within the green roof substrate were included in this sampled value. For instance *Tradescantia* has modified leaves and a basal stem within the bulb which was considered part of the belowground biomass. *Asclepias* had the greatest below-ground biomass at harvest 1. *S. kamtschaticum* and *T. ohiensis* both had significantly less below-ground biomass than *A. verticillata*, but significantly more than S. album.By the second harvest at 10/1/12, *S. album* was had significantly lower biomass than the other species, which showed no differences among each other. By harvest 3 on 11/30/12, *S. kamtschaticum* had the greatest below-ground biomass with *A. verticillata* and *T. ohiensis* with similar biomass, and *S. album* still less than all other species. *S. kamtschaticum* and *T. ohiensis* had similar biomass by harvest 4; *S. album* and *A. verticillata* had significantly less biomass, but were equivalent to each other. Differences between species were the same through to the fifth harvest, 76 days later. ..

Asclepias did not change root mass significantly between harvests. *Sedum kamtschaticum* did not change significantly between the first two harvests, increased significantly between harvest 2 and 3, but . remained at the same level after that. *Sedum album* added a significant amount of root mass between harvests 2, 3 and 4, but showed no change from harvests 4 and 5. *Tradescantia ohiensis* did not add below ground biomass between the first and second harvest but did show growth between harvests 2, 3, 4 and 5.

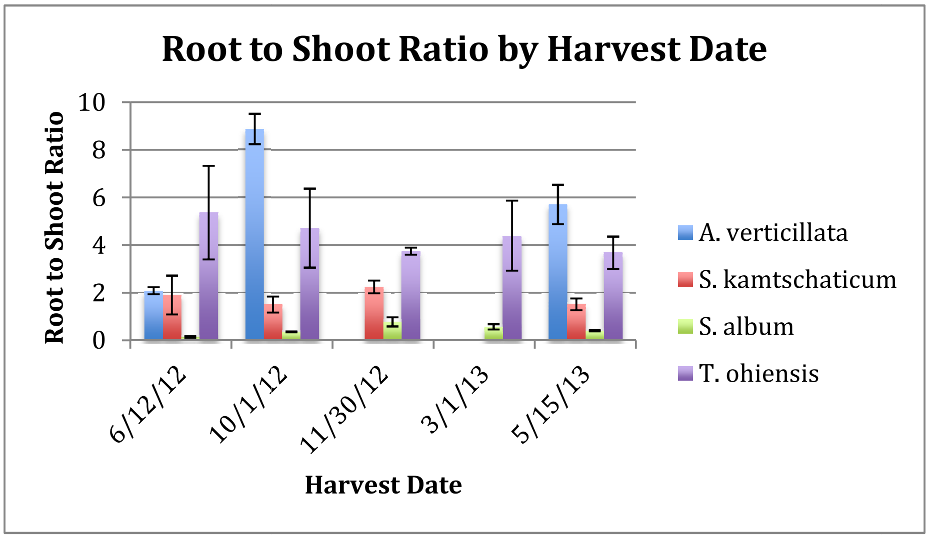
Figure 4.1 Total biomass (A), dry aboveground biomass (B) and dry belowground biomass (C) in grams for all species within harvest dates. Error bars illustrate standard error about the mean.



4.1.5 Root to Shoot Ratio

Root to shoot ratio (RSR) is a metric used to establish how growth is partitioned to root and shoots, which can be species-dependent. It is a potentially important value in predicting belowground biomass where destructive harvests are not desirable (Mokany et al. 2006, Monk, 1966). RSR was calculated as belowground dry biomass divided by aboveground dry biomass. The RSR of *Asclepias verticillata* increased between 6/12/12 and 10/1/12 due to a decrease in aboveground biomass while belowground biomass remained the same (Fig. 4.2). *Tradescantia ohiensis* maintained a consistent ratio throughout all five harvests. *Sedum kamtschaticum* RSR increased during the fall, but decreased slightly by the final harvest. During the early spring harvest on 3/1/13 only *T. ohiensis* and *S. album* had any aboveground biomass from which to derive a ratio from, and were significantly different from each other. Overall, the RSR of *Tradescantia* was greater than both *Sedum* species. *S. kamtschaticum* was greater than *S. album* and *A. verticillata* varied considerably throughout the course of the study.

Figure 4.2 Root : Shoot tatio for all species, by harvest dates. Error bars illustrate standard error about the mean.

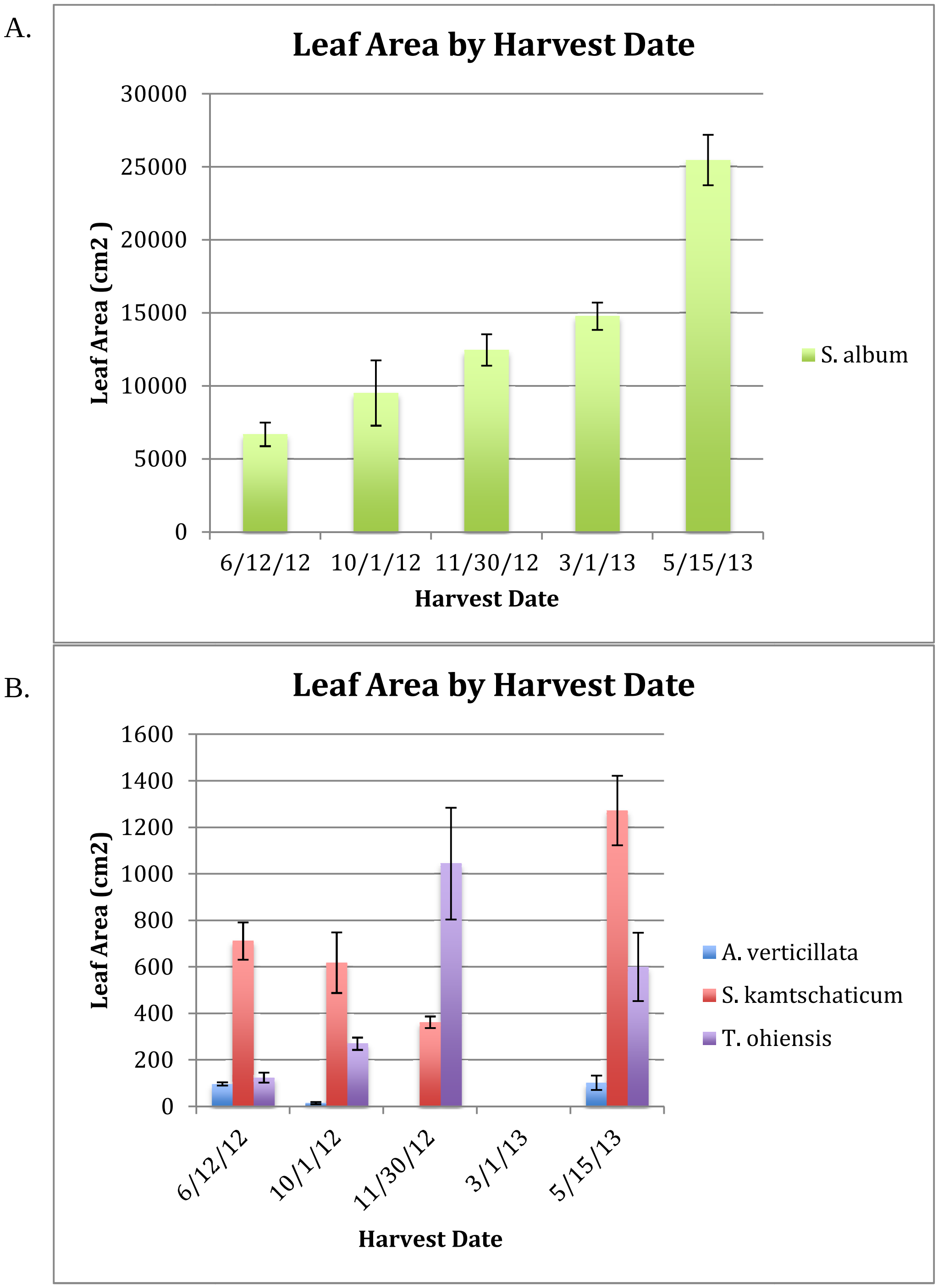


4.1.6 Leaf Area

The leaf area of *Sedum album* was calculated using a regression relating leaf area to dry weight (Starry, 2013). As the leaf shape of *S. album* is an ellipse calculation of area does not reflect a single sided leaf area as was directly measured for the other species. Given this fact and the relatively flat nature of the other species leaf area was doubled to better reflect total leaf area. However *S. album's* leaf area remained so great that it could not be plotted with the other species (Fig. 4.3A).

Tradescantia ohiensis increased its leaf area between 10/1/12 and 11/30/12 to a degree which was greater than would be expected, considering its relatively small increase in aboveground biomass at the same time (Fig. 4.3B).

Figure 4.3 Average leaf area (cm^2) for (a) S. album and (b) for all other species within harvest dates. Error bars illustrate standard error about the mean.



4.1.7 Whole Plant Relative Growth Rate

Whole plant relative growth rate (RGR) was calculated using the formula:

$$RGR = \frac{lnW2 - lnW1}{t2 - t1}$$

In other words the species mean total dry biomass from harvest one (*W1*) subtracted from the species mean total dry biomass from harvest five (*W2*), divided by the duration (time) of interest. The study was divided into two intervals: 6/12/12- 11/30/12 (171 days) and 11/30/12- 5/15/13 (176 days). Relative growth rates were not calculated between each harvest due to the fact that not all species showed statistically significant growth between individual harvest periods.

Table 4.1 Relative growth rates (RGR) over the study period between 6/12/12- 11/30/12 and 11/30/12- 5/15/13

Time Interval	***Asclepias***	***Sedum kamt.***	***Sedum album***	***Tradescantia***
6/12/12-11/30/12	-0.0027	0.0074	0.0055	0.0056
11/30/12-5/15/13	0.0007	0.0015	0.0037	0.0046

4.1.8 Discussion

Basic plant growth analyses do provide some indication of the relative health of the species in a green roof environment. *Asclepias verticillata* lost biomass during the summer between the first two harvests, but remained the same throughout the rest of the study. This may indicate that it is poorly adapted to grow in a green roof environment, though it is able to persist. *S. kamtschaticum*, *S. album* and *T. ohiensis* all grew significantly throughout the study. This alludes not only to an ability to survive seasonally, but also an ability to grow and persist indefinitely.

Sedum kamtschaticum and *T. ohiensis* had the greatest biomass at the end of the study period. *T. ohiensis* partitioned a large portion of its growth into belowground tissue. If aboveground biomass had been the only value measured then it would have appeared that *S. kamtschaticum* and *S. album* were most successful species during the study period. This demonstrates the importance of measuring both above- and below-ground plant parts when using biomass as a metric for plant success.

Nondestructive measures of above-ground biomass are common practice in many green roof studies (MacIvor et al., 2011, MacIvor and Lundholm 2010, Monterusso et al., 2005) and partial destructive harvests of above ground biomass are used on occasion (Wolf and Lundholm 2008). However the results of this study clearly indicate that this only yields a partial picture of plant growth dynamics. Below-ground biomass should be sampled in some way as morphological differences in partitioning of growth can yield misleading results as to both the growth rates of a species and relative success under green roof conditions. In addition, should the results reported in Dunnett et al. (2008) hold true and increasing dry root mass relates to increasing rainfall retention on green roofs, then not being able to assess the amount of below-ground biomass accumulated by different plant species is a serious deficiency when attempting to relate above-ground biomass levels alone to performance differences in storm water mitigation functions. *Sedum album* had significantly less biomass than these two species but had 100% survival, whereas the other two lost 4.4% and 5.5% respectively.

Derived values such as root to shoot ratio are potentially very useful. Root to shoot ratios vary in many plant species based on nitrogen availability (Agren and Franklin 2003). This means that root to shoot ratios are at least a partial measure of plant health relative to nitrogen uptake and availability. However this requires an accurate picture of how root to shoot ratios change in response to nitrogen on a species to species basis. Root to shoot ratios are also a useful means of predicting below ground biomass where harvest of roots is impractical (Mokany et al. 2006, Monk, 1966). Root to shoot ratios could perhaps be used to predict levels of biomass present on large established green roofs if these values were well established for a particular species. *Sedum kamtschaticum* and *T. ohiensis* were found to have no significant variability in root to shoot ratios throughout the study period. This may indicate that accurate prediction is possible for these species using an average ratio. However this study only took place over a single growing season more mature plants may not hold to these values. *Sedum album* did vary significantly during the course of the study with a greater root : shoot ratio during harvest 4. This may be indicative of seasonal variability, but a single growing seasons values are insufficient to draw concrete conclusions.

The relative growth rate (RGR) for each species is a measure of the plants biomass accumulation rate per day. *Sedum kamtschaticum* had the greatest RGR during the first half of the study period, from 6/12/12 to 11/30/12. Perhaps indicating that it was best adapted to grow under the conditions it experienced. During the same time interval *Sedum album* and *Tradescantia ohiensis* had similar RGR values and *Aslcepias verticillata* lost biomass. During the second half the study *Tradescantia* had the highest

RGR followed by *Sedum album* and *Sedum kamtschticum*. This indicates that seasonal variability in growth does occur in these species.

While *Sedum album* greatly exceeded the other species in LA during the course of the study it is difficult to find meaning in this variable. Leaf area does not directly reflect potential evapotranspiration as other physiological processes, such as stomatal conductance, dictate it to a greater degree.

Plant species did exhibit different rates of accumulation of biomass over the course of the study period as was hypothesized. *Chielanthes lanosa* was deemed unsuitable for use on green roofs with conditions similar to those experienced in this study, as no individuals survived. *Sedum kamtschticum*, *Tradescantia ohiensis*, and *Sedum album* all grew significantly over the study period, while *Asclepias verticillata* loss biomass during the study. This indicates that the first three of these species were well adapted to the environmental conditions they experienced in the green roof system. *Asclepias* was not able to grow in the same conditions indicating that it is likely unsuitable for use on green roofs in the Mid-Atlantic.

Chapter 5. Summary Discussion and Conclusions

My hypothesis that the species evaluated in this study would exhibit different growth and survival rates based on their suitability for planting on green roofs within the Mid-Atlantic region was supported by the destructive harvest data. *Cheilanthes lanosa* was shown to be unable to survive undergreen roof conditions. It appears likely that it is poorly adapted to the temperature and water stress experienced during the summer in green roof modules in the Mid-Atlantic. All individuals in the study died after 6 months despite the summer of 2012 not being significantly hotter or drier than 30-year average temperatures. *Asclepias verticillata* was able to persist throughout the study period yet had a negative relative growth rate, indicating that it was not well adapted to the conditions it experienced; yet was still better able to tolerate them when compared to *C. lanosa*. *Tradescantia ohiensis* had the highest average relative growth rate of all species tested, possibly indicating that it is well-adapted to green roofs, especially given the overall conditions during this study. The two *Sedum* species, *S. album* and *S. kamtschaticum,* both exhibited positive, relative growth rates that were close in magnitude to each other during this establishment period. *However Sedum kamtschaticum* grew much more rapidly during the summer and early fall than it did during the winter and spring. *S. kamtschaticum* invested more resources in below-ground biomass than *S. album*. Similarly *S. kamtschaticum* and *T. ohiensis* had equivalent levels of accumulated biomass at the end of the study period, yet *T. ohiensis* put less growth into above-ground biomass than did *S. kamtschticum*. As part of the experimental design of this study all plants were established under irrigated conditions in a greenhouse prior to being moved outside for the remainder of the study. This was done to all the plants to be well and fully grown into the substrate prior to being subjected to drought conditions. The basis for this was that the most vulnerable time for these plants would be during the early period, right after planting. Drought during this time could yield much greater mortality than during any other and could have skewed the results in favor of the extremely drought tolerant species such as *Sedum album*. Irrigating a green roof in early phase of establishment right after planting may in the long term yield more successful establishment of plant species. However since the focus of this study was not on factors that aided or detracted from plant establishment, it was determined that the best approach would be to evaluate plants based on their ability to survive after the initial stress period was past.

I hypothesized that there would be differences in temperatures experienced within the green roof substrate, storm water retention and substrate water loss between treatments and that the data collected through destructive harvests would be found to relate to the magnitude of these performance variables. While some significant differences were found for both temperature and water relations between treatments these values did not appear to have clear influences on growth rates or the partitioning of biomass. The effect of seasonal environmental conditions masked the direct effect that may have potentially affected green roof performance by the different species. Between-treatment differences in performance did not show statistically significant separations that could be attributed to biomass, most likely because this study was conducted over a relatively short establishment period of a year. This may indicate that the relationship between biomass and green roof function is not simply quantitative but also has a qualitative aspect. In other words the morphological characteristics of each species may influence how much effect each unit of biomass has on substrate temperature and water, with each species having a different level of effect for each unit of biomass. This would require further investigation and controlled experimentation, the data from this experiment does not provide evidence to confirm or disprove this.

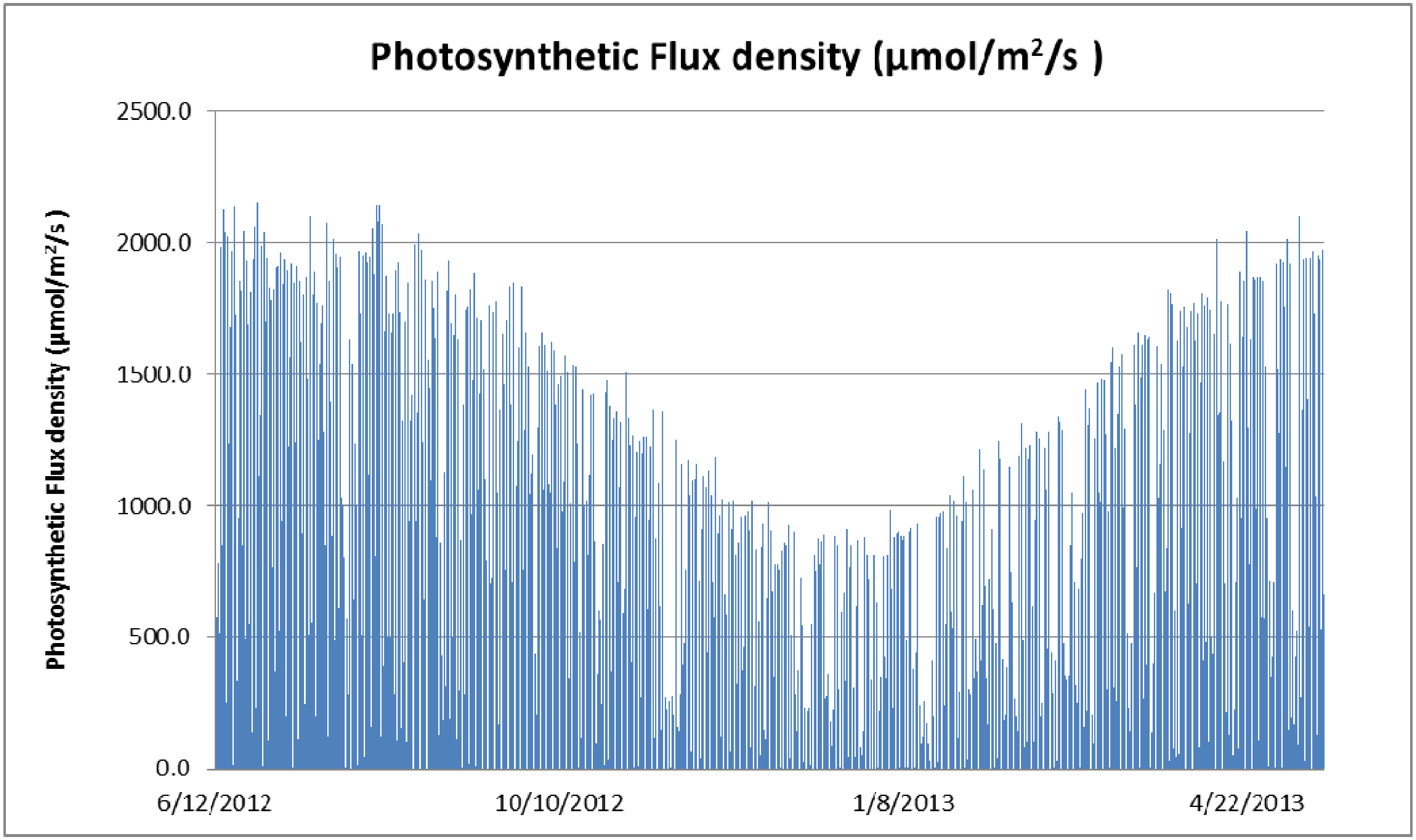
Green roofs have been shown to lower roof temperatures when compared to conventional black tar roofs (Getter et al. 2007). The effect of species on the magnitude of temperature reduction has been investigated in several studies, but without sufficient replication of measurements. Continuous monitoring in this study allowed for detection of any consistent effects that could be attributed to treatment. The main interest in lowering green roof temperatures would be during the heat extremes in the summer months in the Mid-Atlantic. During the summer months in this study, the planted experimental units had both significantly lower daily average temperatures and daily maximum temperatures than unplanted treatments, excluding *Asclepias verticillata* which was actually warmer. This indicates that planted roofs in general may be cooler than unplanted roofs. However the scale of this difference was only 1-2 C cooler for daily averages and 1-3 C cooler for daily maximum depending on treatment. The value of a decrease of this small an amount to a green roof system is unclear and would need further investigation to establish the benefits of these temperature reductions.

The final hypothesis for this study was that there would be detectable differences in storm water retention and substrate water loss between modules planted with different species; additionally, that these differences could again be attributed to traits measured through destructive harvests over the course of the study period. Only one treatment (*Tradescantia ohiensis)* experienced consistent significantly different performance for any green roof water relation variables, The visibility and degree of the effect of this species on storm water retention varied throughout the study, likely due to changes in seasonal environmental conditions (refer Appendix A data). *Tradescantia* maintained significantly greater substrate volumetric water contents than the unplanted control between the dates Oct. 1, 2012 and May 15, 2013. *Tradescantia* also retained more storm water during medium sized storms throughout the study and had a significantly greater water loss rate during the summer and spring compared tothe unplanted control. As posited in chapter 3.2.7, these improvements in performance for storm water retention may be due to morphological traits of *Tradescantia.* Higher levels of storm water retention could be an artifact of stem flow funneling more rainfall directly to the crown of the plant, where the substrate water content sensor was located. This would mean that *Tradescantia* is not increasing the ability of the roof capture stormwater but rather just redistributing the capture of rainfall within the green roof substrate. It could also be due to higher water content of the roots and crown of *Tradescantia* when compared to the other species used in the study. This would mean that when roots of this species are present in the substrate, the water capture and water holding capacity of the substrate is actually increased. These two results could both have implications for green roof performance. If the first is true, then there may actually be no improvement in overall roof rainfall retention. If the second is true then there may be distinct benefits to planting green roofs with species such as *Tradescantia ohiensis*. Further investigation is necessary to determine the cause of this effect on storm water retention for this species. A controlled study that measured substrate water retention in multiple locations around specimens of *Tradescantia* could result in evidence that could sway conclusions towards one hypothesis or the other.

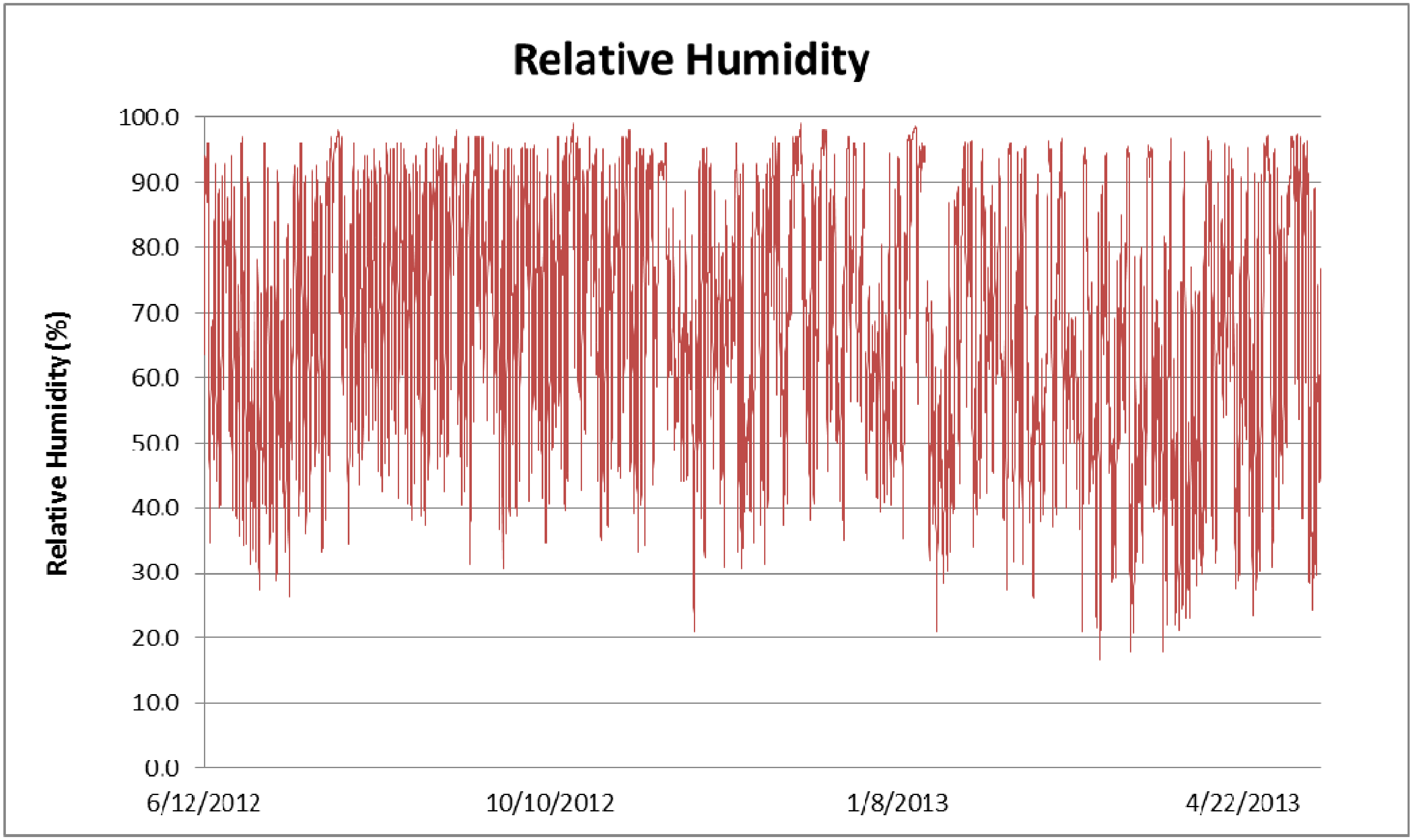
There is need for further investigation into the effects that different plant species have on the performance of green roof function. It is clear from this study that some results are evident within a single growing season. However a longer study with similar species as those used in this study would likely show greater differences, that could also be attributed to precise morphological traits measured through destructive harvests. Indoor controlled experiments could also identify more precisely what the thresholds for mortality are in species that are not able to survive on green roofs, compared to than an outdoor experiment such as in this research. While further work is necessary this study did provide useful information about several species that are commonly planted on green roofs in the Mid-Atlantic region of the United States.

Appendix A: Environmental data for the study period (6/12/2012 to 5/14/2013)

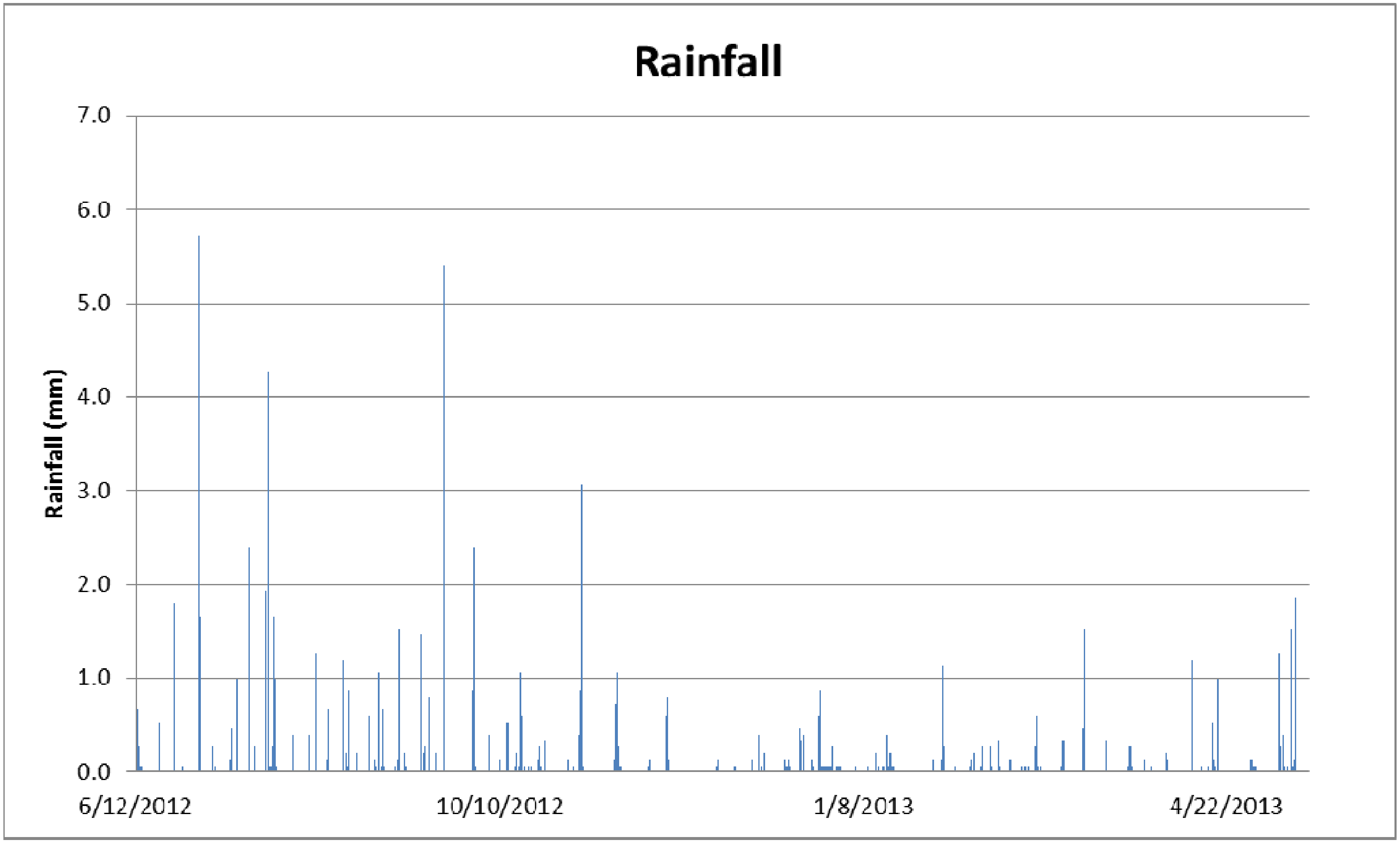
Appendix Figure A.1



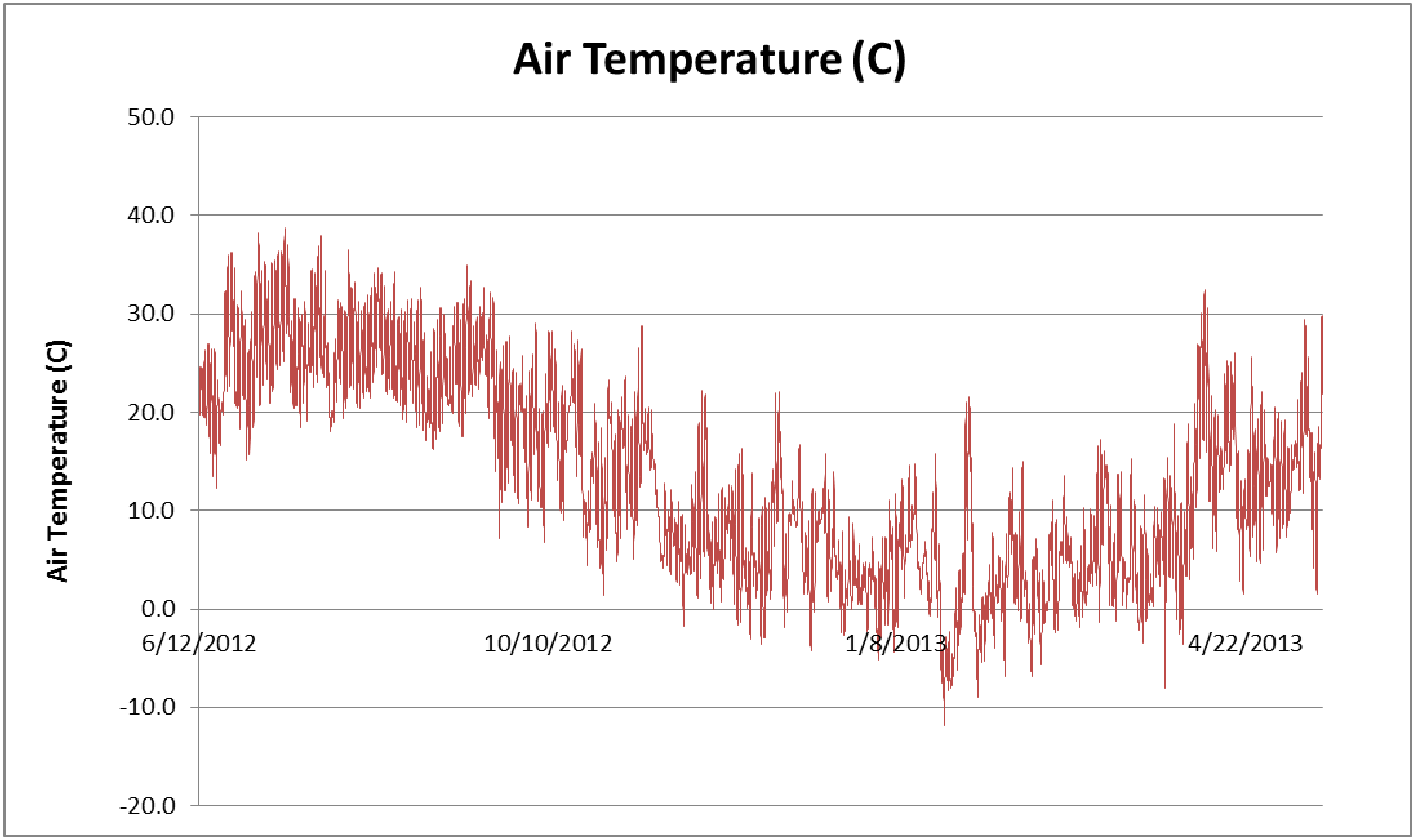
Appendix Figure A.2



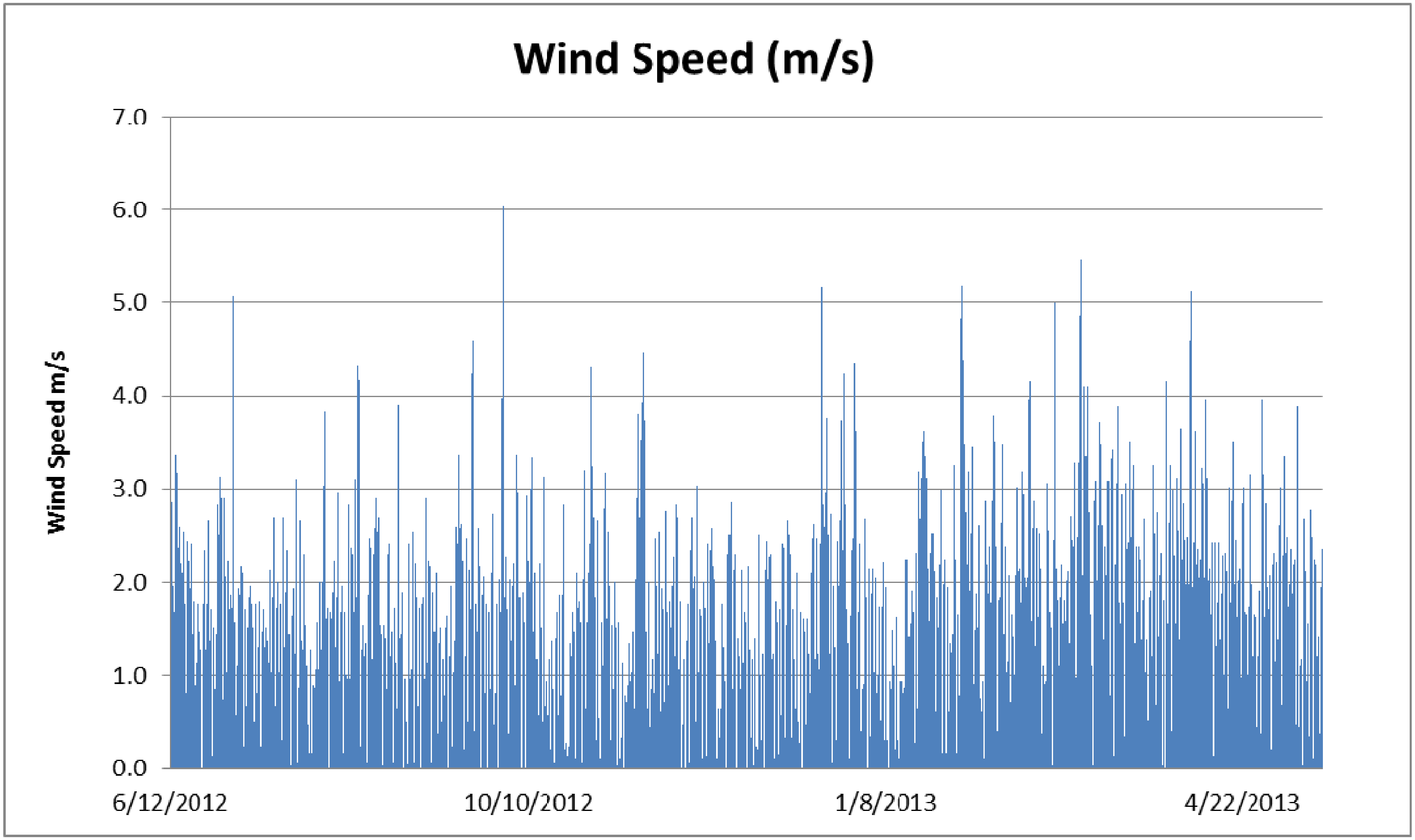
Appendix Figure A.3



Appendix Figure A.4

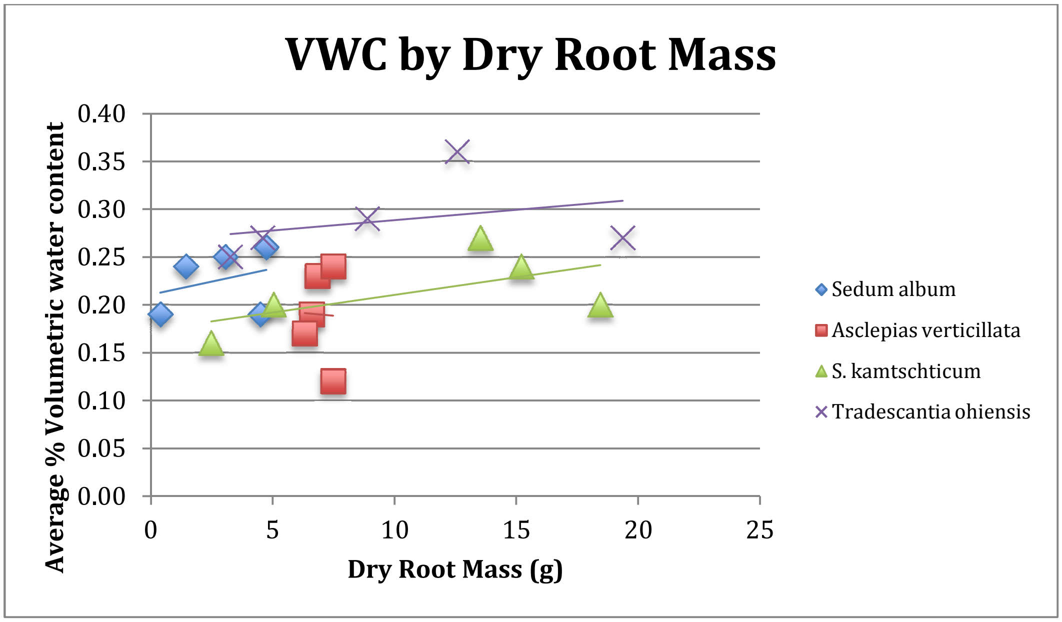


Appendix Figure A.5

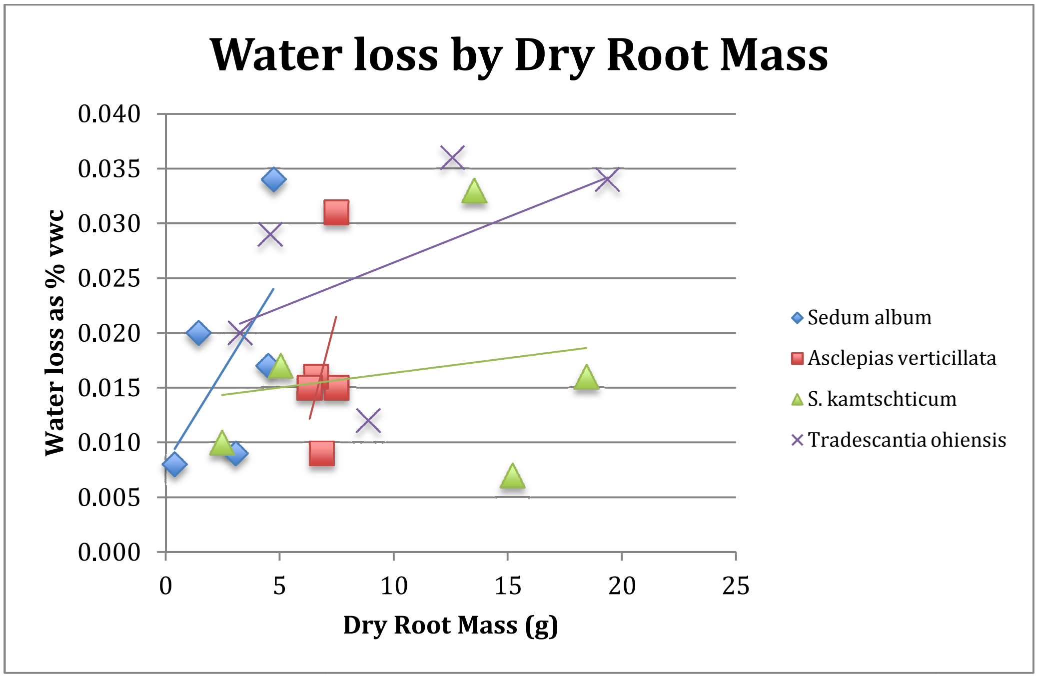


Appendix B: Regression R-Squared values and associated P-Values from Chapter 3.2.6

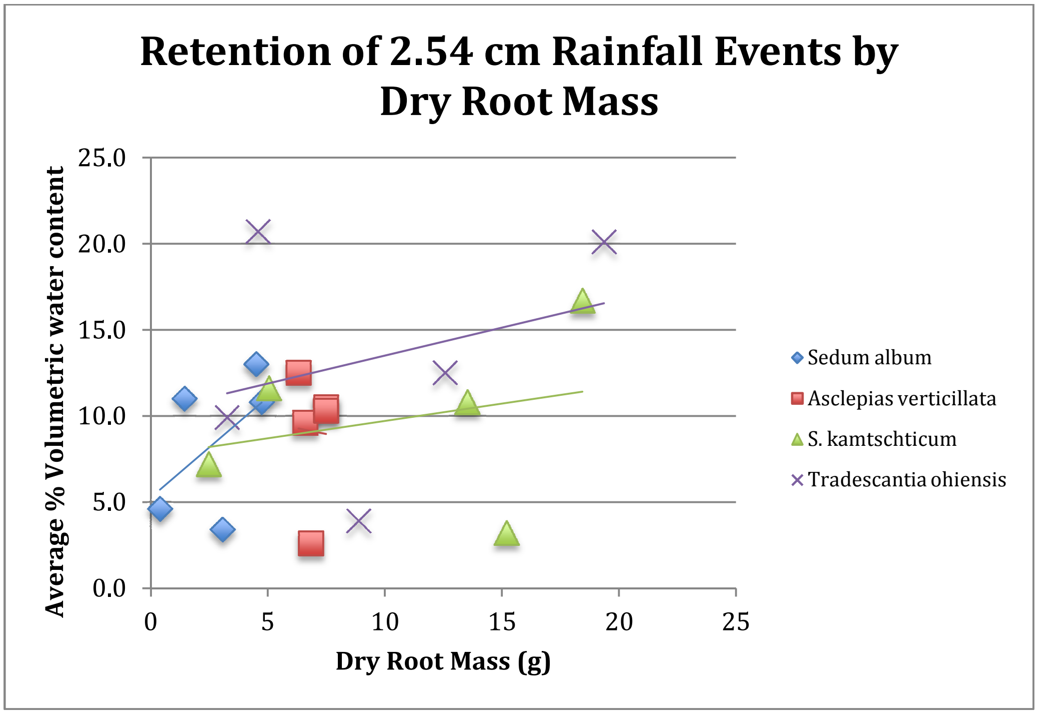
Appendix Figure B1: Volumetric water content averaged by harvest date (from 3.2.6) and regressed against dry root mass at the same harvest time.



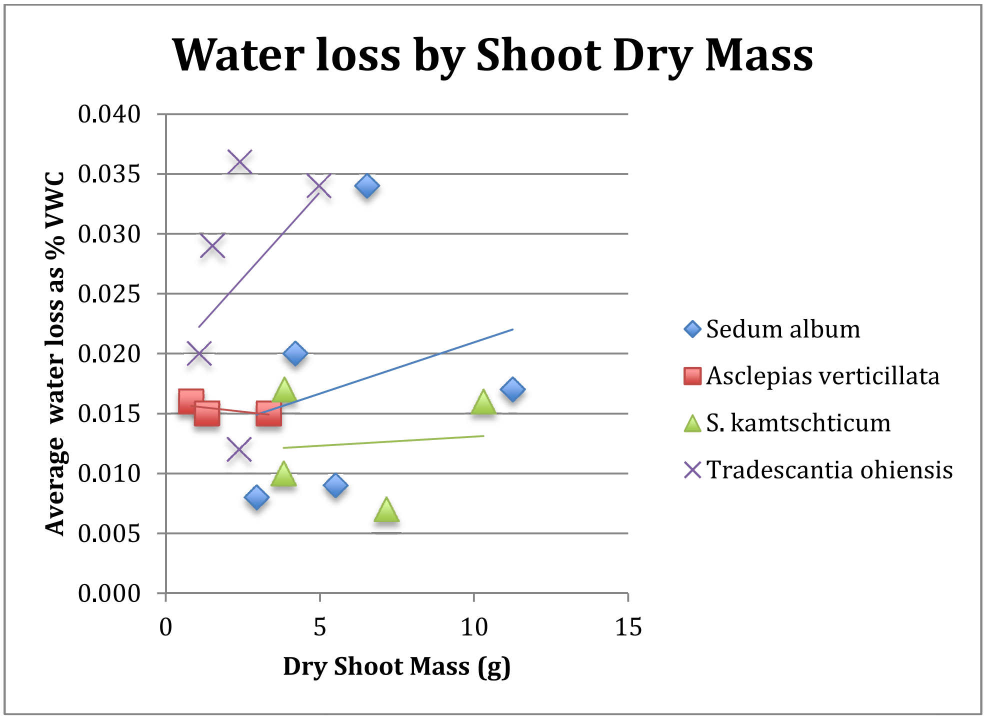
Appendix Figure B2: Water loss rates averaged 15 days (from 3.2.6) around harvest date and regressed against dry root mass within species.



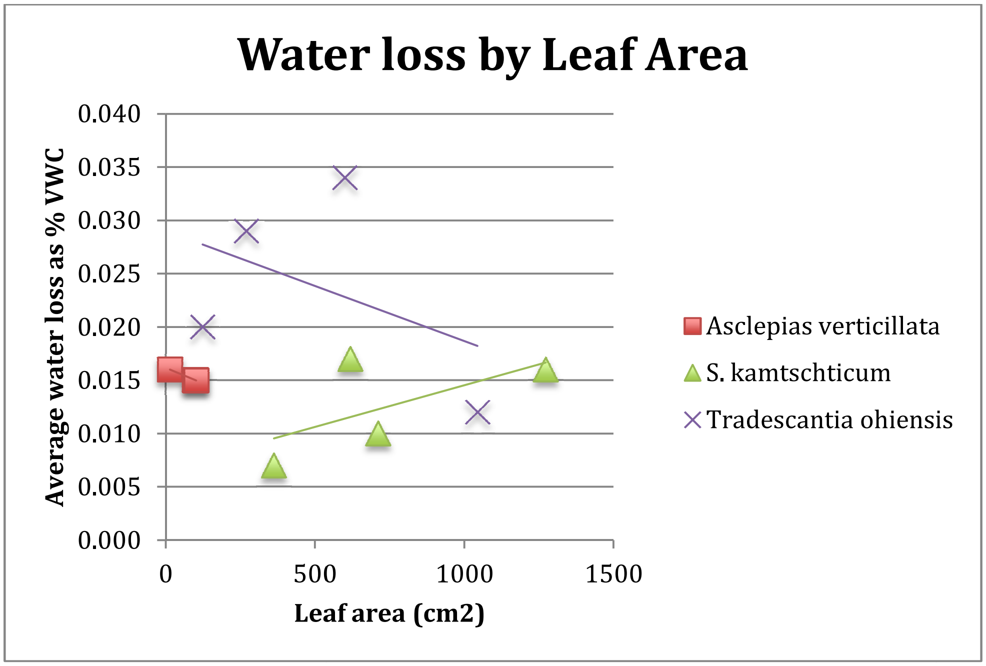
Appendix Figure B5: Storm water retention rates for 2.54 cm (1 inch) storms near harvest dates (from 3.2.6) and regressed against dry root mass within species



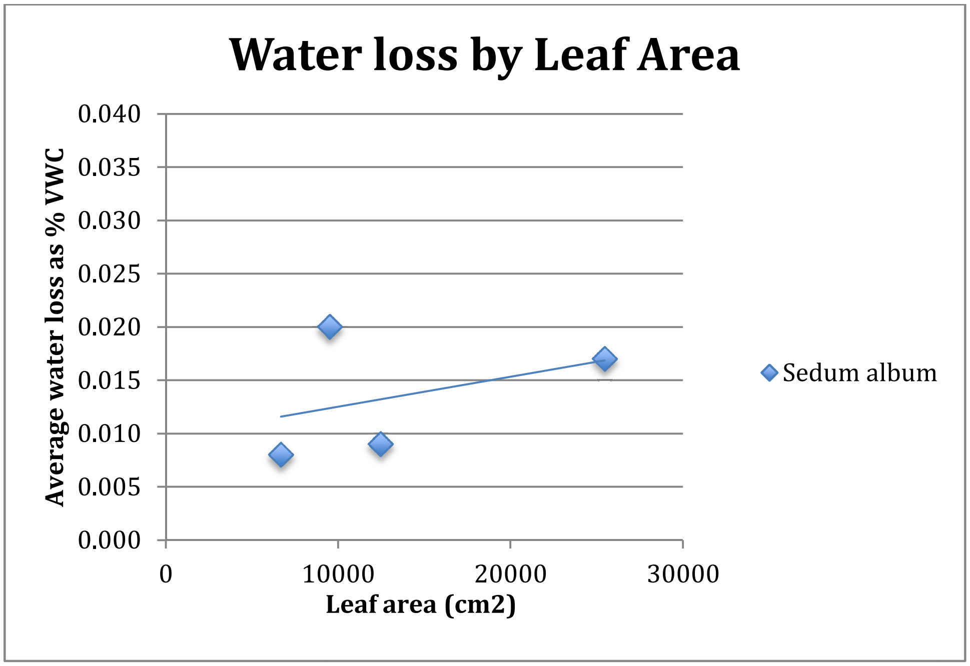
Appendix Figure B6: Water loss rates averaged 15 days (from 3.2.6) around harvest date and regressed against dry shoot mass within species



Appendix Figure B7 Water loss rates averaged 15 days (from 3.2.6) around harvest date and regressed against leaf area within species



Appendix Figure B8 Water loss rates averaged 15 days around harvest date and regressed against leaf area for *Sedum album* (from 3.4.6).



Appendix Table B1: Volumetric Water Content vs Root Dry Mass (Fig B1)

Regression	**p-value**	**R^2**
Sedum album	0.61	0.10
Asclepias v.	0.97	0.001
Sedum k.	0.29	0.36
Tradescantia o.	0.59	0.11
All	0.19	0.05

Appendix Table B2: Water Loss by Root Dry Mass (Fig B2)

Regression	**p-value**	**R^2**
Sedum album	0.28	0.36863
Asclepias v.	0.38	0.2594
Sedum k.	0.77	0.0335
Tradescantia o.	0.35	0.28789
All	0.17	0.0513

Appendix Table B3: Retention(1inch) Storms vs Dry Root Mass (Fig B3)

Regression	**p-value**	**R^2**
Sedum album	0.37	0.26773
Asclepias v.	0.95	0.00134
Sedum k.	0.66	0.07392
Tradescantia o.	0.63	0.08873
All	0.14	0.0653

Appendix Table B4: Water Loss vs Dry Shoot Mass (Fig B4)

Regression	**p-value**	**R^2**
Sedum album	0.67	0.0674
Asclepias v.	0.44	0.4331
Sedum k.	0.07	0.01
Tradescantia o.	0.47	0.1841
All	0.75	0.0065

Appendix Table B5: Water Loss vs Leaf Area (Fig B6)

Regression	**p-value**	**R^2**
Sedum album	0.21	0.1722
Asclepias v.	0.45	0.2995
Sedum k.	0.26	0.3938
Tradescantia o.	0.18	0.1875
All	0.24	0.0316

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