ABSTRACT

Title of Document:	EXTENSIVE GREEN ROOF SUBSTRATE COMPOSITION: EFFECTS OF PHYSICAL PROPERTIES ON MATRIC POTENTIAL, HYDRAULIC CONDUCTIVITY, PLANT GROWTH, AND STORMWATER RETENTION IN THE MID-ATLANTIC. Whitney Nicole Griffin, Doctor of Philosophy, 2014
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While green roof (GR) systems have gained popularity as storm water management tools, more emphasis has been applied to studying performance aspects, including stormwater retention. Of particular importance is the substrate layer in which the vegetation grows, which contributes the majority of stormwater retention capabilities. This research investigated many aspects of GR substrate performance, including component durability and component effects on hydraulic conductivity, matric potential, and plant growth. Several commercial substrate blends were tested for durability against successive freeze/thaw cycles with before and after-treatment granulometric distribution analyses. All substrate blends showed significant ($p<0.05$) particle degradation after 30 freeze-thaw cycles, compared to German (FLL) guidelines. The hydraulic conductivity and matric potential of three experimental GR substrates with increasing volumetric proportions (10%, 20%, 40%) of organic matter (OM), were determined using the HYPROP© method, which extends the traditional measurement range for soils. However, the high porosity of GR substrates resulted in tensiometer water column cavitation near -30kPa. Further studies with the same experimental substrates and OM ratios included both growth chamber studies to rigorously quantify the effects on plant growth and evapotranspiration and outdoor platform experiments to determine effects of OM content on stormwater retention. Growth chamber studies with *Sedum kamptschaticum* showed that increasing substrate OM increased plant root and shoot biomass. Consecutive periods of water stress showed no differences in evapotranspiration between planted substrate OM treatments levels, but greater water loss was noted from the planted treatments compared to unplanted controls ($p<0.05$). Substrate volumetric water content (VWC) during the stress periods reached 5% VWC for all planted treatments and all dry-down periods, highlighting differences in plant-available water between these and the laboratory results. While outdoor platform studies showed no effects of OM content on stormwater retention, increasing organic content increased plant canopy coverage ($p<0.05$). It is likely that differences in retention will be more defined over time as the system matures. Stormwater retention data represented the second growing season for

the experimental platforms; given the effects of organic matter on plant growth, analysis of three- or even five-year retention will likely better predict the effects of organic matter on stormwater performance.

EXTENSIVE GREEN ROOF SUBSTRATE COMPOSITION: EFFECTS OF PHYSICAL PROPERTIES ON MATRIC POTENTIAL, HYDRAULIC CONDUCTIVITY, PLANT GROWTH, AND STORMWATER RETENTION IN THE MID-ATLANTIC

By

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Dedication

For my grandmother Marcelle, who watched the final year of this journey from a happier place.

“Our hearts would lose their tenderness if we never shed a tear” – Marcelle Waldrep

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Chapter 1: Literature Review

1.1 Urbanization and its effects on stormwater

The land area for the contiguous United States is approximately 769 million hectares (Wuerthner, 2002). Of that, 26 million hectares are classified as urban developed land, and while this comprises only 3% of the total available land of the lower 48 states, more than 75% of the U.S. population resides within urban / suburban regions (Wuerthner, 2002). This differs somewhat from a report by the USDA's Economic Research Service, which reported in 2006 that only 24 million hectares were attributed to urban developed land (Lubowski et al., 2006). Wuerthner reports another 56 million hectares is categorized as developed and rural residential land, commonly referred to as urban sprawl. This fraction comprises rural and semi-rural subdivisions, as well as rural farm houses and structures (2002); however, the USDA reports that 38 million hectares of land were estimated to be rural residential areas with 228 million acres categorized as 'miscellaneous' (Lubowski et al., 2006). The USDA also reported that since 1945 the major uses of land in the U.S. show a trend towards growth in special-use and urban areas with a decline in grazing lands. Between 1997 and 2002 total cropland area reached a new 57-year low, continuing a downward trend since 1978 (Lubowski, et al., 2006). Despite variation in the specific numbers, the general trend of increased urbanization in the United States is clear.

Urban development increases the total acreage of impervious surfaces, which are surfaces impenetrable to rainfall and prevent filtration and percolation of water. The District of Columbia Water and Sewer Authority defines an impervious surface as 'a manmade surface that cannot be easily penetrated by water, such as rooftops, driveways, patios, tennis courts, parking lots, and other paved areas' (DCWSA, 2011). Forested and grassland areas usually allow 70% to 90% of a rainfall event to infiltrate, while impervious surfaces result in storm water runoff (Ferguson, 1998) with the amounts varying from 80% in suburban housing areas to 10% in large lots with single homes. The amount of runoff in dense urban areas may approach 95% (Davis and McCuen, 2005). With increasing population, land use changes are often significant, resulting in major changes to runoff characteristics of a watershed (Anderson 1970).

Significant overall reduction of stream and wetland health, begins at only 10% impervious coverage (Arnold and Gibbons, 1996), as measured by criteria such as pollutant loads, habitat quality, and aquatic species abundance and diversity. Three numeric thresholds establish stream health based on percent impervious coverage within the watershed:

Table 1.1. Percent impervious coverage impacts stream health.

Impervious Coverage	*Stream Health*
<10%	Protected
10 to 30%	Impacted
≥30%	**Degraded**

Source: Davis and McCuen, 2005.

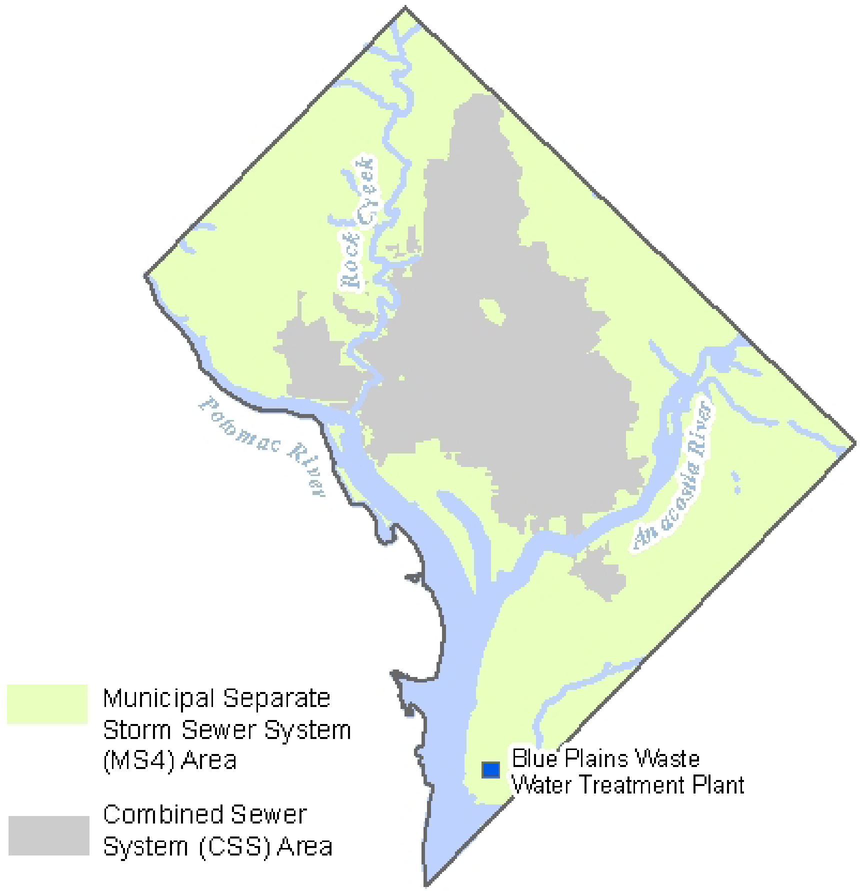
As stormwater runoff flows over impervious surfaces, pollutants are picked up from roadways, sidewalks, and roof tops. These materials eventually end up in streams and wetlands, resulting in damage to the natural ecosystems. Roadways alone play host to countless pollutants, and more are built each year. Over 200K hectares are being paved or repaved in the United States each year (Ferguson, 1996).

Approximately 70% of the water pollution in the U.S. comes from ‘nonpoint’ sources: the excess pollutants that runoff carries from eroding soil, parking lots, roads, and intensely maintained lawns; however, storm water runoff can become point source pollution as well. The EPA defines point source pollution as ‘any single identifiable source of pollution from which pollutants are discharged, such as a pipe, ditch, ship, or factory smokestack (Hill, 1997).

Combined sewer systems (CSO’s) are designed to collect rainwater runoff, domestic sewage, and industrial wastewater in one pipe. These systems usually transport all of their wastewater into a sewage treatment plant, where it is treated and then discharged into a nearby body of water, usually a lake or stream. But during periods of heavy rainfall, the water volume in a combined sewer system often exceeds the capacity of the system, resulting in the overflow and discharge of untreated wastewater directly into nearby streams, rivers, and other bodies of water (US EPA, 2011). Approximately 772 cities in the United States have combined sewer systems resulting in CSO’s, which are classified as point source pollution (US EPA, 2011).

The District of Columbia (DC) surrounds the Anacostia and Potomac Rivers, which feed into the Chesapeake Bay. As shown below, approximately 42% of DC is serviced by a combined sewer system.

Fig. 1.1. Map of the CSS and MS4 Areas in Washington, D.C.



Source: Casey Trees Green Built Out Model.

CSO discharges are common in DC. Eighty-five percent of all rain events are less than 2.5 cm and on average, rain events of 1.25 cm result in CSO's in some parts of DC (Casey Trees, 2007). This is largely due to impervious surface coverage of 42% of the land area. Of that, 15% is attributed to roof tops, 13% to roads, 5% each to parking lots and sidewalks with the remaining 6% attributed to driveways and alleys (Casey Trees, 2007).

The bay is unique in many respects. The bay itself is 313 kilometers long and ranges from 6 to 48 kilometers wide, with a total watershed area of 165,000 kilometers.

But the Chesapeake is relatively shallow, averaging only 6.4 meters (Horton, 2003). Across its watershed, the bay has less than one-tenth volume of water of most other coastal bays, limiting the ability to absorb and dilute whatever pollutants wash into it (Horton, 2003). This ratio equates to over 2700 square kilometers of land for every cubic kilometer of water received by the bay (Costanza and Daly, 1987). Efforts to restore the bay have been hampered due to such large land areas which contribute runoff and pollutants to a relatively small volume of water.

It is estimated that stormwater runoff contributes 10% of the N, 31% of the P and 19% of the sediment pollution (CBF, 2012). Stormwater runoff is arguably the leading cause of degradation to the bay watershed's small tributary streams. A survey conducted in Maryland in the mid-1990's concluded that approximately 90% of the state's 14,000 stream kilometers were in fair to poor health (Horton, 2003). Other studies indicate that hardening, or developing impervious surfaces, in as little as 10-15% of a stream's watershed significantly affects water quality (Horton, 2003), which supports data from Davis and McCuen (Table 1).

While a number of industries can be held liable for the deterioration of the bay - including agriculture, energy, and tourism – it is generally agreed upon that restoring the bay will only result from a collaboration between these and other groups. With that in mind, managing stormwater loads into the Chesapeake Bay watershed will make a significant impact on the health of the bay.

One way to manage stormwater is with green infrastructure, which the EPA defines as an approach to stormwater management that is cost-effective, sustainable, and environmentally friendly (US EPA, 2011). Green infrastructure works to harvest, infiltrate, reuse, and evapotranspire stormwater to incorporate it back into the water cycle. Green infrastructure also offers economic and social benefits including increased land values, reduced energy consumption, and pedestrian and bicycle access (US EPA, 2011). Before the fruition of green infrastructure, most storm water management options centered around retention ponds and concrete swales to send untreated storm water hastily into nearby bodies of water. Because of the limitations of on-site detention, infiltration of urban runoff to control its volume is a primary goal of green infrastructure. Without infiltration, municipalities in wetter regions of the country will experience drops in local groundwater levels, declining stream base flows (Wang et al., 2003), with diminished or stopped flows from springs feeding wetlands and lakes (Leopold, 1968; Ferguson, 1994). Because scientists now realize that traditional methods of retention and detention contribute to the degradation of rivers, lakes, and bays, green infrastructure is utilized at ever-increasing rates by local municipalities across the U.S. For example, in 1993 the city of Portland, Oregon offered a $53 per household subsidy in selected neighborhoods for those willing to redirect roof runoff into their lawns and gardens. As of 2005, forty-seven thousand households are participating in Portland's Downspout Disconnect Program, removing about 4.2 million cubic meters (4.2 billion liters) of stormwater per year from the Portland combined sewer system (PBES, 2006). Similarly, the city of Chicago created a Green Roof Grant Program and Green Roof Improvement Fund, which in 2007 received $500,000 from the city council as a Green Roof Improvement Fund. The Department of Planning and Development was then authorized to award grants of up to $100,000 to green roof projects within the Central Loop District (US EPA GI Case Studies, 2010) as a way of subsidizing green roof installations in the city. Green roofs are one example of green infrastructure that can be included into low impact designs to achieve environmental sustainability.

1.2 Green Roofs and Their Advantages

Green roofs are roofs that are vegetated. Green roofs are generally categorized as intensive or extensive, depending on the total depth of the system although the delineation between the two varies (Table 1.2).

Table 1.2. Example soil thickness of intensive and extensive green roofs as defined by different authors.

Intensive (cm)	*Extensive (cm)*	*Reference*
15-20	5-15	Kosareo and Ries (2007)
>50	N/A	Kohler et al. (2002)
15-35	3-14	Mentens et al. (2006)
>10	<10	Wong et al. (2007)
>30	N/A	Bengtsson et al. (2005)
>10	2-10	Graham and Kim (2005)

Source: Berndtsson, 2010

In general, extensive green roofs are roofs bearing vegetation growing in a thin layer of substrate while intensive green roofs utilize a much deeper substrate layer, increasing the capacity of the system to incorporate a more diverse plant palate; typically intensive roofs require more intensive post-installation maintenance. For the purposes of this dissertation, the following literature will refer exclusively to extensive green roofs. Green roofs are typically constructed with at least four layers on top of the standard waterproofing membrane: a drainage layer, filter fabric to prevent substrate loss, substrate, and plant material layers. In some green roof systems may include a root barrier fabric to prevent root penetration of the waterproofing membrane or a water retention fabric between the substrate and filter fabric.

1.2.1 Stormwater Mitigation

Green roofs offer many advantages, one being stormwater retention. Stormwater runoff is a serious problem in many cities, and most especially in densely urban areas. Green roofs can make major contributions to alleviating this problem, by reducing peak flow from runoff events by retaining a portion of the rain fall to cycle it back to the atmosphere via plant-based evapotranspiration. Kolb (2004) reported 45 – 70% of all rainfall can be recycled using green roofs, depending on substrate selection. VanWoert et al. (2005b) reported that green roofs retained 96% of the rainfall from rain events < 2mm, 82% of the rainfall from 2-6mm rain events, and 52% of the rainfall from >6mm rain events. Overall, 60% of the total rainfall was retained during the 430-day study. Teemusk and Mander (2007) reported 85% and 94% retention from two separate light rain events, respectively. Green roofs retain rainfall even at slopes as steep as 25%. Getter et al. (2007) showed that green roof platforms at 25% slope retained 75% rainfall with those set at 2% slope retaining 85%. Retention was higher with lighter rain events, consistent with results from VanWoert et al. (2005b) and Teemusk and Mander (2007).

In addition to reducing stormwater runoff quantity, green roofs may improve the quality of stormwater runoff, although there is less consensus on this from peer-reviewed literature. Although green roofs retain rain water and reduce negative effects of urban runoff by decreasing runoff volume and increasing lag to peak flow, they could have the potential to contribute to nutrient loading due to the organic portion of the substrate as well as from nutrient applications, which are typically recommended on a yearly basis (FLL, 2008). Studies attributing nutrient loading to green roofs have demonstrated different results. Green roofs increased phosphorous (P) in green roof runoff according to Bliss et al. (2009); but in other studies Berndtsson et al. (2006 and 2009), and Hathaway et al. (2008) green roofs had the lowest mean mass value for phosphate loading when compared to an asphalt roof in Michigan (Carpenter and Kaluvokolanu, 2011). There were no differences in runoff P compared to rainfall P in another study (Monterusso et al., 2004). Kohler et al. (2002) reported green roofs retained 67% of P, and retention increased from 26% in year one to 80% four years after installation.

Results for nitrogen (N) were also varied: Monterusso et al. (2004) reported increased nitrate-N for sedum green roofs and decreased substrate depths compared to native plantings and increased substrate depths. Similarly, Hathaway et al. (2008) reported increased concentrations and total N loading were higher for green roofs compared to rainfall. Carpenter and Kaluvakolanu (2011) reported no differences for nitrate-N from green roof effluent compared to rain fall and that a green roof was an N sink when compared to an asphalt roof. Bliss et al. (2009) found no difference in levels of N in green roof discharge compared to rainfall. Gregoire and Clausen (2011), Berndtsson et al (2009) and Kohler et al. (2002) all reported green roofs stored nitrate- N, but Gregoire and Clausen (2011) found green roofs to be a source of ammonium-N. Kohler et al. (2002) reported increased N storage with increasing roof maturity. Looking past contradictions within the literature, other point sources of pollution (CSO's, for instance) pose a greater threat to the health of the bay than potential green roof nutrient loading.

Regarding green roof runoff quality, a phenomenon to consider is the first flush effect – because particulates and organic compounds accumulate on and within green roof systems, the first flush of runoff after a rain event often contains more total nutrients, or a higher concentration of nutrients, depending on runoff volume. There was no first flush effect identified by Bliss et al. (2009); however, only first flush events were studied by Berndtsson et al. (2009). Similarly, runoff volumes affect nutrient concentration in the effluent. Moderate runoff events resulted in concentrations of total N and P greater than that of a bituminous roof while heavy rain events concentrations were lower but total loading was higher (Teemusk and Mander, 2007). Concentrations were also higher during snowmelt, which the authors attributed to decreased runoff volume. In short, the effects of green roofs on discharge water quality are not straightforward or well documented.

With regards to the overall goal of reduced stormwater runoff volume, a low density of green roofs will have little impact; however, a study (Casey Trees and LimnoTech. 2007) demonstrated the effects of greening large portions of roofs in Washington, D.C. The Green Build Out Model compared intensive and moderate greening scenarios within the district with a goal of reducing (CSO) discharges into the Anacostia River. Combined sewer overflow discharges are the result of excess stormwater flooding the sewer system during heavy rain events and cause untreated sewage to flood into the Anacostia and nearby feeder streams. The intensive greening scenario assumed green roof installation wherever it was physically possible; the moderate greening scenario considered green roofs where it was practical and reasonable to do so (Casey Trees, 2007). In the model, green roof area was assumed to be equal to the building footprint minus 25% of the rooftop area needed for HVAC, access, and maintenance. With 75% coverage and the assumption of no structural or historic preservation issues, the most green roof coverage possible in D.C. according to the model is approximately 18 million square meters. Based on the model, installing 5.5 million square meters of green roofs in DC would reduce combined sewer overflow discharges by 1.6 billion liters (19%) each year. Installing only 3.3 million square meters of green roofs would result in a reduction of 359 million liters (4.2%) annually (Casey Trees, 2007).

1.2.2 Green roofs and noise and air pollution

Green roofs offer further benefits, including a reduction in noise and air pollution. Van Renterghem and Botteldooren (2009) reported a numerical evaluation of reductions in noise pollution by green roofs. The authors reported less-sloped green roofs achieve the best reduction in noise pollution. In 2011, Van Renterghem and Botteldooren reported a reduction in noise pollution of over 10 decibels in a study of 5 roofs pre- and post-green roof installation. Because these measurements were taken under dry conditions, the authors assert even higher reductions in soundwave transference under wet conditions.

Currie and Bass (2005) estimated that 109 ha of green roofs in Toronto could remove a total of 7.87 metric tons of air pollutants annually using the Urban Forest Effects

(UFORE) Model. The same model was used by Deutsch et al. (2005) in a study of Washington, DC which showed that 58 metric tons of air pollutants could be removed if all the roofs in the city were greened. Johnson and Newton (1996) estimate 2000 m^2 of uncut grass on a green roof could remove up to 4000 kg of particulate matter. Extrapolated out using 0.01 g particulate matter produced by automobiles for every mile driven, one square meter of green roof could offset the annual particulate matter emissions of one car (City of Los Angeles, 2006). In Singapore, Tan and Sia (2005) reported sulphur dioxide and nitrous acid were reduced 37% and 21%, respectively directly above a green roof.

1.2.3 Increased Membrane Lifespan

The benefits of green roofs are not limited to the natural environment. The installation of green roofs can increase the lifespan of the standard waterproofing membrane, which is installed on traditional and green roof systems. Approximately 50 German tar paper green roofs (TPG) built between 1880 and 1914 survived both World Wars and continue to thrive (Kohler, 2010). Although the construction materials and methods have evolved over time, the functionality is equivalent. Kohler reported that either primitive 19th century materials or complex modern materials provide long-lasting roof options. The TPG roofs demonstrated professionally-installed waterproofing membrane can last in excess of 100 years when combined with a green roof system (Kohler, 2010). The waterproofing membrane of a traditional roof system breaks down rapidly due to UV radiation, and has a life span of approximately 20 years (Carter and Keeler, 2008).

1.3 Green Roof Substrates

Substrate refers to the material in which plants are grown, and is synonymous with 'media', 'medium', 'vegetation support course' and in some literature 'soil'. Green roof substrates are often a mixture of organic and inorganic materials, often combined to achieve properties pertinent to plant survival as well as the designed roof function. The substrate is arguably the most important element in a green roof system because the majority of the water holding capacity of the system is dependent upon the substrate physical properties. Substrates must be consistent and reproducible while providing adequate air space, water holding capacity, and support for the plants (Handreck and Black, 2002) while maintaining a bulk density appropriate for the load bearing capacity of the roof structure. For this reason, many substrate formulations are composed primarily of lightweight heat-expanded mineral materials such as clay, shale, or slate. This inorganic portion is comprised of particles of varying sizes and composition. These particle sizes and mineral compositions largely determine the nature and behavior of the substrate: the porosity, the relationship with fluids and solutes, as well as its compressibility, strength, and chemical properties such as cation exchange capacity.

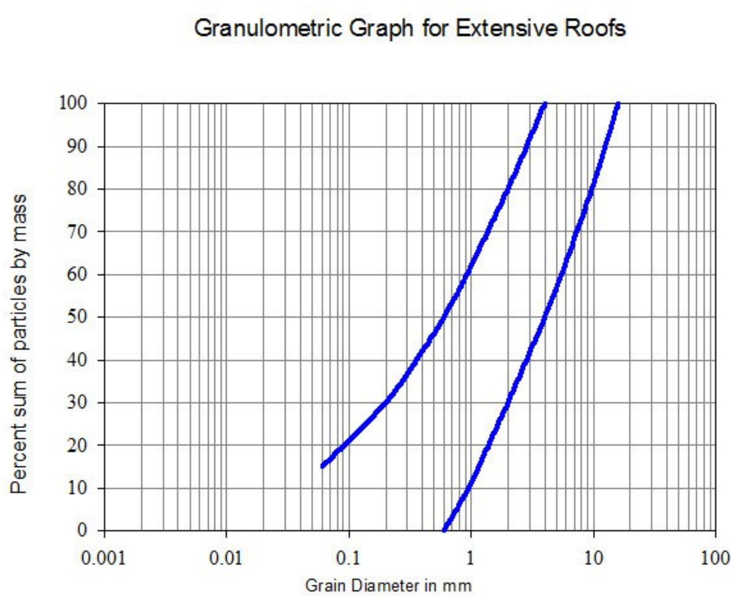
Currently there is no universally accepted standardization for classifying particle sizes. For example, the classification set by the United States Department of Agriculture differs from the International Soil Science Society (ISSS) classification, as well as that of the American Society for Testing Materials (ASTM) and the Massachusetts Institute of Technology (MIT). Soil engineers typically follow different standards than soil scientists, and inconsistencies can be confusing (Hillel, 2004).

Measuring and classifying the complete distribution of particle sizes in a sample of a particular substrate yields the particle size distribution. Particle size distribution is arguably the most important substrate physical property because it determines the physical amount of water a substrate can hold through adhesive and cohesive forces (Handreck and Black, 2002). It also largely determined the porosity of the substrates. The void space created by substrate particles resting against each other is referred to as pore space. The pores range in size based on the particle size distribution of the substrate. These pores hold oxygen and water necessary for plant growth and development. A substrate composed primarily of large particles will have large pores; water will flow rapidly through the substrate profile and the majority of the pore space will be occupied by air (Handreck and Black, 2002). Granular drainage layers are composed primarily of large particles to expedite the flow of water away out of the system. Conversely, a substrate composed primarily of small particles will have small pores; water will flow slowly through the profile. Some pore spaces will hold water (generally smaller or micro pores) while others will hold air (generally larger or macro pores). The proportion of air to water within the substrate profile is integral to plant survival and for this reason guidelines for particle size distribution are available for the green roof industry. Green roof substrates should be comprised of a mix of large and small particles to provide adequate air space and water holding capacity.

The Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL, 2008) is a German landscape industry manual containing guidelines for the planning, execution, and upkeep of green roofs. These German guidelines have been adopted nearly world-wide and are used as the industry standard when developing new substrate formulations. The FLL has set standards for the recommended particle size distribution, percent air and water, and other substrate physical properties. Substrate particle size distribution for extensive green roof substrates should fall between two distribution curves, shown in Fig. 1.2 (FLL, 2008).

Although water holding capacity is largely determined by substrate particle size distribution, the FLL also set standards for the maximum water holding capacity. For extensive substrates with a separate drainage layer, the FLL recommends water holding capacity to be ≥ 35% by volume of the substrate. For single layer extensive green roofs, water holding capacity is recommended to be ≥ 20% by volume. The maximum water holding capacity should not exceed 65% by volume in any green roof substrate to avoid water logging (FLL, 2008).

Fig. 1.2 Particle size distribution range for extensive and single-layer extensive green roof substrates.



1.3.1 Substrate Organic Matter

The FLL also sets standards for substrate composition, although these have changed over the years. In 2002, the FLL's specifications for total organic content for extensive systems were based on density. For substrates with density ≤0.8 (units not given but assumed to be g/L), total organic matter should be ≤8% by mass. For substrates with bulk densities >0.8, total organic matter should be ≤6% by mass (FLL English Version, 2002). For extensive green roofs, the recommendation is ≤65 g/L organic matter, although it is noted a greater proportion of organic matter may be required based on plant selection (FLL English Version, 2008). The change from percent organic matter to a mass: volume ratio leaves room for inquiry. While substrate recommendations may be given based on weight and density due to the load bearing requirements of roofs, horticultural substrate formulations are measured and specified based on volumetric ratios. This discord creates confusion within the green roof industry, which is evolving into required collaborations between engineering and horticultural professionals alike. Furthermore, FLL recommendations are based on green roof systems in Germany. Special attention should be paid to varying climates and weather patterns. The recommendations which create the best green roof systems in Germany may not create the best performing green roof systems elsewhere, for example in the Mid-Atlantic United States.

Substrate composition varies in research studies. A study by Teemusk and Mander (2007) utilized 66% lightweight aggregate, 30% humus, and 4% clay as an extensive substrate. Berndtsson et al. (2009) studied an extensive green roof composed of crushed lava, natural calcareous soil, clay, and shredded peat with a total organic content of 5%. Substrate composition was not detailed in a report by VanWoert et al. (2005a); although a later study by Getter et al. (2007) utilizing the same experimental platforms reported organic contents at installation (the time of the VanWoert study) and at maturity (the time of the Getter study) as 2.33% and 4.25% respectively, based on a loss on ignition test. Gregoire and Clausen (2011) reported 75% expanded shale, 15% composted biosolids, and 10% perlite (GreenGrid® Northeast Extensive Media). A study of a green roof at the University of Auckland reported three different substrate formulations, all based on volumetric ratios, in which the authors reported no differences in stormwater retention based on substrate composition or depth (Voyde et al., 2010). Emilsson (2008) compared two generic media composed primarily of crushed roof tiles against a third media, Roofsoil, and found vegetative cover up to 80% after one year. The report exemplified the potential for alternative green roof construction materials and methods for the Swedish green roof industry.

Although organic matter provides nutrients and additional water holding capacity in soil systems (Hillel, 2004), too much organic matter can result in hydrophobicity or water repellency which are caused when inorganic soil particles become coated with hydrophobic organic matter (Quyum, 2000). Although organic material is the direct cause of soil hydrophobicity, the amount of organic carbon and degree of hydrophobicity are not correlated (De Bano, et al. 1976). Because hydrophobic soils repel moisture, water generally runs off for an extended period of time, until the organic coating can be broken. The initial infiltration rates of hydrophobic soils are very slow or non-existent due to very high initial liquid-solid contact angle (De Bano, 1981; Wallis et al., 1991). Because a green roof's capacity to hold stormwater and delay runoff depends solely on the substrate, hydrophobicity is a soil property that should be avoided.

Recognition of different climates, weather conditions, and material availability may have led to different countries and municipalities creating independent green roof guidelines. Despite these efforts, only some region-based – or country specific – recommendations are available (Voyde et al., 2010; Fassman et al., 2013) and multiple substrate formulations continue to be recommended. The Introductory Manual for Green Roofs published by the Canada Public Works departments suggests a growing medium of 1/3 sand, 1/3 pumice, and 1/3 Humus Builder (a product comprised of composted wood and composted fertilizer), although wood sources are not specified, nor are whether the ratios are based on weight or volume. Particle size distribution is not addressed at all in the Canadian manual (Canada Public Works, 2002). The 2010 Sydney City Council Green Roof Resource Manual recommends humus, citing the FLL's 6-8% organic matter guidelines in one paragraph, but then cites research that suggests 75-80% inorganic with 15-20% organic matter (Sydney City Council, 2010). The Seattle specifications require 4% organic matter by mass for single-course systems, 6% for extensive systems, and 8% for intensive systems, utilizing the loss on ignition test (City of Seattle, 2010). Clearly there are no scientifically tested ratios of substrate components in extensive green roofs. Additionally, it is likely that one recommendation will not be the most efficient or effective substrate mixture in every climate. For the Mid-Atlantic region no performance-based work has been reported on the use, amounts, or types of organic matter for extensive green roof formulations.

1.3.2 Inorganic Substrate Materials

The FLL recommendations are also not specific with regard to the primary substrate component, the inorganic portion. Lightweight aggregates are used often in North America; usually heat-expanded mineral materials which offer decreased bulk density, which is important in roof load considerations. One environmental disadvantage to heat-expanded mineral materials is the extreme heat energy requirements which results in large carbon footprint. Generally, expanded clays must be heated to extreme temperatures. A report by Elliott (2007) investigated the carbon footprint of expanded mineral materials commonly used in green roof substrates. One cubic yard of expanded material expends 1.7 million BTU's (Elliott, 2007). This number includes the production process from the point of mining to the point of shipping the final product. One BTU is the energy that raises one pound of liquid water by one degree, or also the energy released by one match. One point seven million BTU's can also be generated by 36.5 kg propane. Burning 1kg propane releases 3kg CO_2. Therefore, burning 36.5 kg propane (which generates 1.7 million BTU's, or the amount of heat energy utilized in creating 1 yd^3 expanded aggregate) creates 110 kg CO_2. In 2012 the Expanded Shale, Clay, and Slate Institute independently reported the embodied energy required to manufacture expanded mineral lightweight aggregates verifying Elliott's estimations (ESCSI, 2012). The ESCSI report was based on a survey of 13 plants across North America.

The carbon cost associated with an expanded slate substrate is equivalent to 0.44 kg C/kg substrate manufactured. Getter et al. (2009) reported a 6 cm deep substrate with a density of 1600 kg/cubic meter has 5.7 kg C/ m^2. The entire green roof system has a carbon cost of 6.6 kg C/ m^2, meaning 86% of the carbon cost of a green roof is attributed to the substrate. In 2013 Washington, DC had a reported 232,000 m^2 green roof (2.5 million ft^2) (Peck, 2013). Assuming a 6 cm substrate depth with Getter and Rowe's density assumptions, the district's green roofs have a carbon equivalency of consuming over 560,000 liters of gasoline, or burning 635,000 kg of coal. It will take over 33,000 tree seedlings 10 years to sequester the carbon created from the manufacturing of the district's green roof substrates (Carbon Equivalency Calculator, EPA.gov). For this reason, alternatives have been investigated as a replacement or supplement to heat-expanded materials in order to decrease the embodied energy of green roofs, including scoria and crushed brick.

Scoria is a porous basaltic to andesitic lava rock. The porosity of scoria is due to the escape of volcanic gases during eruption (USGS, 2011). Scoria is heavier than pumice so it does not float, and it is very durable. In volcanic regions of the U.S., scoria is often quarried and used as a base material for roads (USGS, 2011). While scoria has not been reported as a green roof substrate component, it is known to sustain long-term plant growth and increase species diversity in mine reclamation projects (Prodgers, 2009). A ten-year study of a southeast Montana coal mine compared plant performance in topsoil, scoria, and spoil applied over exposed sodic soil after mining operations were completed. The study found that topsoil had more plant cover than spoil and scoria treatments; however, a drought in 2006 resulted in more plant cover in scoria than in topsoil (Prodgers, 2009). Scoria was the premier plant species diversity substrate; initially seeded with 12 species, 23 species were present after 10 years. Some of the recruited native species were rarely ever seen in revegetation efforts (Prodgers, 2009). Treatment analysis found scoria to have particle sizes equivalent to a sandy loam.

Crushed brick is the U.K. green roof industry standard substrate base (Molineux et al., 2009). The U.K. green roof industry is built on two different systems: *Sedum spp.* mats providing an instant green effect, and substrate-only system composed of waste materials (broken bricks or demolition waste) to mimic natural brownfield sites. These 'brown' roofs are usually constructed to increase biodiversity and create bird or invertebrate habitat (Molineux et al., 2009). The same study reported seedlings grown in crushed brick amended with bark compost (the control treatment) yielded suitable plant height and biomass, suggesting crushed brick could be utilized a substrate component for traditional green roof systems planted with seedlings in North America. Crushed brick in the U.K. is reported to be sourced back to one factory (Molineux et al, 2009); the demand for crushed brick is relatively high leading to a high cost for the end user. Because the material is sourced from a single factory, the carbon footprint associated with shipping are extremely high (Molineux et al., 2009). In the United States, however, waste brick may be available in certain regions and should be investigated as a potential green roof substrate component.

The carbon footprint associated with substrate materials is important, as is the substrate density, which is the parameter used to determine whether or not a roof structure can bear the weight of a green roof. Lightweight materials decrease the total density, which is helpful in retrofitting buildings without the load capacity. If the ability of a roof structure to sustain a green roof is dependent on the weight of the green roof system, then a lighter-weight substrate is more desirable. A substrate component that lowers the density of the substrate without changing the physical properties is crumb rubber. Crumb rubber (CR) is a granulized rubber product derived from waste tires. Granule size is typically one-quarter inch (six millimeters). Crumb rubber has been investigated to amend substrates in horticultural production (Newman et al., 1997), turf grass, and playground installations (Groenevelt and Grunthal, 1998). Solano (2010) investigated crumb rubber amendments for green roof substrates. Zinc (Zn) was found to leach from crumb rubber in quantities that could negatively affect plant growth; however, when paired with a high cation-exchange-capacity substrate, crumb rubber could be utilized up to 30% by volume without Zn toxicity to plants. Further testing is necessary to determine the possibility of long-term Zn leaching even with high cation exchange capacity substrates. Crumb rubber may be a useful substrate component; however, its use should be further proven through long-term substrate performance analyses.

1.4 Green Roof Plants

As previously discussed, not all plants are appropriate for green roof systems. The decreased substrate thickness immediately provides a challenge for plants in terms of water availability, not to mention growing plants under high environmental stress (high temperature, light and wind) conditions on roofs. Periods of drought or excessive rainfall also hinder plant health. Generally, the most successful green roof plants are low-growing, shallow-rooted perennial plants that are tolerant to various stressors, e.g. heat, cold, sun, wind, drought, salt, insect, and disease (Snodgrass and Snodgrass, 2006). Adjusting substrate depth can have a positive impact on plant survival and growth. Durhman et al. (2007) reported increased substrate depth results in faster plant coverage. Similarly, VanWoert et al. (2005) reported increased *Sedum spp.* biomass accumulation in 6 cm substrate compared to 2 cm substrate depth (with and without moisture mat) when watered at least every 14 days.

A current trend in the green roof industry is the incorporation of native species into green roof plant palates (Lundholm et al., 2009; MacIvor and Lundholm; 2011; Monterusso et al., 2005). Monterusso et al. (2005) reported only four of eighteen species native to the region were suitable for unirrigated extensive green roofs; conversely all nine *Sedum* species evaluated were determined to be suitable unirrigated extensive green roofs. DeLong (2014) reported the Maryland native plant *Tradescantia ohioensis* demonstrated a comparable ability to store stormwater and increase biomass when compared to traditional *Sedum* species in a study in the Mid-Atlantic region.

Given the harsh conditions to which green roofs are exposed, it is the interaction of substrate properties, plant species, and environmental conditions that determine the overall success of a green roof system. "Success" can be perceived multiple ways – the presence of green vegetation, a measurable decrease in storm water runoff from the rooftop, or a property manager that is pleased with the aesthetic value of the roof, to name a few. The factors that dictate the delineation of failure and success are likely driven by the design intent of the green roof; however, regardless of the measure applied to the system, the relationship between plant, substrate, and environment will ultimately determine the success of the green roof.

1.5 Statement of Research Objectives

The purpose of this research was three-fold. The first research objective was to explore the durability of standard heat-expanded substrate materials to freeze-thaw stress. The Mid-Atlantic region can experience numerous freeze-thaw cycles each winter and currently no work has been reported regarding substrate durability. The second research objective was to explore the effects of green roof substrate composition on water retention and matric potential, especially the effects of increased volumetric proportions of substrate organic matter on plant available water. Finally, the third objective was to quantify the effects of green roof substrate composition on plant growth, evapotranspiration, and stormwater retention. This objective was explored in a controlled-environment growth chamber study and in a platform-scale field study.

Chapter 2: Evaluating ready-to-plant commercial green roof substrates for durability to freeze/thaw cycles

2.1 Introduction

Green roofs are gaining popularity as storm water management tools (Kohler *et al.,* 2002; Villarreal and Bengtsson, 2005; Berndtsson *et al.*, 2006; Getter *et al.*, 2007; Voyde *et al.,* 2010) and are increasingly being incorporated into regulatory policies [Washington, D.C. (District Department of Environment, 2013); the state of Maryland (Maryland Department of Environment, 2009), and Auckland, New Zealand (Fassman-Beck and Simcock, 2013)]. Although green roofs can vary in aesthetic and design, systems designed for storm water retention are often thin (defined below), extensive green roofs. Green roofs are generally classified based on substrate depth, although the specific depths differentiating extensive and intensive systems are undefined: Kohler *et al.* (2002) designated intensive substrate depth as greater than 50 cm, while Mentens *et al.* (2006) site 3-14 cm substrate depth as extensive and 15-35 cm substrate depth as intensive. Wong *et al.* (2007) are more conservative, reporting intensive substrate depth to be any depth greater than 10 cm. Nonetheless, it is agreed that extensive systems are typically lower-maintenance designs - usually a layer of mineral-based substrate planted with drought- and heat-tolerant succulent species.

The standards for green roof system design and installation can vary by municipality and geographic location (Canada Public Works Guidelines, Oberlander *et al.*, 2002; Seattle, Washington, Seattle Stormwater Code, 2009; Sydney City Council Green Roof Resource Manual, 2010); however, these generally borrow heavily from the

Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL, 2008). The FLL contains the German landscape industry's guidelines for the design, installation, and maintenance of green roof systems and addresses a range of system parameters from the drainage layer to vegetation type. While the FLL is comprehensive, it is by no means complete.

One guideline set by the FLL is substrate particle size distribution (PSD), which describes the percentage (by weight) of particles falling within various particle diameters. This is arguably the single most important substrate physical metric, as it determines the mixture of particle sizes, which in turn defines substrate porosity, and which also greatly affects substrate characteristics such as water retention, water holding capacity, and air-filled porosity. Large particles tend to dictate high porosity (higher proportion of large sizes) while small particles dictate lower substrate porosity and higher water-holding capacity (Handreck and Black, 2007). It is the ratio of large to small pores which ultimately characterizes the water holding capacity (WHC) and air-filled porosity (AFP) of the substrate. Water is primarily held by small or micropores, termed 'capillarity' while free drainage and air-filled porosity is facilitated by large pores (Drzal *et al.*, 1999). A green roof substrate should have an appropriate ratio of large to small particles to allow adequate water holding capacity to support plant growth and effective storm water retention while also permitting sufficient air movement for gas exchange in the root zone, as roots require a constant supply of oxygen (Raviv *et al.*, 2002).

The FLL guidelines for PSD are indicative of the importance of maintaining this balance and are thorough; FLL recommendations are very specific based on the green roof design (i.e. single- or dual-course extensive and intensive designs each have different PSD recommendations). The FLL guidelines also include a recommendation for frost resistance (10.2.3, 2008 FLL):

> "The frost resistance of the mineral structural materials must be ensured by the manufacturer. The frost resistance requirements of aggregates …… are based on materials and components subjected to high levels of static and/or dynamic stress….."

The inclusion of frost resistance suggests the intent to maintain substrate PSD and the physical properties that are dependent on PSD. Degradation of particles would affect the PSD, which would eventually change water holding capacity, air-filled porosity, and other hydraulic properties over time. Continual particle degradation could result in substrates which hold excessive amounts of water, resulting in decreased stormwater retention capacity (via increased dry down time) and inhibition of root function and plant growth. Although its inclusion within the FLL is significant, no methodology for determining frost resistance and no allowable limits for changes in PSD are suggested.

Expanded minerals (typically clay, shale, or slate) are the most common mineral component of ready-to-plant green roof substrate blends manufactured in North America. Commonly referred to as lightweight aggregates, these materials are produced by heating the minerals in a rotary kiln at temperatures that range between 1050 and 1200°C to induce an expansion within the mineral layers as gases are liberated (Harmon, 2000). Lightweight aggregates have internal porosity, so water can be absorbed within the particles after expansion. It is this internal water-holding capacity that provides the greatest potential for particle degradation: intra-particle water expands as it freezes, creating outward stress on the interior walls of the particle. It is conceivable that lightweight aggregate particles could fracture due to freeze-thaw weathering, especially in climates experiencing significant temperature fluctuations throughout the winter months. Unfortunately, no literature is currently available addressing green roof substrate durability in North America. Furthermore, no methodologies are available for testing green roof substrate durability. Because manufacturers are responsible for guaranteeing frost resistance, the methods used are not reported and comparisons between various manufacturers are not reliable. This work addresses three basic hypotheses for green roof substrates commonly used in the Mid-Atlantic region of the United States.

1. H_O: Ready-to-plant commercial substrate blends meet FLL-based guidelines for particle diameter ranges when obtained direct from the manufacturer.

   H_A: Ready-to-plant commercial substrates blends do not meet FLL-based guidelines for particle diameter ranges when obtained direct from the manufacturer.

2. H_O: Ready-to-plant commercial substrate blends maintain particle size distribution after being subjected to 30 freeze-thaw cycles.

   H_A: Ready-to-plant commercial substrate blends do not maintain particle size distribution after being subjected to 30 freeze-thaw cycles.

3. H_O: Substrates of established green roofs (3-7 years post-installation) in the Mid-Atlantic region, representing commonly used ready-to-plant blends, fall within FLL-based guidelines for particle diameter ranges.

   H_A: Substrates of established green roofs (3-7 years post-installation) in the Mid-Atlantic region, representing commonly used ready-to-plant blends, do not fall within FLL-based guidelines for particle diameter ranges.

2.2 Materials and Methods

Three commercial green roof substrates were obtained directly from the manufacturers. The PSD from 'as received' and 'after 30 freeze-thaw cycles' were then determined for each blend. Particle size distribution ranges for both treatments were compared to FLL-recommended guidelines; independent student t-tests were used to compare 'as received' to 'after 30 freeze thaw cycles' for each particle range in each blend, to determine whether or not any significant ($p<0.05$) degradation had occurred within any particle diameter range, as a result of freeze-thaw weathering.

2.2.1 Commercial Substrate Blends

Three ready-to-plant commercial green roof substrate blends were acquired between September 2011 and April 2012. One blend was shipped as a 2 cubic foot sample for lab analysis direct from the manufacturer. A second blend was shipped as a 3 cubic yard bulk order direct from a local blender of the manufacturer's choice. The bulk order arrived in two 1.5 cubic yard super sacks, and 11 L of each super sack were taken and mixed thoroughly to create a 22 L representative sample for lab analysis. The third blend was received as a 1.5 cubic yard bulk order direct from a local blender of the manufacturer's choice. Twenty-two liters of the third blend were taken and mixed thoroughly for lab analysis. All three blends were stored in 22 L air tight containers in walk-in cold storage at 6°C for the duration of the study, to slow any microbial-based degradation of the substrate organic components.

Thirty 100 mL replicate samples were taken from each blend. Fifteen replicates of each blend were immediately oven-dried at 105°C in a Thelco Laboratory Oven (Precision

Instruments, Winchester, VA) for 48 hours prior to sieving. Replicates were sieved with ASTM sieves #8, 16, 30, 45, 60, 100, and 200 (E.H. Sargent & Co., Chicago, IL) for 20 minutes per sample using a Meinzer 11 shaker (CSC Scientific Company, Inc., Fairfax, VA). The percent weight of particles retained by each sieve size was averaged across the 15 replicates to obtain the average gravimetric percent of particles falling within each particle diameter range. The collective distribution of particles retained by each diameter range constituted the PSD for each blend.

The remaining replicates were placed in aluminum tins with 30 mL deionized water, and placed in a Thermo Scientific (Waltham, MA) laboratory freezer at -28° Celsius overnight. Samples were moved to room temperature the following morning for 8 hours, completing one freeze-thaw cycle. A total of 30 cycles were performed; after the tenth and twentieth cycles respectively, an additional10 mL deionized water was re-added to each sample to account for evaporative losses. It has been reported that Baltimore, Maryland experiences an average of 88 freeze-thaw cycles per year (NIST, 2012) although unpublished data shows substrate layers in experimental green roof plots at the University of Maryland experienced anywhere from 8 to 22 freeze-thaw cycles for the 2012-2013 winter. We believe 30 cycles are representative of the minimum number of freeze-thaw cycles experienced by established roofs in the region (at least 3 years post-installation). I chose 30 freeze-thaw cycles because it represents the approximate number of freeze-thaw cycles that a Mid-Atlantic green roof system would experience during establishment (at least three years). Also, I assumed 30 freeze-thaw cycles would be enough to identify any significant particle degradation without unnecessarily extended the time for the study (each cycle took one day).

At the end of the thirtieth cycle, replicates were oven-dried at 105°C for 48 hours prior to sieving as previously described. The resultant PSD for 'as received' and 'after freeze-thaw' was plotted for each blend against the FLL-recommended granulometric distribution for extensive green roof substrates. Gravimetric percentages of each particle diameter range for each treatment were compared using independent student t-tests (α=0.05) to determine significance (α=0.05) of losses or gains at each particle diameter range (SAS version 9.3, SAS Institute INC, Cary, NC).

2.2.2 Established Green Roof Sampling

Substrates from five established (3-7 years post installation) extensive green roofs in the Mid-Atlantic region were sampled between April and June 2012 to determine existing substrate PSD for established green roofs. Four roofs represented the three commercial substrate blends investigated in Section 2.1; the fifth roof was planted with a blend that was created and mixed to specification by the roof contractor who was awarded the installation. One sample per thousand square feet of roof area was taken from each roof and homogenized to reduce variability associated with roof microclimates. Plant roots were hand-picked from the homogenized samples using tweezers. Five replicates were taken from each homogenized sample and oven-dried and sieved as described in section 2.1. The PSD for each established roof was plotted and compared to FLL-recommended granulometric distribution curves for extensive green roofs, as previously described.

2.3 Results and Discussion

2.3.1 Commercial Substrate Blends

Every blend demonstrated significant particle loss (gravimetric percent) in at least one particle diameter range and a significant gain in the smallest particle diameter range (Table 2.1) indicative of particle degradation. In addition, none of the commercial blends analyzed in this study met FLL recommendations for particle diameter ranges when obtained direct from the manufacturer (Figures 2.1, 2.2, and 2.3).

Table 2.1. Gravimetric percentages of substrate particles falling within designated particle ranges of three ready-to-plant commercial green roof substrate blends as received from the manufacturer and after 30 freeze-thaw cycles. Asterisks indicate significance (*p<0.05, **p<0.01, ***p<0.001).

ASTM Sieve No.	Mesh size (mm)	Blend 1					Blend 2					Blend 3				
		As Received		After Freeze-Thaw			As Received		After Freeze-Thaw			As Received		After Freeze-Thaw		
8	**>2.4**	47.68	±2.61	43.84	±1.04	***	73.87	±1.01	68.22	±1.58	**	38.82	±1.52	36.93	±2.17	
16	**1.2-2.4**	20.96	±0.98	20.89	±0.41		9.44	±0.54	10.18	±0.80	***	16.14	±1.03	18.03	±1.57	*
30	**0.6-1.2**	12.09	±0.70	13.84	±0.25	***	7.84	±0.35	10.09	±0.64	**	15.96	±0.39	17.45	±1.98	**
45	**0.4-0.6**	7.09	±0.37	6.64	±0.16	***	3.44	±0.12	3.70	±0.25		8.71	±1.20	5.75	±0.41	**
60	**0.3-0.4**	3.20	±0.21	2.75	±0.18	***	1.36	±0.58	1.87	±0.09	**	4.55	±0.69	3.22	±0.19	**
100	**0.2-0.3**	4.14	±0.27	4.00	±0.29		1.26	±0.06	2.14	±0.08	***	4.77	±0.81	6.29	±0.21	**
200	**0.1-0.2**	3.08	±0.21	4.86	±0.38	***	1.17	±0.89	1.44	±0.08		5.97	±1.33	7.72	±0.45	***
pan	**<0.1**	1.76	±0.45	3.20	±0.57	***	1.62	±0.88	2.36	±0.10	***	4.39	±0.33	6.54	±0.26	***

Figure 2.1. Particle size distribution of a ready-to-plant commercial extensive green roof substrate (Blend A) manufactured in North America, plotted against FLL guidelines. Red lines indicate "as received" particle size distribution while blue lines indicate "after 30 freeze-thaw cycle" particle size distribution. Means and SE (n=5) for each particle diameter range are presented.

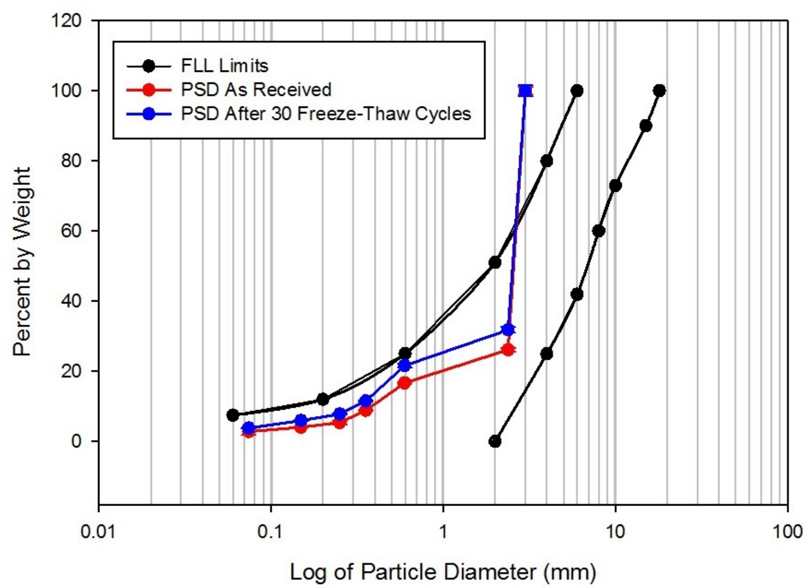


Figure 2.2. Particle size distribution of a ready-to-plant commercial extensive green roof substrate (Blend B) manufactured in North America, plotted against FLL guidelines. Red lines indicate "as received" particle size distribution while blue lines indicate "after 30 freeze-thaw cycle" particle size distribution. Means and SE (n=5) for each particle diameter range are presented.

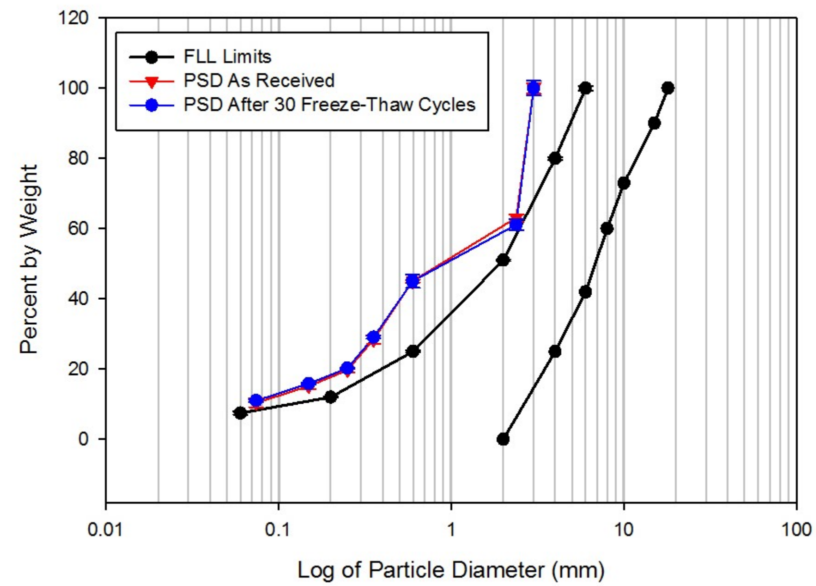
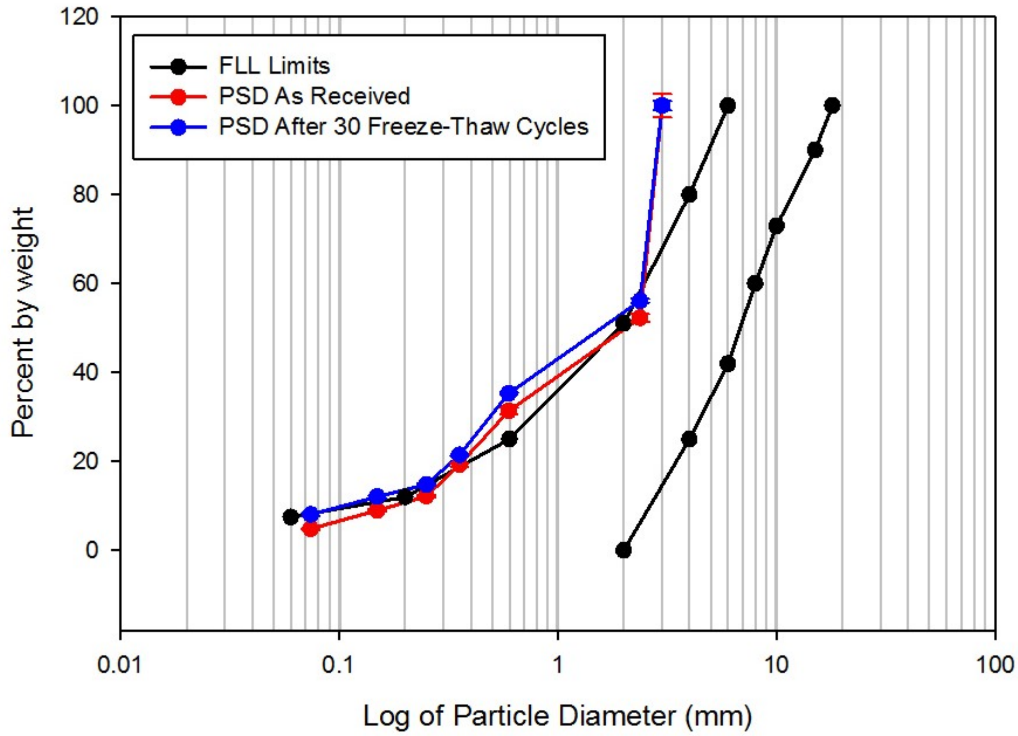


Figure 2.3. Particle size distribution of a ready-to-plant commercial extensive green roof substrate (Blend C) manufactured in North America, plotted against FLL guidelines. Red lines indicate "as received" particle size distribution while blue lines indicate "after 30 freeze-thaw cycle" particle size distribution. Means and SE (n=5) for each particle diameter range are presented.



Every blend analyzed for freeze-thaw weathering was composed primarily of heat-expanded minerals (slate, shale, or clay). We hypothesize water entered the expanded mineral particles as expected, but upon freezing expanded beyond the limits of the particle's inner porosity, resulting in fracturing and eventual particle degradation.

2.3.2 Established Green Roof Sampling

None of the roofs sampled met FLL guidelines for extensive green roof substrate granulometric distribution (FLL, 2008) (Table 2.2). When plotted against the FLL particle diameter curve limits, each substrate demonstrated a decline in the recommended particle size distribution (Figures 2.4, 2.5, 2.6, 2.7, and 2.8) representative of too many small particles, or not enough large particles. The substrate particle size distribution of the Roof A sample fell completely outside of the recommended guidelines. While all of the roofs fell partially outside of the FLL PSD recommended range, we believe Roof D may have met those guidelines if we had added a larger sieve (i.e. ASTM Sieve #4) to the analysis to further separate large particles.

Table 2.2. Gravimetric percentages of substrate particles falling within designated particle ranges of substrates sampled from five green roofs ranging from 3 to 7 years post-installation in the Mid-Atlantic region. Means (n=5) are presented for each particle diameter range.

ASTM Sieve No.	Mesh size (mm)	Roof A		Roof B		Roof C		Roof D		Roof E	
8	**>2.4**	21.80	±1.04	35.88	±2.49	55.16	±1.34	76.76	±2.26	52.04	±2.24
16	**1.2-2.4**	29.95	±0.87	15.98	±1.43	17.56	±1.19	10.51	±1.43	11.51	±0.99
30	**0.6-1.2**	16.49	±0.43	24.95	±1.15	11.69	±0.51	6.39	±0.52	13.44	±1.11
45	**0.4-0.6**	9.09	±0.28	11.96	±0.84	4.55	±0.28	2.28	±0.11	9.00	±0.38
60	**0.3-0.4**	4.72	±0.18	4.17	±1.10	2.44	±0.17	0.79	±0.11	3.45	±0.14
100	**0.2-0.3**	5.68	±0.13	4.88	±0.12	3.22	±0.25	1.45	±0.17	4.30	±0.94
200	**0.1-0.2**	6.29	±0.38	2.29	±0.12	2.96	±0.24	1.05	±0.12	2.40	±0.49
pan	**<0.1**	5.97	±0.43	2.39	±0.15	2.41	±0.16	0.78	±0.06	1.35	±0.01

Figure 2.4. Particle size distribution from a three year old Mid-Atlantic green plotted against FLL-recommended granulometric distribution for extensive green roofs. Means and SE (n=5) for each particle diameter range are presented.

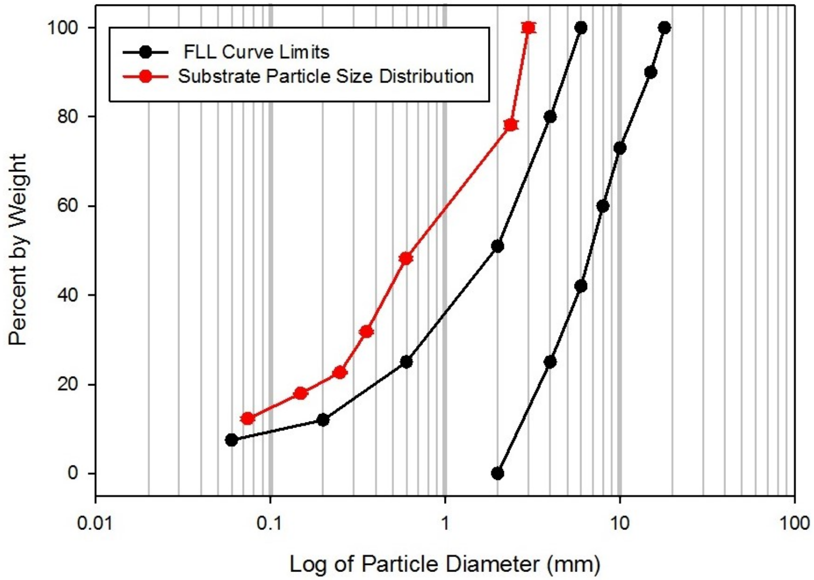


Figure 2.5. Particle size distribution from a four year old Mid-Atlantic green plotted against FLL-recommended granulometric distribution for extensive green roofs. Means and SE (n=5) for each particle diameter range are presented.

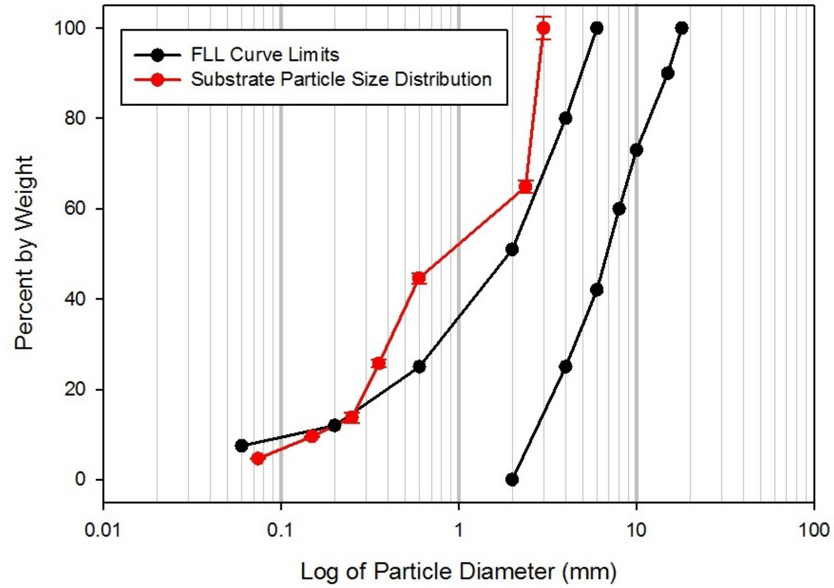


Figure 2.6. Particle size distribution from a three year old Mid-Atlantic green plotted against FLL-recommended granulometric distribution for extensive green roofs. Means and SE (n=5) for each particle diameter range are presented.

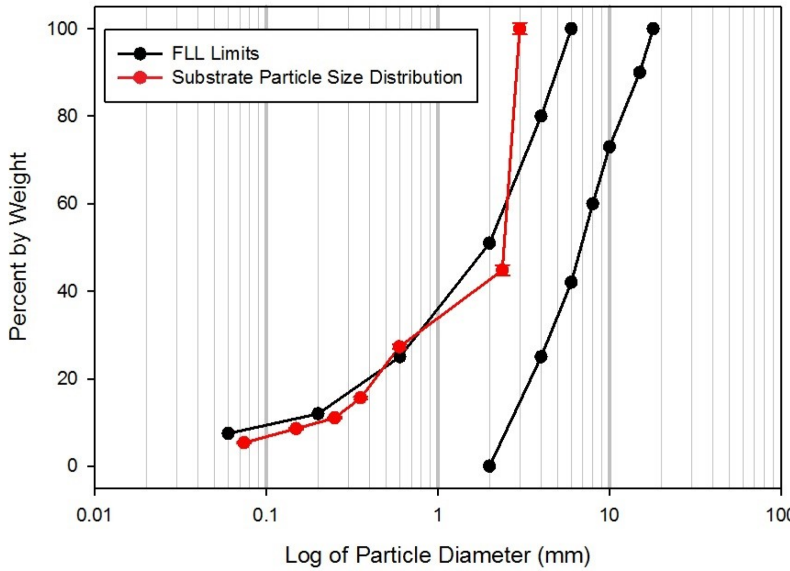


Figure 2.7. Particle size distribution from a seven year old Mid-Atlantic green plotted against FLL-recommended granulometric distribution for extensive green roofs. Means and SE (n=5) for each particle diameter range are presented.

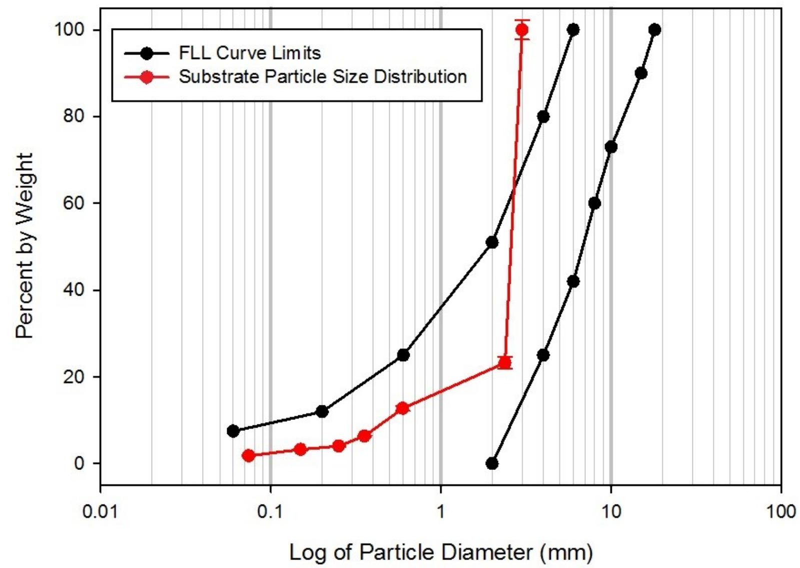
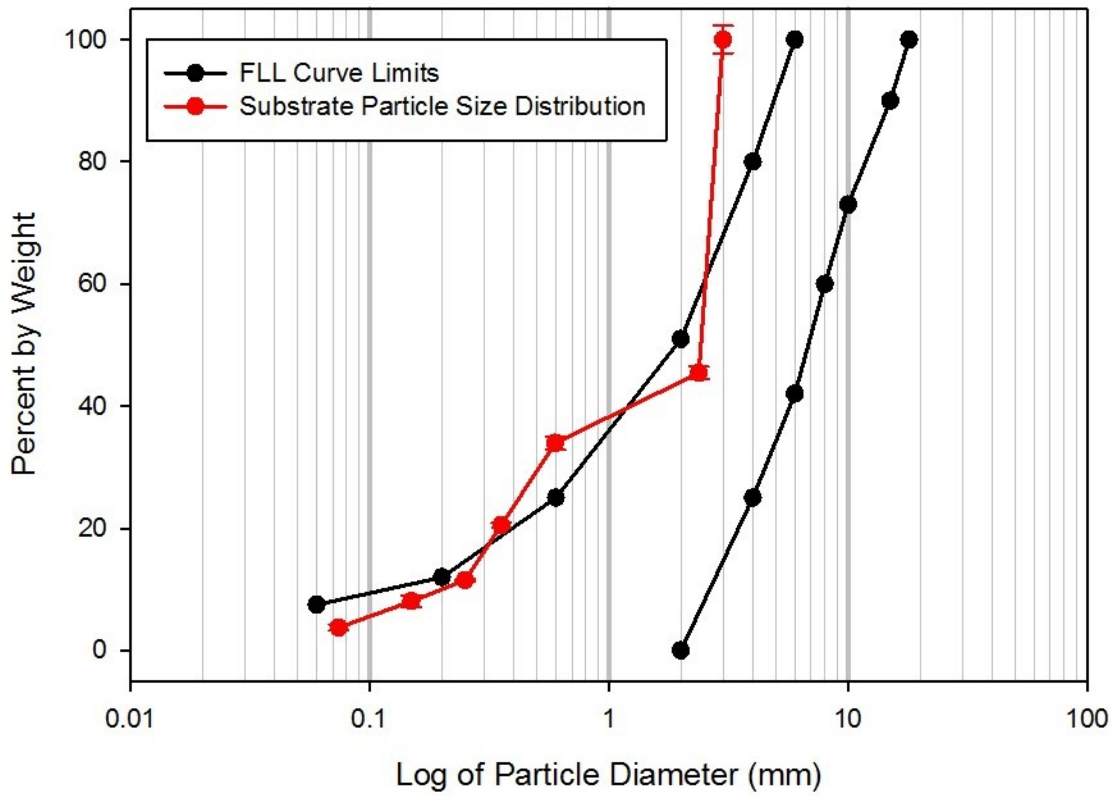


Figure 2.8. Particle size distribution from a five year old Mid-Atlantic green plotted against FLL-recommended granulometric distribution for extensive green roofs. Means and SE (n=5) for each particle diameter range are presented.



2.4 Discussion

The freeze-thaw analysis of three major commercial substrate blends that are widely used in the Mid-Atlantic region demonstrated significant ($p<0.05$) particle degradation after only 30 freeze-thaw cycles. In addition, substrate samples taken from established extensive green roofs did not meet FLL granulometric guidelines 3-7 years post-installation. Because I was unable to obtain substrate samples at the time of installation from any of the established roofs I cannot be certain that these blends met FLL guidelines prior to installation. Nevertheless, a significant ($p<0.05$) particle degradation was observed in the laboratory analyses in these same commercial blends with just 30 freeze-thaw cycles. In addition to significant loss of particle structure, I observed that manufactured commercial blends did not conform to FLL guidelines in the first place. These results offer three important reflections on current substrate standards within the green roof industry.

This study highlights the need for performance-based standards for green roof systems and their components. While current guidelines make recommendations for green roof system components, these apparently are not enforced prior to or at the time of installation. More importantly, while the FLL does have a recommendation for frost resistance (10.2.3, FLL 2008), there is no recommended allowable particle loss. Furthermore, the frost resistance recommendation places the responsibility of verification entirely on the manufacturer, with no suggestions for methodology. Various manufacturers are likely using different techniques to verify frost resistance, if at all. A standardized methodology would create cohesiveness within the substrate industry and allow for more reliable comparisons between commercial green roof substrate blends.

None of the commercial blends met FLL guidelines for granulometric distribution upon receipt from the manufacturer, even prior to freeze-thaw weathering (Figures 2.1, 2.2, and 2.3). It is also evident these materials are not maintaining their physical characteristics in climates that experience numerous freeze-thaw cycles each year. With the advancement of green roof research and our increased understanding of the science behind these systems, standards and guidelines based on dynamic performance rather than static component characteristics at the time of installation would only further benefit the industries and academic communities associated with them. Furthermore, since green roofs have been accepted as storm water management tools at a regulatory level, performance-based standards would better inform storm water retention policies and credits. These data call into question the relevancy of component-based rather than performance-based guidelines and standards.

These results also highlight the need for regionalization of standards. Green roofs in Auckland, New Zealand are not likely to experience freeze/thaw cycles because their temperatures rarely fall below freezing (NIWA – New Zealand, 2013). Similarly, green roofs in Toronto should be expected to freeze but they are likely to stay frozen as a result of daily maximums remaining below freezing (Canadian Climate Data, 2013), lessening the impacts of freeze-thaw weathering on substrate particles. The FLL has been adopted worldwide; even guidelines written at the municipal level have heavily borrowed their recommendations from the FLL. A more common-sense best practice could be to investigate green roof system performance regionally to account for the idiosyncrasies created by varying climatic conditions in regional standards. Furthermore, the FLL guidelines for PSD may not be optimal with respect to storm water retention potentials. Until the effects of PSD on substrate hydraulic characteristics, plant growth, and resultant evapotranspiration are quantified, we cannot know the ideal ranges for particle diameters within a substrate.

These results also demonstrate the need for regionalization of green roof system components. Given the seasonal differences of green roof stormwater retention performance (Schroll *et al.* 2011) and regional variations in climate, one can assume green roof stormwater retention would vary regionally; such variation would likely apply to the system components as well. Expanded mineral-based substrate blends may not be appropriate for regions experiencing repeated freeze-thaw cycling – designers of green roof systems should be mindful of climate and explore alternatives to these materials in regions experiencing freeze-thaw. Similarly, we believe our results create an opportunity for manufacturers to respond with alternatives to expanded-mineral components for these regions. A one-size-fits-all approach to system components and design may not provide optimal or even expected results.

2.4 Conclusions

I have identified a need for further research regarding substrate durability to freeze-thaw weathering. Studies exploring the rates of particle degradation as well as which particle diameters and mineral compositions are most susceptible to fracturing are needed. Additionally, further work is needed to quantify the effects of PSD on substrate hydraulic conductivity and related storm water retention performance. This study only quantified total gains or losses of particle sizes after 30 freeze-thaw cycles, but a dynamic approach could provide a better understanding of the mechanisms and ramifications of substrate PSD and potential particle weathering on storm water retention potential.

Chapter 3: Using the HYPROP© procedure to determine the matric potential and hydraulic conductivity of extensive green roof substrates

3.1 Introduction

Substrates, or the material in which the vegetation is grown, are one of the most important components of a green roof system, as they provide the physical and chemical properties necessary for plant growth. Since the purpose of the substrate is to provide adequate water, nutrient, and gas exchange for plant growth, substrate physical properties have a direct effect on plant growth, rates of evapotranspiration, and the resultant potential for storm water mitigation. As municipalities increasingly recognize green roofs as a primary stormwater management tool, improving the understanding of substrate water relations will lead to better quantification of system performance, and more accurate allotments of stormwater credits.

3.1.1 Substrate Water Holding Capacity and Stormwater Regulations

Current guidelines and regulations generally rely heavily on a combination of substrate depth and water holding capacity (WHC) as a means of determining potential storm water retention capacity in Maryland (Maryland Department of Environment ESD Manual, 2011); Washington, DC (District Department of Environment SWM Guide, 2013); Auckland, New Zealand (Fassman-Beck and Simcock, 2013). Typically, WHC is determined by calculating the amount of water held by a porous media after gravitational drainage, also termed field capacity (FC) in field-based agronomic systems, container capacity (CC) in container-based horticultural systems. It is considered part of the total porosity, with air-filled porosity being the other part of total porosity. The air-filled porosity is the pore space that drains freely – i.e., the total pore volume holding air following gravitational drainage (Handreck and Black, 2002). While field- or container-capacity do provide a starting point for determining potential retention, lab-obtained values may differ from actual in-field values, because samples are often saturated prior to gravitational drainage in the lab compared to a rain event percolating through the substrate immediately. Here, I offer a more specific designation of FC_{sat} to represent saturated field capacity – the WHC of a substrate after at least 24 hours' saturation and FC_{unsat}, representing unsaturated field capacity – the WHC of a substrate after water has been applied in volumes to result in gravitational drainage but without extended periods of saturation.

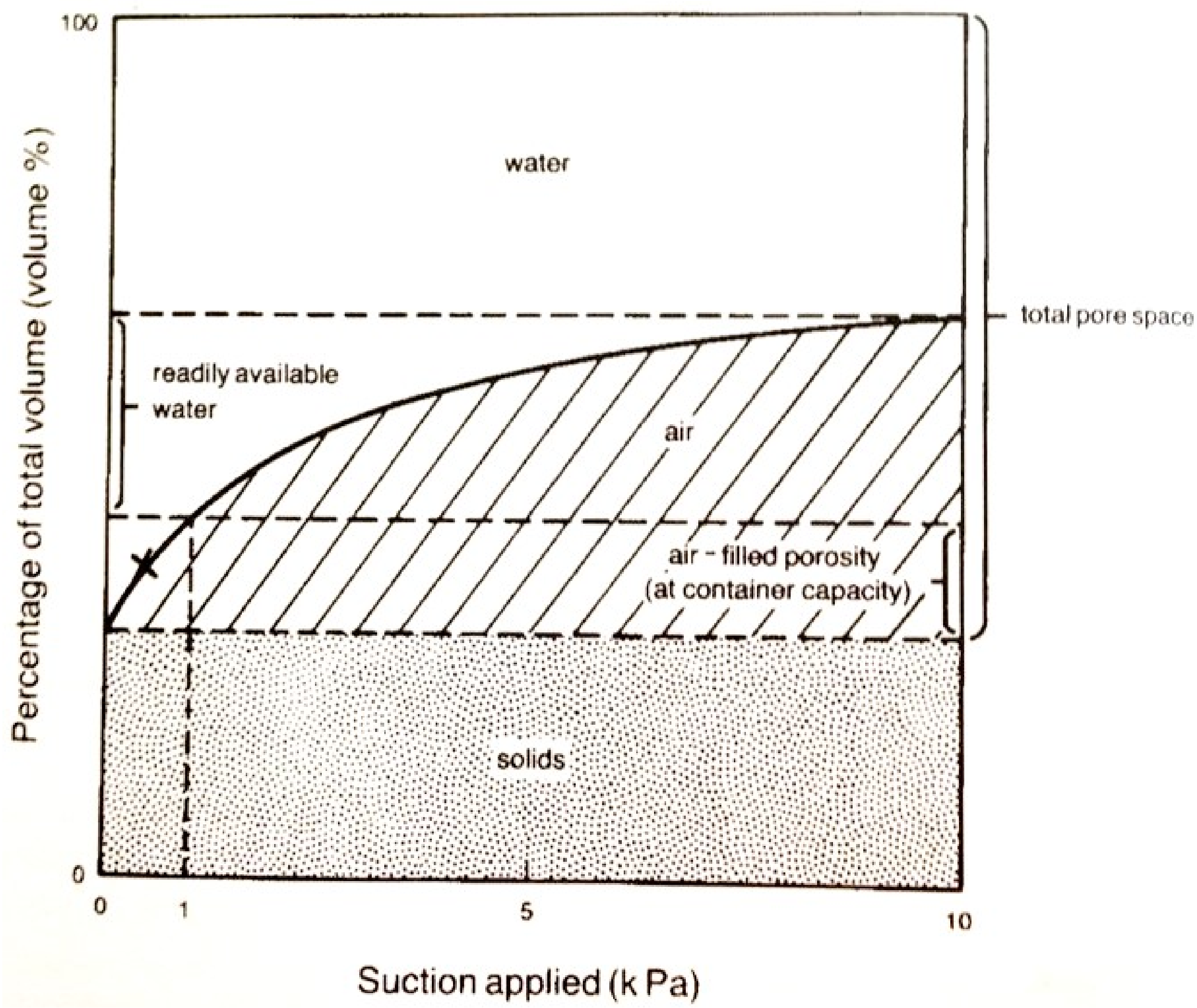
3.1.2 Matric Potential, Hydraulic Conductivity, and Plant Available Water

Water tends to move from a state of higher energy to a state of lower energy. To determine how water may move in porous materials, the energy status of the water in the substrate is compared to that of pure water at a standard pressure and temperature (STP), assumed to be unaffected by soil and at some reference elevation. The difference in energy between the water in this reference state and the substrate water is defined as soil water potential (Brady and Weil, 2000). Matric potential is one component of total soil water potential and is a measure of the attraction of water to solid surfaces, measured in some unit of pressure (typically bar, kPa, or MPa) and may be expressed as a positive or negative value. Matric potential is the proportion of total water potential that is most affected by substrate physical properties.

Matric potential becomes more negative or more positive, depending on the units used, as a substrate dries down. As the substrate dries, plant water needs may exceed substrate volumetric water content. The point at which matric potential is so great that plant roots can no longer extract water out of the soil matrix, and plants permanently wilt, is termed permanent wilting point (PWP) and is assumed to occur when soil water potential reaches -1500 kPa. Because FC is assumed to be equal to -10 kPa (mid-point of a column of 20 cm height), plant available water (PAW) for horticultural substrates is assumed to be the volume of water retained in soils between

0 kPa and -10 kPa (Handreck and Black, 2007) (Fig. 3.1). Using PAW to determine storm water mitigation potential of green roof systems could provide a better estimation of retention potential because it considers substrate properties as well as plant functionality; however in order to do this, PAW must be defined for green roof substrates.

Fig. 3.1. Graph of volumetric water content versus matric potential with designations for plant-based terms. From Handreck and Black (2002), Fig. 9.16, page 76.



Historically, measuring the matric potential of a porous media was time or labor intensive or not sensitive enough at optimum water contents (Table 3.1), and most methods were developed specifically for soils. Quantifying matric potential in horticultural or soilless substrates has proven even more difficult – many of these materials are more porous than soils or are composed primarily of organic matter (Arguedas-Rodriguez, 2009). Water is typically held less tightly and requires lower pressures to extract, resulting in narrower matric potential curves. DeBoodt and Verdonck (1972) characterized the water characteristics of several soilless horticultural substrates and described plant-specific parameters relating volumetric water content to matric potential: easily available water (EAW), 0 to -5 kPa and water buffering capacity (WBC), -5 to -10 kPa. Handreck and Black (2002) expanded on these parameters by defining readily available water (RAW), which is the sum of EAW and WBC (0 to -10 kPa), synonymous with PAW.

Hydraulic conductivity, typically represented by the symbol K, describes the ease with which water moves through a porous material. Pore spaces within a substrate are created by particles of varying sizes and shapes; this variability in pore geometry makes accurate quantification of water movement through porous materials difficult. Henry Darcy first described hydraulic conductivity, which is represented by Darcy's Law, describing water movement in a saturated medium:

$$q = - K\Delta H/L \qquad \text{[Eq.3.1]}$$

where:

q is the volume of water flowing through a unit cross sectional unit area per unit time
H is the hydraulic head drop
L is the length of the column

Hydraulic conductivity is directly affected by soil or substrate structure and porosity, and primarily by the sizes of the pores (i.e., particle diameter). Quantifying hydraulic conductivity for these materials is integral to understanding the plant-water-substrate relationship that drives evapotranspirational stormwater mitigation (Palla et al., 2008).

Table 3.1. Various methods of determining soil matric potential. *After: Brady and Weil, 2000, page 141.*

Method	Measures water Content	Measures water Potential	Useful Range (kPa)	Appropriate use Field	Appropriate use Lab	Comments
Gravimetric	X		0 to <-10,000		X	Destructive to the sample, used as the standard for calibration.
Neutron Scattering	X		0 to <- 1,500	X		Requires radiation permit, expensive, not appropriate for materials with high organic content.
Time Domain Reflectometry (TDR)	X		0 to <-10,000	X	X	Accurate to 1 kPa, expensive.
Tensiometer		X	0 to -85	X		Accurate to 0.1 kPa, limited range, inexpensive
Resistance Blocks		X	-100 to <-1,500	X		Must be individually calibrated, not sensitive near optimum plant water contents.
Thermocouple psychrometer		X	-50 to <-10,000	X	X	Moderately expensive, accurate only to ±50 kPa.
Thermal dissipation blocks		X	-50 to <-1,500	X	X	Moderately expensive, must be individually calibrated.
Pressure membrane apparatus		X	-50 to <-10,000		X	Used in conjunction with gravimetric method to construct a water retention curve.

Green roof substrates are composed primarily of mineral materials; in this way they are more similar to soils. However, the particle size distribution is such that that, given their porosity, they are more similar to horticultural or soilless substrates (Arguedas-Rodriguez, 2009). Quantifying the matric potential of green roof substrates to define PAW could better inform estimates of retention capability, offer increased understanding of the plant-substrate-water relationship, and provide guidance regarding optimal substrate composition.

3.1.3 Methods for Determining Matric Potential of Soils and Soilless Substrates

Recent advances in technology offer a potential method for determining matric potential of soils beyond -400 kPa using tensiometers (Schindler et al., 2010; Schindler et al., 2010b). This limit is far beyond the traditional tensiometer limit of -70 to -90 kPa (Schindler et al., 2010b; Brady and Weil, 2000). The former limitations of tensiometers (Table 3.1) were the result of water column cavitation, which is particularly a problem in porous soilless substrates (Arguedas-Rodriguez, 2009; Schindler et al., 2010b). Most often, tension table columns cavitated at pressures less than 40kPa for a range of soilless substrates, irrespective of column height (Arguedas-Rodriguez, 2009).

The HYPROP© system was developed by UMS, INC (Munich, Germany) based on the evaporative method theory (Peters and Durner, 2008) and further described by Schindler et al. (2010, 2010b). The HYPROP© is intended for use with soils; the recommended methodologies (Decagon Devices, Inc, Pullman, WA; Schindler et al., 2010, 2010b) were adjusted to account for increased particle size and porosity of green roof substrates.

This study therefore addressed the following hypotheses:

1. H_O: The matric potential of extensive green roof substrates will not be affected by increasing the proportion (10%, 20%, and 40%) of organic matter in a soilless substrate blend.

H_A: Matric potential of extensive green roof substrates will increase (i.e., the curve will shift to the right, to increasing pressures) by increasing (10%, 20%, and 40%) the proportion of organic matter, since organic matter increases the water holding capacity of a soiless substrate.

2. H_O: The field capacity (i.e., maximum water holding capacity) of extensive green roof substrates will not be affected by increasing (10%, 20%, and 40%) the proportion of organic matter in a soilless substrate blend.

   H_A: The field capacity (i.e., maximum water holding capacity) of extensive green roof substrates will increase by increasing (10%, 20%, and 40%) the proportion of organic matter, since organic matter increases the water holding capacity of a soiless substrate.

3. H_O: The hydraulic conductivity of extensive green roof substrates will not be affected by increasing the volumetric proportions (10%, 20%, and 40%) of organic matter in a soilless substrate blend.

   H_A: The hydraulic conductivity of extensive green roof substrates will decrease by increasing the volumetric proportions (10%, 20%, and 40%) of organic matter since organic matter increases the water holding capacity of a substrate; thus, water will move less quickly through the substrate matrix.

3.2 Materials and Methods

The HYPROP© system and methodology was developed for use with soils, as opposed to engineered aggregate media, so the methodology proposed by Schindler et al. (2010, 2010b) and outlined by UMS, INC (Munich, Germany) and Decagon Devices (Pullman, WA) was modified to overcome challenges created by the coarseness and increased porosity of green roof substrates, as clearly demonstrated by Arguedas-Rodrigueas (2009). Because of the proportion of large particles (>2mm diameter) (Appendix **A**), substrate cores could not be taken using the proposed method of hammering the core directly into soil and using a knife or blade to scoop the 'undisturbed' core out of the earth (HYPROP© manual, Decagon Devices). Instead, cores were hand-packed utilizing an adjusted methodology based on the North Carolina State Porometer Method (Fonteno and Harden, 2003). Each 250 mL sampling ring was placed onto the perforated

Fig. 3.2. Photograph illustrating an amended packing procedure for HYPROP© cores for use with coarse substrates.

Fig. 3.3. Photograph illustrating an amended packing procedure for HYPROP© cores for use with coarse substrates.

base and filter fabric (both supplied by UMS, Munich, Germany), and 100 mL media poured into the ring. (Figs. 3.2 and 3.3). The entire assembly was then tapped five times firmly on the table using equal pressure for each tap. Another 100 mL media were poured into the ring and tapped five times as before. A final 100 mL media were poured into the ring, overfilling it. After five taps a metal straight edge was used to carefully remove any remaining media which extended above the top of the ring (Figs. 3.4 and 3.5).

Fig. 3.4. Photograph illustrating an amended packing procedure for HYPROP© cores for use with coarse substrates.

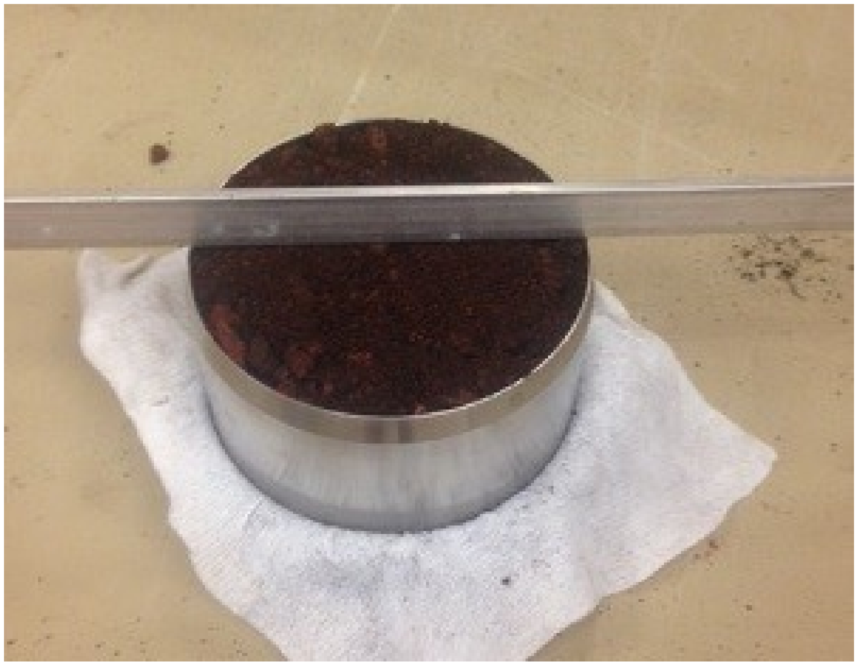
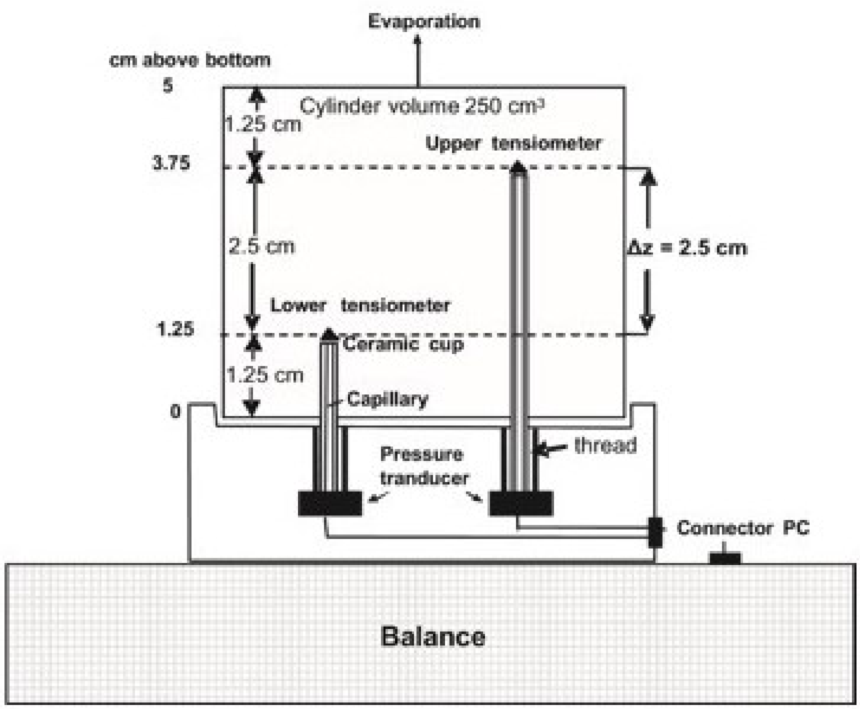


Fig. 3.5. Photograph illustrating an amended packing procedure for HYPROP© cores for use with coarse substrates.

In this way, replicate cores were packed at the same moisture content to the same bulk density within treatments. After packing, cores were placed in a water bath for 48 hours to achieve complete saturation (FC_{sat}). After saturation, cores were allowed to drain for 10 minutes and then installed onto HYPROP© sensor bases (Fig. 3.6) per standard methodology (Schindler et al., 2010; Schindler et al., 2010b).

Fig. 3.6. Diagram of the HYPROP© system illustrating tensiometer placement within sample cores. From Schindler (2010).

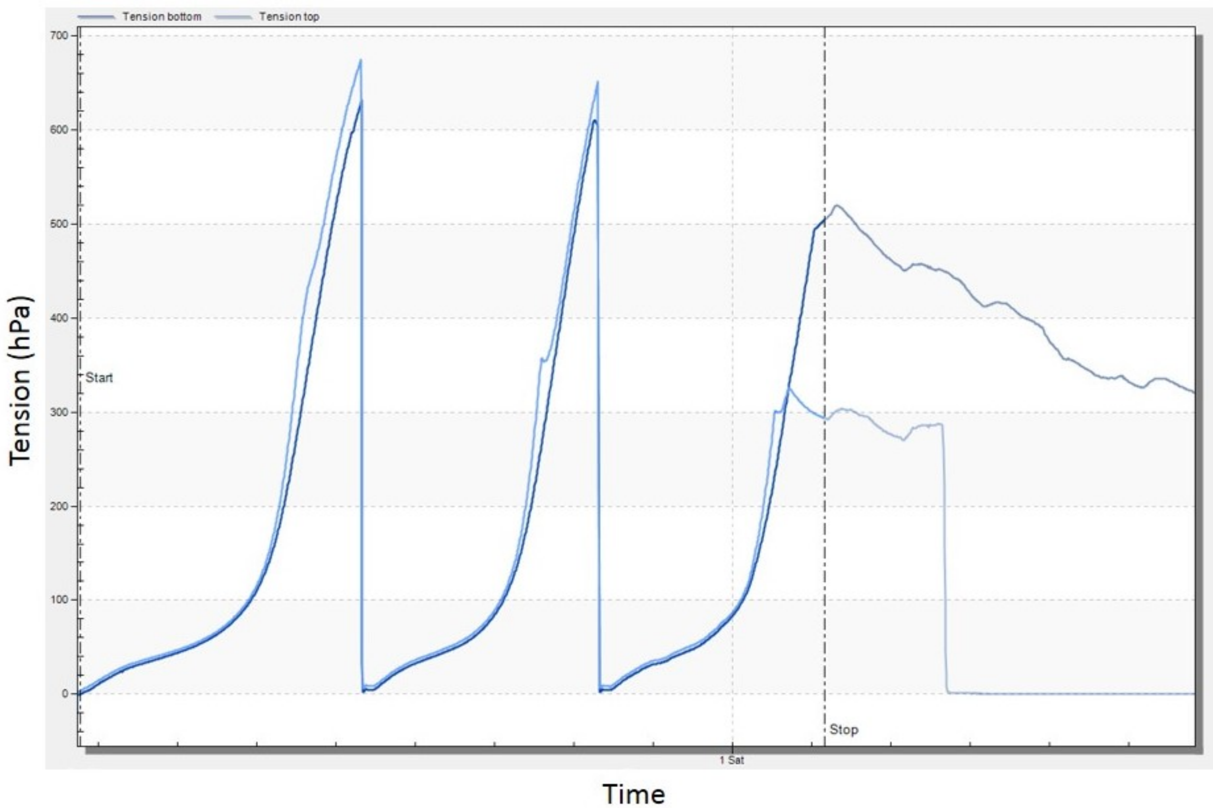


After draining, two holes were drilled into the top of the sample using a bore tool included in the HYPROP© kit; one hole is drilled 3.75 cm into the sample (for the top tensiometer), the other is drilled 1.25 cm into the sample (for the bottom tensiometer). The hole depths are determined by the tool, to ensure contact between the ceramic cap of the tensiometers and the substrate; it is the continuous water column from the sample water through the ceramic cap and tensiometer to the pressure transducer which allows for an accurate pressure reading. After holes were drilled, the HYPROP© sensor base was inverted and inserted into the substrate core, taking care not to disturb the sample, and placing the correct tensiometer into the correct hole. The entire assembly – sensor base, packed core, filter fabric, and perforated base – were then turned right side up and the perforated base and filter fabric were carefully removed so as not to disturb the packed sample. The sensor base has two clamps that secure the sampling ring – these were clamped and the sensor base was then plugged into the computer using via USB, included in the HYPROP© kit. Each HYPROP© unit was assigned a separate balance [Kern EG 2200, KERN Incorporated, Balingen, Germany; Mettler Toldedo PB3001-S, Mettler-Toledo INC, Columbus, Ohio; Mettler Toledo XS4002S, Mettler-Toledo INC, Columbus, OH] and connected to the TensioView software program (UMS INC., Munich, Germany).

Matric potential is measured by the HYPROP© by measuring the suction force of the tensiometer column through the porous ceramic cap which is in contact with the substrate sample water. The TensioView program records tensiometer readings from the sensor base and a simultaneous weight measurement from the balance every ten minutes. Measurement continues as long as the water column from the pressure transducer to the substrate water remains intact. As macropores lose water, this continuous column of water is dependent upon water in micropores and water films at the edges of substrate particles.

The standard methodology allows for a single dry-down period - the cores are allowed to dry via evaporation until the tensiometer water columns cavitate, at which time the units are disassembled and cores are oven-dried to quantify soil dry weight. However, since increased organic content in porous media can result in water repellency (DeBano, 1981), I modified the methodology in an attempt to quantify between-dry down differences in matric potential and hydraulic conductivity due to differences in water adsorption during re-wetting. Cores were re-saturated by applying deionized water evenly across the top of the cores in 10 mL increments using a pipette over one-half hour *prior to* water column cavitation. The software displays real-time measurements, so cores were re-hydrated once the tensiometer readings showed inflection, prior to column cavitation (Fig. 3.7)

Fig. 3.7. Screen capture taken from the TensioView software program used in conjunction with the HYPROP© to show the tension measurements during three consecutive dry-down runs from a single sensor base. Tension increases as the sample dries. The light blue line represents the top tensiometer readings, the dark blue line represents the bottom tensiometer readings, and the dashed vertical line shows column cavitation.



Each replicate core was re-saturated twice using this procedure, for a total of three dry-down periods per core per treatment, for a total of nine replicate soil moisture curves per treatment. A 60:40 crushed recycled brick:scoria mineral component was blended with mushroom compost

(Frey Brothers, Lancaster, Pennsylvania) at 10%, 20%, or 40% volumetric proportions (designated as 10%OM, 20%OM, or 40%OM), which constituted the three treatments in this study. Retention data were analyzed using the HYPROP-FIT© software (UMS INC., Munich, Germany) and fit using the van Genuchten bimodal/ Mualem model (Durner, 1994; Mualem, 1976):

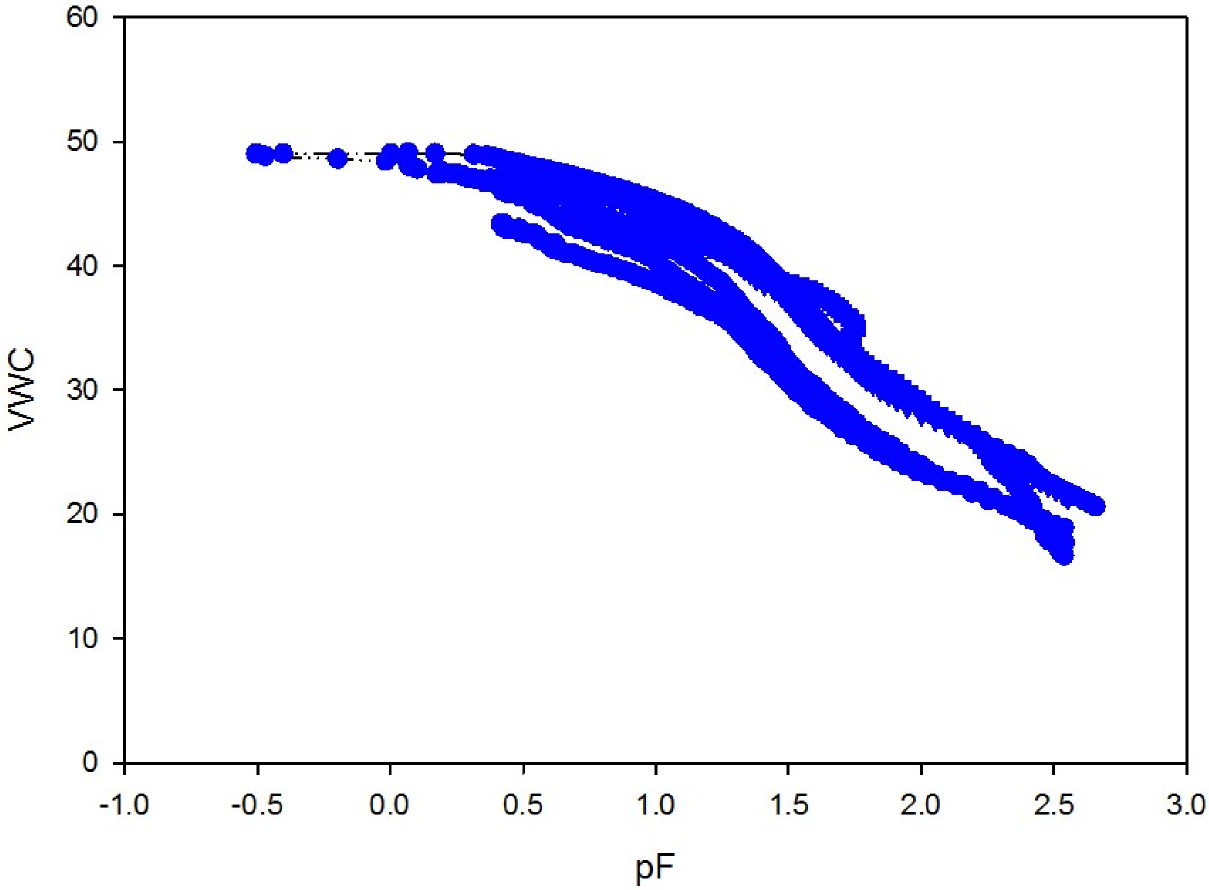
$$S_e(h) = \sum_{i=1}^{2} w_i \left[\frac{1}{1 + (\alpha_1|h|)^{n_i}}\right]^{m_i} \qquad \text{Eq. 3.2}$$

where
S_e is the effective water content (cm^3/cm^3);
h is the suction head (cm);
w_i is a unitless parameter based on weight where all w parameters sum to 1;
α is related to air-entry suction pressure;
n is a measure of the pore-size distribution, $n>1$; and
$m_i = 1 - 1/n_i$

This model is the result of Durner's modification to van Genuchten's (1980) adjustment to the Richard's Equation, which describes water movement in saturated porous media. van Genuchten's adjustment considered unsaturated conditions while Durner considered constraints presented by unequal pore space distribution. The results of the nine replicate dry downs (three HYPROP© instruments, three dry downs per treatment) were averaged together because there was no between-rep or between-dry down effect (Fig 3.8).

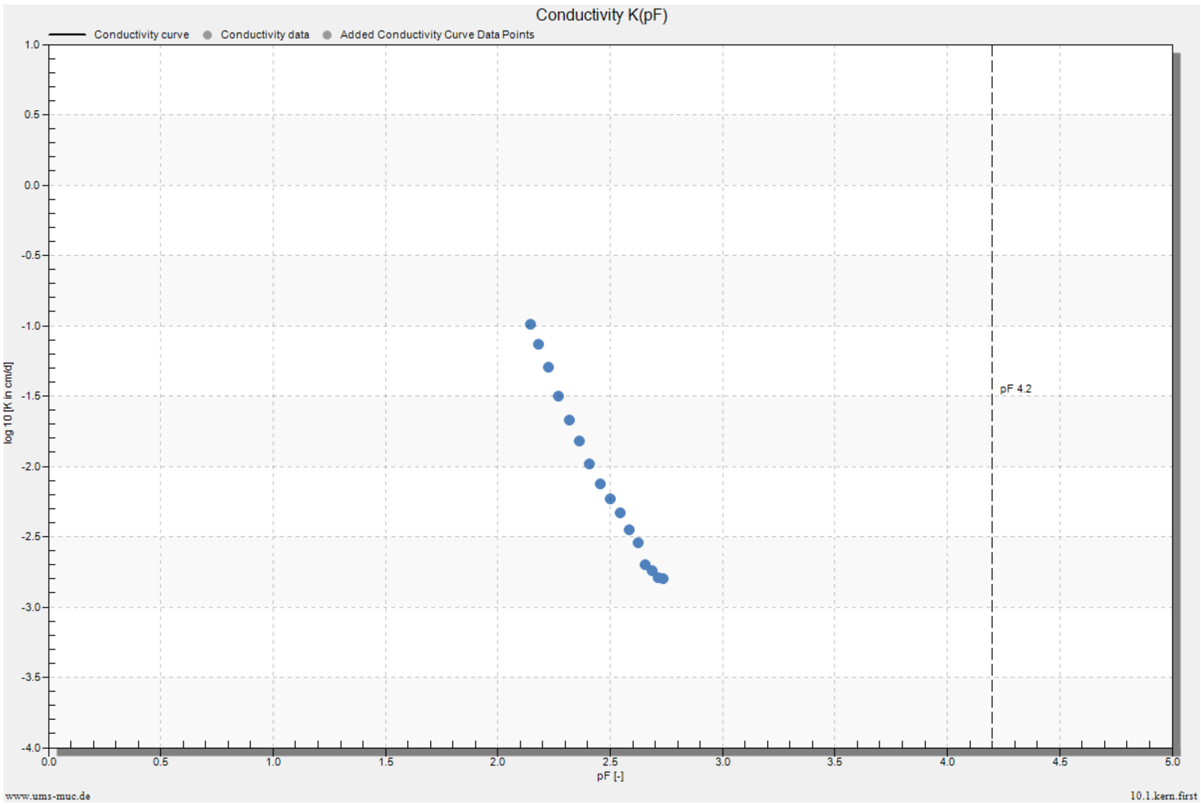
Fig. 3.8. Matric potential of an extensive green roof substrate with 20% organic matter, as

determined by the HYPROP© method. Three HYPROP© instruments were used to measure matric potential in three consecutive dry-down periods, for a total of nine retention curves (all plotted here). Between-replicate effects were non-significant, so results were averaged together for all treatments.



The hydraulic conductivity data output from the HYPROP-fit© software was incorrect. This was determined by double-checking the output values with the raw data output. Because the HYPROP© was designed for soil analyses, hydraulic conductivity measurements may not be reliable for higher porosity media (Leo Rivera, Decagon Devices, Inc. *pers. comm.*). The measurement range of hydraulic conductivity may also be limited by the HYPROP© because measurements are not recorded until a certain difference in the prior measurement has been reached (determined by the software), s measurements only ranged from about 1.8 to 2.5 pF (Carlo Bibbiana, University of Pisa, Italy, *pers. comm.*) Correct values were obtained via hand calculation of the raw data (weight, VWC_{real}, time, and tension). These data had to be spliced together to create full hydraulic conductivity curves; an example of one of these curves is presented in Fig. 3.9.

Fig. 3.9. Hydraulic conductivity K(pf) as determined by the HYPROP© method, for an experimental green roof substrate with 10% organic matter.



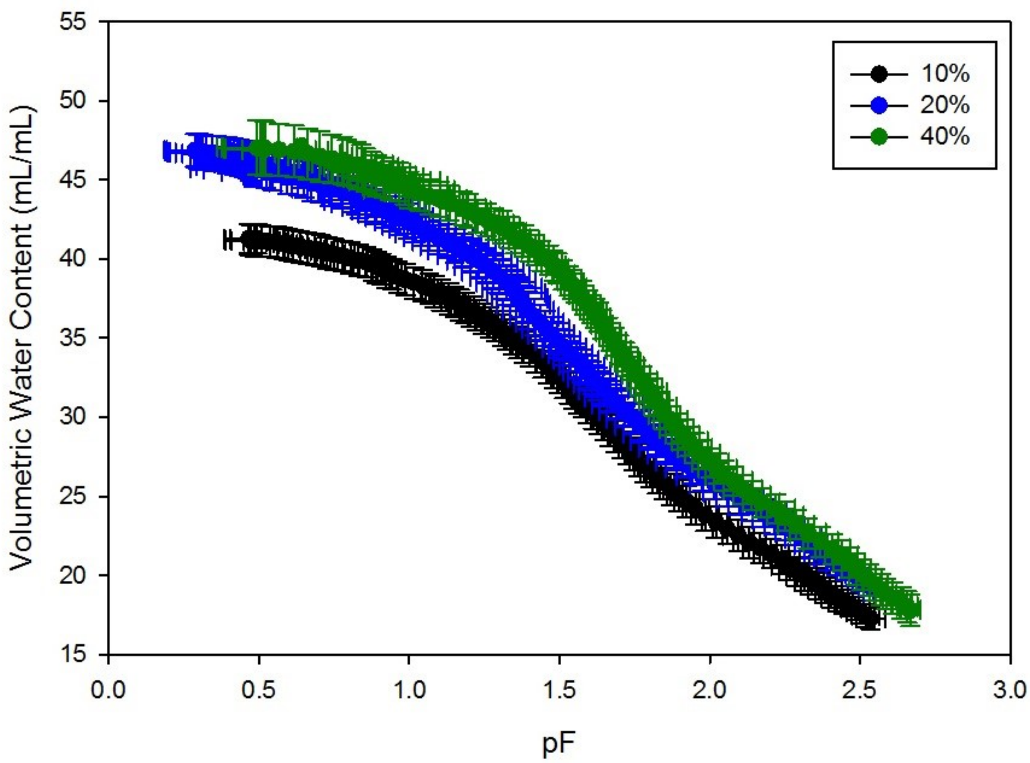
Hydraulic conductivity data were analyzed using the HYPROP-fit© software (UMS INC., Munich, Germany) and fit using the Mualem model (Mualem, 1976). Matric potential and hydraulic conductivity data were analyzed using logarithmic regression via the PROC LOGISTIC command (SAS 9.3, SAS Institute, INC., Cary, NC) to account for the log scale of the pF variable.

3.3 Results and Discussion

3.3.1 Field Capacity

The starting VWC for 10%OM was 41%, significantly lower than the 46% for 20%OM and 40%OM (Fig. 3.9). Substrate maximum VWC ranging from 41-46% may be considered high, considering maximum VWC for a commercial green roof substrate blend was reported as 34% (Starry, 2013) using direct moisture measurements for platform-scale experimental green roof field research.

Fig. 3.10. Matric potential of three green roof substrates with increasing volumetric proportions (10%, 20% and 40%) of organic matter, obtained by using the HYPROP© system. Means (n = 9) are shown for all treatments.



Although Voyde (2011) also reported a range of 40.8 to 49.6% for maximum WHC, this was based on the recommended FLL method, which like the HYPROP© method requires a saturation period of at least 24 hours. In Voyde's study the actual substrate VWC was not directly quantified; rather, the data was estimated using a water-balance approach subtracting discharge from rainfall using the lab-based WHC metric. In contrast, my results, although based on a truly saturated sample, present real or actual VWC (VWC_{real}) values, quantified from direct gravimetric measurements of the sample throughout the drying process. Nonetheless, the maximum VWC for an extensive green roof in the Mid-Atlantic region will likely not exceed 30% except in very large, intense rain events where rainfall equals discharge (Mr. Charlie Miller, P.E. [RoofMeadow], *pers. comm.*).

For this reason, I have chosen to differentiate between FC_{sat} and FC_{unat}. Since the substrate cores were saturated 48 hours and allowed to drain gravitationally before initiation of the experiment, these values refer exclusively to FC_{sat}, while field-observed values would represent FC_{unsat}, given that green roof substrates are engineered to be drain rapidly and are unlikely to be saturated for extended periods, except under extreme (flooded) conditions; this is therefore most likely an artifact of the laboratory protocols currently used. Applying a delineation between FC_{sat} and FC_{unsat} to regulatory estimations of green roof storm water mitigation potential based on lab-derived maximum WHC (FC_{sat}) would be a more informed method of approximating potential retention because green roofs rarely, if ever, reach true saturation.

3.3.2 Green Roof Substrate Matric Potential

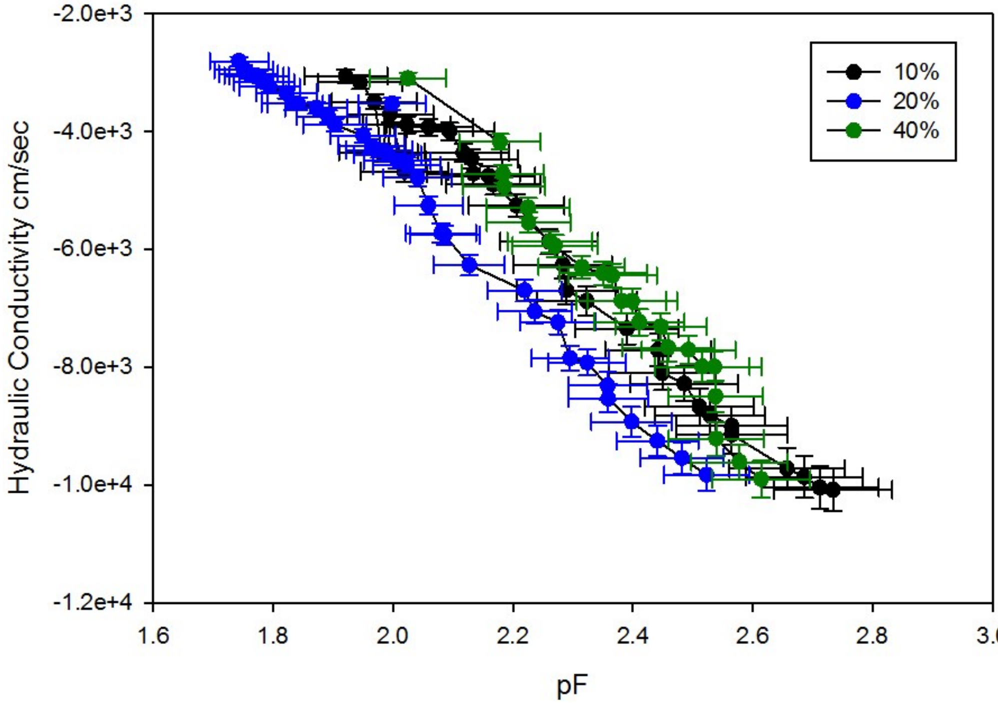
The matric potential of three experimental green roof substrates was characterized for pressures up to approximately 2.5 pF (approximately -30 kPa), at which point the tensiometer water columns cavitated, ending the experiment. Although -30 kPa is far below the -1500 kPa (4.2 pF) assumed value of PWP, it exceeds the -10 kPa maximum attained by Arguedas-Rodriguez (2009) when characterizing the matric potential of pine bark, a soilless substrate with similar maximum VWC (48%) and porosity, utilizing a tension table method with a 5-cm column. Furthermore, it far exceeds the -10 kPa designation for plant unavailable water reported by DeBoodt and Verdonck (1972) and confirmed by Handreck and Black (2002) for horticultural soilless substrates. In this way, the HYPROP© does somewhat extend the measurement range of matric potential for porous soilless substrates; however, water column cavitation occurred at approximately 18% VWC, far above PWP (Arguedas-Rodriguez, 2009). Based on data presented in Chapter 3, plants were evapotranspiring water from these same experimental substrate blends below 5% VWC. Despite reaching tensions beyond -30 kPa, unavailable water in green roof substrates, it seems that this PWP still cannot be well-defined using the HYPROP© method. There were no differences ($p>0.05$) in matric potential between any treatment in the tension range (0.25-2.5 pF) measured. As it is assumed that substrate organic content will mostly affect the increasingly unavailable water in the substrate at higher (more negative) matric potential than 2.5 pF, I cannot confidently predict the effects of organic content on matric potential with regards to plant-water relations from these results. From this perspective, it is probably more reliable to estimate plant water use from the VWC substrate data, as will be illustrated in Chapters 4 and 5.

The cavitation of the tensiometer water column at tensions around 2.5 pF (± 30 kPa) is assumed to be a result of the overall porosity of the substrates. Given the proportion of large (>2 mm diameter) particles in the three experimental blends (Appendix B), I assume that macropore drainage may have contributed to a premature cavitation of the water column. Also of importance is tensiometer placement within the cores (Fig. 3.5). Because the HYPROP© apparatus uses on the evaporative theory (Peters and Durner, 2008), tensiometers take measurements continuously as cores dry via evaporation from the top of the sample. Because the samples dry from the top to the bottom, a significant amount of water could remain below the tensiometer caps after cavitation – due to material porosity and macropore water loss – which would go unmeasured by the tensiometers, although it would be correctly quantified into VWC_{real} based on balance measurements. These two principles may indicate that despite the increased measurement range, the HYPROP© system may not be appropriate for measuring matric potential in very porous green roof substrates.

3.3.3 Green Roof Substrates and Hydraulic Conductivity

There were no statistical (α=0.05) differences in hydraulic conductivity between any treatments, which suggests that increasing the organic content of a green roof substrate does not affect multi-dimensional water flow through the media (Fig. 3.10). These results are counterintuitive, given that organic matter can hold up to nine times its weight in water (Hillel, 2004) and therefore increasing a substrate's organic content should increase water holding capacity, thereby decreasing hydraulic conductivity.

Fig. 3.11. Hydraulic conductivity for three experimental green roof substrates with increasing (10%, 20%, and 40%) volumetric proportions of organic matter as determined by the HYPROP© method. Means (n=9) are presented for each treatment.



3.3.4 Model Parameters

Green roof substrates rarely saturate, as these data have demonstrated, and the particle size distribution (Appendix B) demonstrates a wide range of pore space. Model parameters for the three experimental substrate blends using the van Genuchten bimodal/ Mualem model (Durner, 1994; Mualem, 1974) are presented in Table 3.2.

Table 3.2. Presentation of van Genuchten bimodal (Durner, 1994) parameters for water retention and hydraulic conductivity of three experimental green roof substrate blends with increasing volumetric proportions of organic matter (10%, 20%, or 40%).

	Alpha 1 (0.00001-0.5)			*n* 1 (1.01-15)			Alpha 2 (0.00001 - 0.2)			*n* 2 (1.01-8)			*w* 2 (0-1)		
TRT	Estimate	2.50%	97.50%	Estimate	2.50%	97.50%	Estimate	2.50%	97.50%	Estimate	2.50%	97.50%	Estimate	2.50%	97.50%
10	0.5000	0.3785	0.6604	8.821	1.582	10.161	0.0578	0.0507	0.0659	1.496	1.452	1.544	0.769	0.739	0.799
20	0.0639	0.0596	0.0685	1.76	1.690	1.838	0.0022	0.0019	0.0025	4.464	3.211	6.427	0.386	0.364	0.408
40	0.0242	0.0222	0.0265	4.706	4.279	5.188	0.0367	0.0273	0.0493	1.211	1.180	1.246	0.805	0.769	0.841

3.4 Conclusions

This experiment clearly defines a need for better-defined protocols for the analysis of porous green roof substrate physical properties, especially with regards to WHC and FC. The current use of lab-determined WHC and FC values most likely overestimate potential green roof storm water retention due to saturation-based methodologies. I have therefore delineated FC_{sat} from FC_{unsat} as a means to separate saturation-based field capacity and substrate VWC after gravitational drainage exclusive of saturation, which is likely more representative of actual green roof retention potential.

The HYPROP© system could provide a slightly better quantification of matric potential of green roof substrates, beyond the traditional range offered by tension table analysis of porous soilless substrates; however, the HYPROP© method still could not characterize matric potential (and therefore, VWC) for green roof substrates beyond tensions which are assumed to designate plant unavailable water (>-50kPa to -500 kPa). Retention and hydraulic conductivity data were fit using the van Genuchten bimodal (Durner, 1994) model, which considers porous media with a range of particle sizes in unsaturated conditions.

This lab analysis of extensive green roof substrates shows few differences in hydraulic properties with increasing (10%, 20%, and 40%) volumetric proportions of organic matter, a surprising result given that organic matter provides water holding capacity, especially in soilless systems. Data presented in Chapters 4 and 5 indicate that lab-based analyses of green roof system components may not accurately predict or represent component behavior in the field.

While the HYPROP© offers an improved methodology for determining green roof substrate matric potential, challenges presented by system design and substrate characteristics prevent the characteristic of the entire moisture curve. Additional work to continue to expand the measurement range of matric potential in green roof substrates would only further inform scientists, designers, and regulatory entities with regards to green roof storm water retention performance. Unfortunately, the quantification of component performance doesn't really speak to or predict entire system performance, nor do lab-based analyses adequately predict field-based measurements. Since regulatory agencies determine system specification requirements based on predicted or estimated stormwater retention, a more valuable use of research resources would be to develop more accurate predictions of stormwater retention performance based on system design.

Chapter 4: Growth and rates of evapotranspiration of container-grown *Sedum kamptschaticum* grown in four different green roof substrates in a growth chamber.

4.1 Introduction

As researchers continue to investigate green roof components and system performance (VanWoert et al., 2005; Rowe et al., 2006; Molineaux et al., 2009; Berndtsson et al., 2006; Mentens et al., 2006; Teemusk and Mander, 2007), the total green roof area in North America continues to increase (Erlichman and Peck, 2013). As the layer which supports the biological functioning of any green roof system, green roof substrates (GRS) hold water for plant growth, allow air movement for root gas exchange, offer stability and structure for root anchoring, and provide nutrients for plant uptake. While GRS do retain a proportion of storm water through substrate water holding capacity (buffering immediate storm water runoff), plants provide the additional ecosystem service of storm water removal through transpirational water cycling. In this way, water held in the GRS is taken up through the plant roots and cycled directly back into the atmosphere as water vapor, decreasing the water content of the GRS to allow for further capture of the next rain event. While water does leave the substrate through evaporative losses, Starry (2013) demonstrated that with the exception of large (>62.5 mm) rain events, planted experimental green roof platforms in the Mid-Atlantic region were 30% more efficient at moving storm water than unplanted experimental green roof platforms. Starry (2013) illustrated that this efficiency was directly tied to storm intensity, i.e. the amount of rainfall falling during a specific time period. This contradicted VanWoert et al.'s (2005) conclusion that brown or unplanted experimental roof platforms were just as effective at evaporating storm water as planted experimental platforms. This illustrates that the effects of GRS composition on plant growth and evapotranspiration should be investigated to better inform storm water retention predictions and green roof system design.

4.1.1 Green Roof Substrates

In general, any soilless substrate should be consistent in composition, free of pathogens and weed seed, and provide adequate water, air, and nutrients for plant survival and growth (Handreck and Black, 2007). In addition to these properties, GRS must also have an appropriate bulk density to resist wind uplift without surpassing roof structural live load limits for the roof; they are also engineered to rapidly drain to avoid ponding on any area of the roof. In the early nineteenth century, green roofs in Berlin did not use engineered media; rather, construction rubble was spread over tar paper roofs and the living systems developed over time (Kohler and Poll, 2010). Modern green roof substrate composition is largely based on recommendations in the *Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau* (FLL), the German landscape industry's guidelines for the design, planting, and maintenance of green roof systems. The FLL makes recommendations for particle size distribution and organic content as well as specific physical properties such as water holding capacity, bulk density, and total porosity (FLL, 2008).

Beyond the basic FLL recommendations, GRS composition varies internationally and regionally, usually due to material availability. North American GRS are largely composed of lightweight aggregates – usually slate, shale, or clay that have been kiln-fired to create expanded mineral particles (Beattie and Berghage, 2004). Particles of varying diameter are mixed together to achieve appropriate particle size distribution and physical properties such as water holding capacity, total porosity, and bulk density (Handreck and Black, 2007). Interestingly, while the North American green roof industry largely uses manufactured aggregate for GRS, research from other countries indicates efforts to utilize lower-carbon recycled or natural materials for the inorganic component of GRS. For example, New Zealand green roof substrates are largely composed of naturally-occurring zeolite and volcanic rock (Fassman and Simcock, 2008). A study based in Northern Italy used a blend of locally available naturally-occurring mineral materials as the extensive green roof substrate (Nardini et al., 2012). Molineaux et al. (2009) reported that in the U.K., broken brick is the most commonly-used mineral portion of extensive green roof substrates. In Sweden, extensive green roof substrates were traditionally natural soil amended with naturally-occurring lava or scoria, and Emilsson (2008) reported the results of a study utilizing broken roof tiles as a component of extensive green roof substrates as an alternative to mined minerals.

The organic content of GRS varies depending on the design intent of the system; however, most ready-to-plant blends roughly follow FLL guidelines of ≤65g/L (FLL, 2008). The recommendation is based on the verification method of ashing or loss on ignition; however, horticultural substrates are generally mixed volumetrically. The guideline is a weight per volume metric – a value that could vary widely depending on the bulk density of the blend. Appendix C data indicates that given the difference in densities of the mineral and organic portions of GRS, a substrate could have up to 40% organic matter (volumetrically) and still fall within the FLL guidelines. Since organic matter provides cation exchange and water holding capacity, varying the organic content of a GRS could have significant impacts on plant growth and evapotranspiration. The effects of increasing the volumetric proportion of organic matter in GRS on plant growth and evapotranspiration therefore need to be further investigated to gain a better understanding of how substrate composition may affect green roof plants and stormwater mitigation potential.

4.1.2 Green Roof Plants

Green roofs present a unique environment for plants – a thin substrate layer requires a fibrous, non-aggressive root system so as to avoid compromising the integrity of the waterproof membrane of the roof; the reduced rooting zone also limits the volume of water that can be stored after rain events. Green roof plants must tolerate extreme diurnal temperature ranges, diect sun exposure, and high wind exposure can increase stomatal water loss; all these factors combine to provide a drought-prone system even in climatic areas with relatively consistent rainfall. Although green roofs are most often found in urban areas, the environmental challenges they present to plants are in many ways comparable to deserts or rocky outcroppings, and the plants that are most often used in extensive green roof systems are succulent species which have evolved physiological responses to extreme heat and drought conditions.

One such mechanism is a variation on the traditional C3 photosynthetic pathway termed the Crassulacean Acid Metabolism (CAM). CAM allows for a water use efficiency, or the weight of plant material per volume of water used, six-fold greater than C3 plants (Nobel, 1996) because carbon uptake occurs nocturnally. CAM plants can keep their stomata closed during the day to prevent water loss – Carbon (CO_2) is sequestered at night when stomata are open, and is converted to malic acid until sunrise. Even though stomata are closed during the data (primarily for water conservation), photosynthesis can continue during the day (albeit at a reduced rate) by converting the malic acid back into CO_2 for use in photosynthesis (Taiz and Zeiger, 2010). Various degrees of CAM expression exist – 'CAM cycling' refers to the internal re-fixation of carbon stored as malic acid while 'CAM' indicates nocturnal carbon fixation via the enzyme PEPcase with the potential for periods of stomatal opening at the beginning and end of the day. 'CAM idling' refers to stomatal closure for the entire 24-hour day, in which no new carbon is harvested but malic acid is still created nocturnally via the recapture of respiratory CO_2 (Borland et al, 2011).

Starry (2013) identified CAM metabolism in two popular green roof species, *Sedum album* and *Sedum kamtschaticum*, which supported Butler et al.'s (2011) designation of *Sedum album* and *Sedum rupestre* as facultative CAM species. Regardless of the photosynthetic pathway, the effects of GRS on plant growth and evapotranspiration of green roof plants has not been explored. In this study, the effects of substrate organic content on green roof plant growth and evapotranspiration were evaluated by growing *Sedum kamptschaticum* in four different substrates in a growth chamber for sixteen weeks.

The hypotheses that were formulated were:

1. H_O: Plant root and shoot biomass will not be affected by substrate composition.

   H_A: Plant root and shoot biomass will be affected by substrate composition, with 40% organic matter substrate producing greater root and shoot biomass than 10% and 20% substrates because of the additional cation exchange and water holding capacity provided by the organic matter.

2. H_O: Green roof substrate organic content will not affect evapotranspirational water loss from pots planted with *Sedum kamptschaticum*.

   H_A: Green roof substrate organic content will affect evapotranspirational water loss from pots planted with *Sedum kamptschaticum*, since shoot growth is expected to increase with increasing proportions of organic matter, which should lead to greater leaf area and canopy volume and thus greater evapotranspiration.

4.2 Materials and Methods

In June 2012 a 60:40 crushed recycled brick:scoria mineral component was blended with mushroom compost (Frey Brothers, Lancaster, Pennsylvania) in a drum mixer to create three different substrates on a volumetric (m^3/m^3) basis: 90 mineral:10 organic, 80 mineral: 20 organic, or 60 mineral:40 organic. The total volume of each blend was adequate for platform-scale lab analyses plus 22 L to be stored in cold storage in airtight containers. In addition to the experimental blends, 1.5 cubic yards of a ready-to-plant extensive green roof substrate (Rooflite™ manufactured by Skyland, USA (Landenburg, PA) were stored in supersacks at the Research Greenhouse Complex (College Park, Maryland), and 22L of the Rooflite™ media were also placed in an airtight container in cold storage.

On 6 June 2013 a pot-scale growth chamber study was installed using the three experimental blends plus Rooflite™ as a control, utilizing the media which had been in cold storage. Oyama pot-in-pots were used; these containers are designed for African Violet production (AV Planters, San Lorenzo, CA), as previously described in Solano (2010) and Solano et al. (2012). In addition to the four planted treatments, three single-pot replicates of each substrate were left unplanted and watered with all other replicates for the duration of the study. Fifteen single-pot replicates of each substrate were planted with one *Sedum kamtschaticum* plug from a 72-plug flat that had been rooted for approximately one year (Emory Knoll Farms, Street, MD). Before planting, the propagation media was washed from the plug roots. The Oyama container volume was 500 mL; the top container rested inside a separate container, allowing the measurement of leachate following irrigation events. Pots were watered with 100 mL (equivalent to 1.27 cm rainfall based on container surface area) every third day, and leachate was immediately emptied from the bottom container to remove excess water reserves for plants.

All pots were placed in a growth chamber at 29°C day, 16°C night, with a 12-hour photoperiod at 1200 $\mu mol/m^2/s$ (light intensity) in a completely randomized design. Three single-pot replicates from planted treatments were harvested on three separate occasions (15 July, 5 September, and 14 October). Root length, root fresh and dry weight, shoot fresh and dry weight, and leaf area were recorded at each harvest. Leachate volumes were recorded for all replicates after the irrigation event most closely preceding a harvest. After the final harvest, six single pot replicates from each planted treatment plus three single pot unplanted replicates remained in the growth chamber and pot weights were recorded twice daily. Resultant weight loss was attributed to evapotranspiration (planted replicates) and evaporation (unplanted replicates). After 10 days, all replicates were re-watered with 20 mL water every 12 minutes until each replicate had received 100 mL of water to mimic a 1.27 cm rain event occurring over one hour. Leachate volumes were recorded for each replicate as before, and weights were recorded twice daily for the next 7 days. Replicates were not re-watered for five additional days – totaling 12 days without water – however, they were watered as before, mimicking a one-hour, half-inch rain event and leachate volumes from each replicate were recorded. Water loss was again recorded for the next 10 days. After the third dry-down period all plants were destructively harvested as previously described.

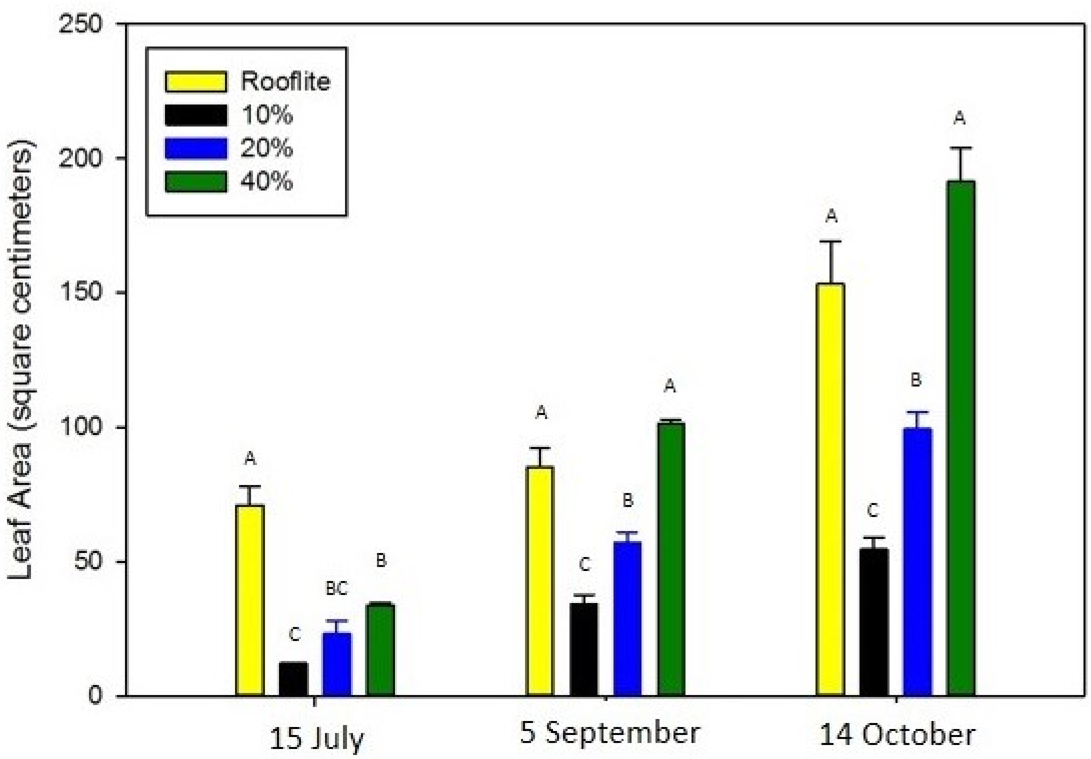
Data were analyzed using the MIXED procedure in SAS 9.3 and the LSMEANS statement; Scheffe's adjustment was used for multiple means comparisons for all data with α=0.05.

4.3 Results and Discussion

4.3.1 Destructive Harvests

Sedum kamptschaticum leaf area was greater for plants grown in the industry standard (Rooflite ™) blend for the first harvest but was not different from the 40% OM treatment for the second and third harvests (Fig. 4.1). Plants grown in 20% OM substrate had less leaf area than those grown in 40% OM and greater leaf area than those grown in 10% OM, which was expected given the benefits of increased water availability with increasing proportions of organic matter.

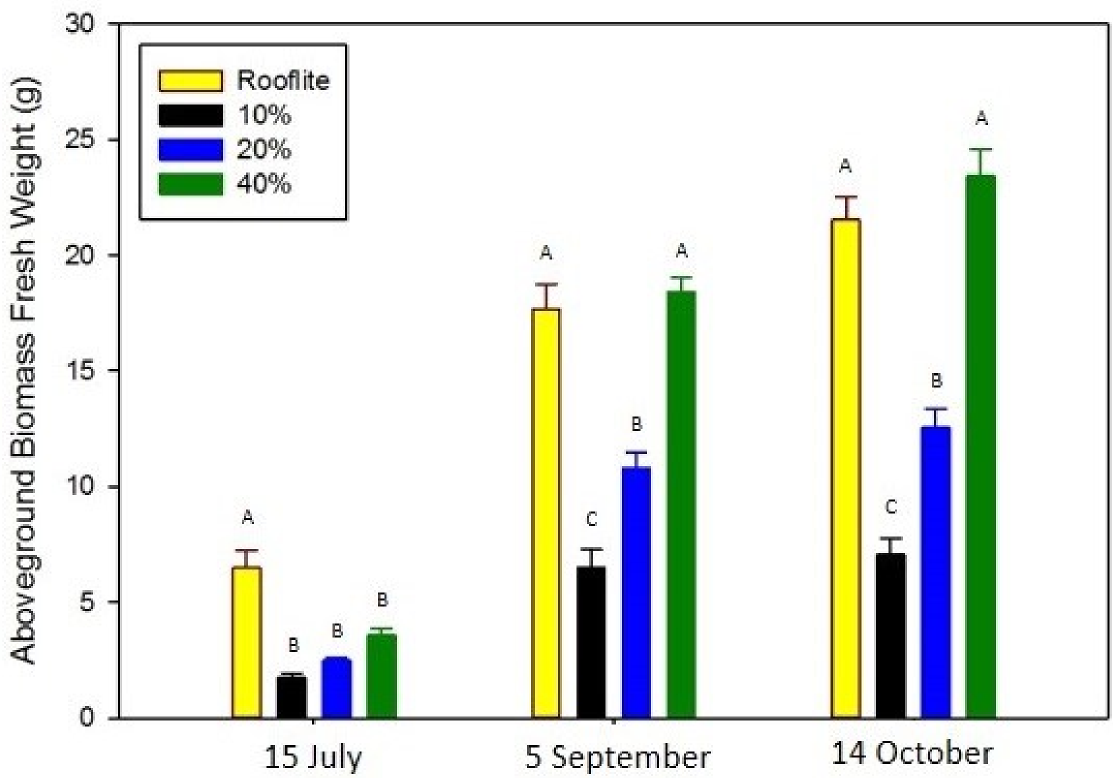
Fig. 4.1. Leaf area of *Sedum kamptschaticum* in three green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry standard control (Rooflite™) substrate. Means (n=3) are shown for each treatment per harvest date. Letters indicate significance at α=0.05 using Scheffe's adjustment for multiple means comparison.



Although the Rooflite™ has similar organic content gravimetrically (Appendix C), the volumetric proportion of OM is unknown. Nonetheless, the increased leaf area for plants grown in the industry standard blend for the first harvest may be due to increased water availability as a function of particle size distribution (Appendix B, Table B.2.). Although Rooflite™ has fewer small-diameter particles compared to the experimental blends, (<0.355 mm), it has a greater proportion of medium-diameter particles (0.355-2.36 mm, which increases the water holding capacity of the substrate. The increased growth during the first six weeks of the study may demonstrate that water availability plays a greater role than increased nutrient availability.

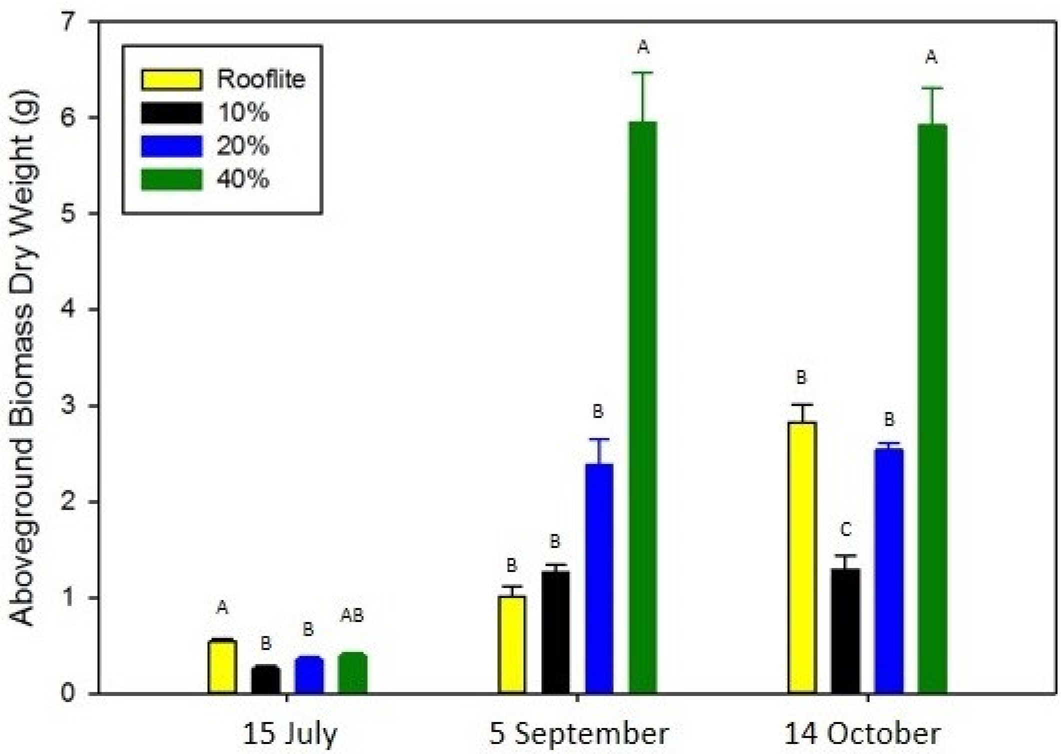
The trend was similar for aboveground biomass fresh weight as the Rooflite™ industry standard substrate outperformed the three experimental blends, but only for the first harvest. By the second harvest the 40% OM blend was no different than the Rooflite™ with 20% OM and 10% OM producing less fresh biomass each, respectively (Fig. 4.2).

Fig. 4.2 Aboveground biomass fresh weight of *Sedum kamptschaticum* plants grown in three green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter compared to an industry standard control (Rooflite™) substrate. Means (n=3) are shown for each treatment per harvest date. Letters indicate significance at α=0.05 using Scheffe's adjustment for multiple means comparison.



Aboveground biomass dry weight indicated that although leaf area and fresh weight may be more sensitive to water availability than nutrient availability during early establishment (in this case approximately 6 weeks) (Fig. 4.3), dry mass accumulation is more sensitive to nutrient availability, given the differences in particle size distribution between the Rooflite™ and experimental blends (Appendix B, Table B.2.). Dry mass for plants grown in the industry standard was similar to that of plants grown in the 40% OM blend for harvest one, but the 40% OM blend outperformed all other treatments for subsequent harvests.

Fig. 4.3. Aboveground biomass dry weight of *Sedum kamptschaticum* plants grown in three green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry standard control (Rooflite™) substrate. Means (n=3) are shown for each treatment per harvest date. Letters indicate significance at α=0.05 using Scheffe's adjustment for multiple means comparison.



Differences in below-ground biomass fresh weight were only detected at the second harvest, when the 20% OM blend produced less biomass than the other three treatments (Fig. 4.4). There were no differences in belowground biomass dry weight for any of the harvests (Fig. 4.5).

Fig. 4.4. Below-ground biomass fresh weight of *Sedum kamptschaticum* plants grown in three green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry standard control (Rooflite™) substrate. Means (n=3) are shown for each treatment per harvest date. Letters indicate significance at α=0.05 using Scheffe's adjustment for multiple means comparison.

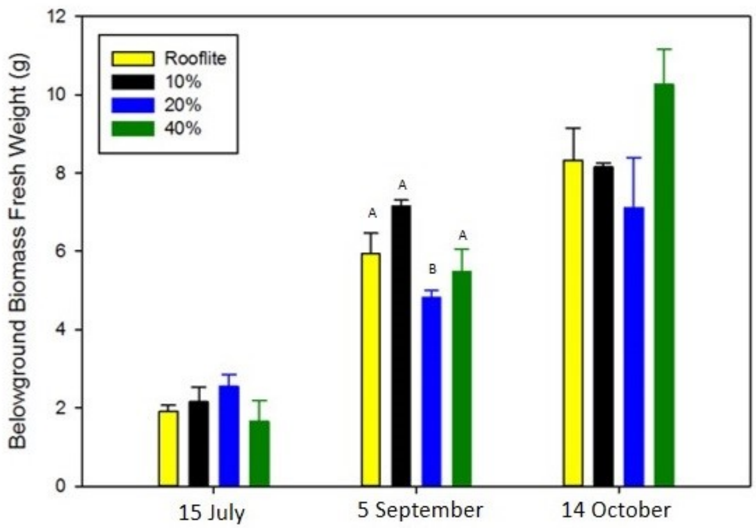
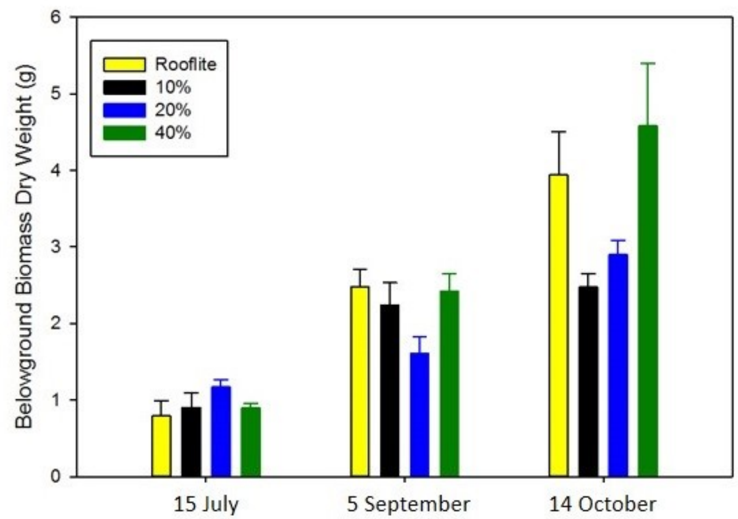
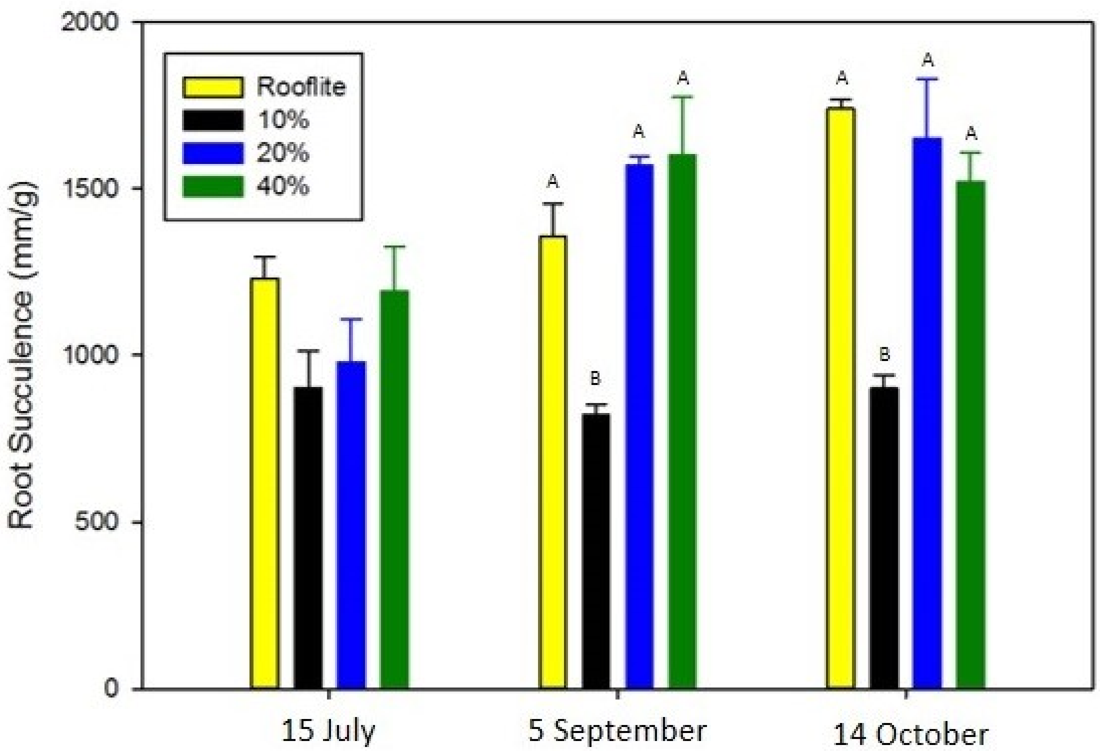


Fig. 4.5. Below-ground biomass dry weight of *Sedum kamptschaticum* plants grown in three green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry standard control (Rooflite™) substrate. Means (n=3) are shown for each treatment per harvest date. Letters indicate significance at α=0.05 using Scheffe's adjustment for multiple means comparison..



Root succulence was calculated by dividing the total root length (mm) by the belowground biomass fresh weight (g) to account for variability in root structure. There were no differences in root succulence for harvest one; however, plants grown in the 10% OM blend demonstrated less root succulence than all other treatments for remaining harvests (Figure 4.6). Total in-pot nutrient availability per treatment is presented in Appendix E. Given the limited pot volume, N availability ranged from 0.19 to 0.76 g per pot, indicating that differences in establishment may be more sensitive to water availability than nutrient availability.

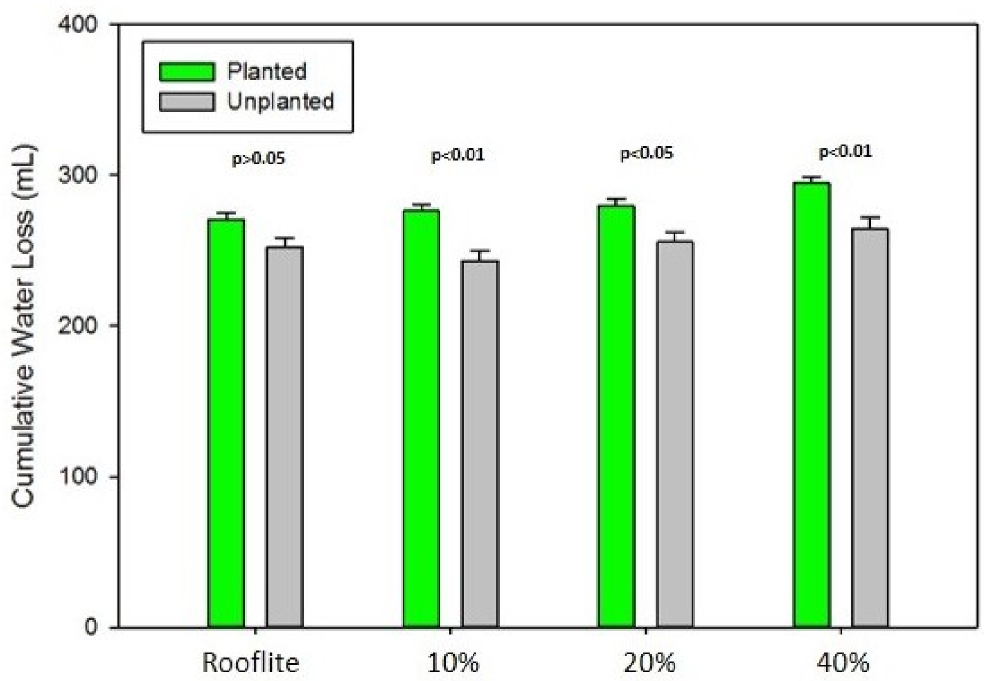
Figure 4.6. Root succulence of *Sedum kamptschaticum* plants grown in three green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry standard control (Rooflite™) substrate. Root succulence determined by dividing total root length (mm) by root fresh weight (g). Means (n=3) are shown for each treatment per harvest date. Letters indicate significance at α=0.05 using Scheffe's adjustment for multiple means comparison.



4.3.2 Plant Dry Downs

Planted replicates lost more water than unplanted replicates over the course of the three cumulative dry-down periods (Fig. 4.7), supporting Starry's (2013) findings that planted green roofs do mitigate more stormwater than unplanted green roofs.

Fig. 4.7. Total cumulative water lost by *Sedum kamptschaticum* planted in three different green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry standard control (Rooflite™) and unplanted pots with the same substrate. This represents the sum of averaged water loss after three separate 100-mL irrigation events, for a total of three dry-down periods. Means (n=6 and n = 3 for each planted and unplanted treatment, respectively) are shown for each treatment. P values indicate significance (α=0.05).



After accounting for whole plant dry biomass (Fig. 4.8), plants growing in 20% and 10% OM lost more water over the course of the three dry-down periods than those plants growing in 40% OM and the industry standard blend (Figs. 4.9 and 4.10). Note that it is not assumed that substrates with greater proportions of organic matter produce less efficient plants; rather, they produce plants with significantly greater biomass (Figs. 4.3, 4.5, and 4.8) which reduces the water loss of these larger plants when it is expressed on a per gram biomass basis. Hence, when the data are normalized in this way between treatments, it looks like the smaller plants use more water, which is not true since we are not showing total water loss per plant.

Figure 4.8. Dry mass of *Sedum kamptschaticum* grown in three different green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry standard substrate (Rooflite™). Means (n = 3) are shown for each treatment for each harvest date.

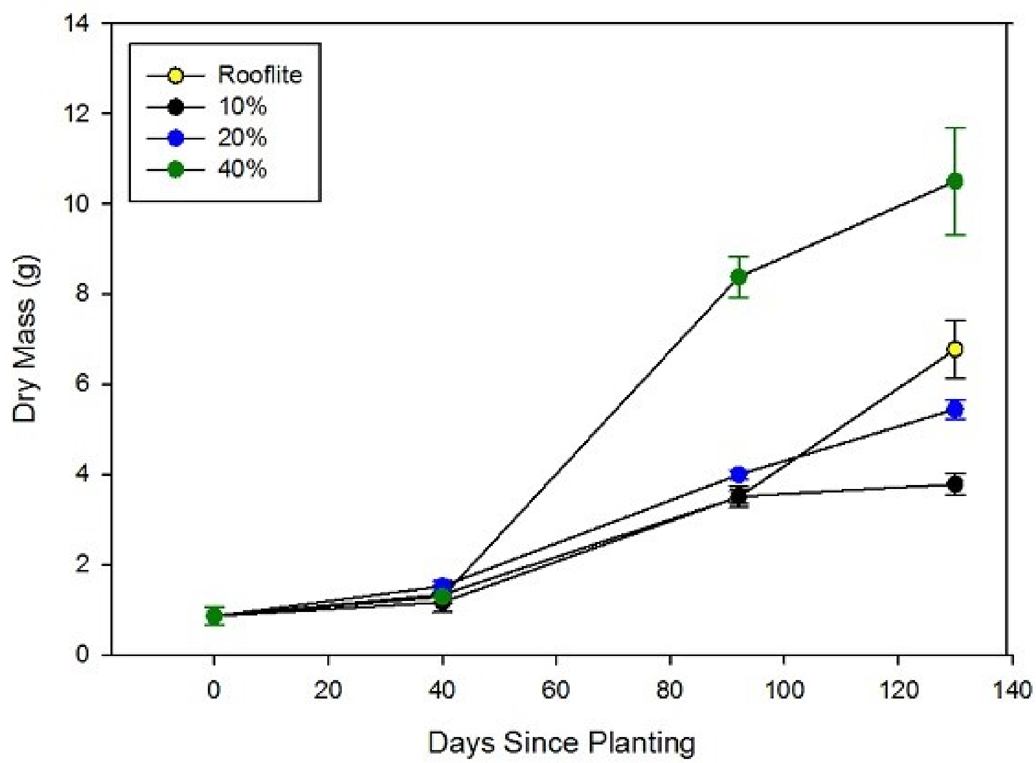


Fig. 4.9. Cumulative water loss per gram dry weight of plant biomass by container-grown *Sedum kamptschaticum* grown in three different green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry standard substrate (Rooflite™) for the first of three dry downs. Means (n = 6) are shown for each treatment at each measurement interval.

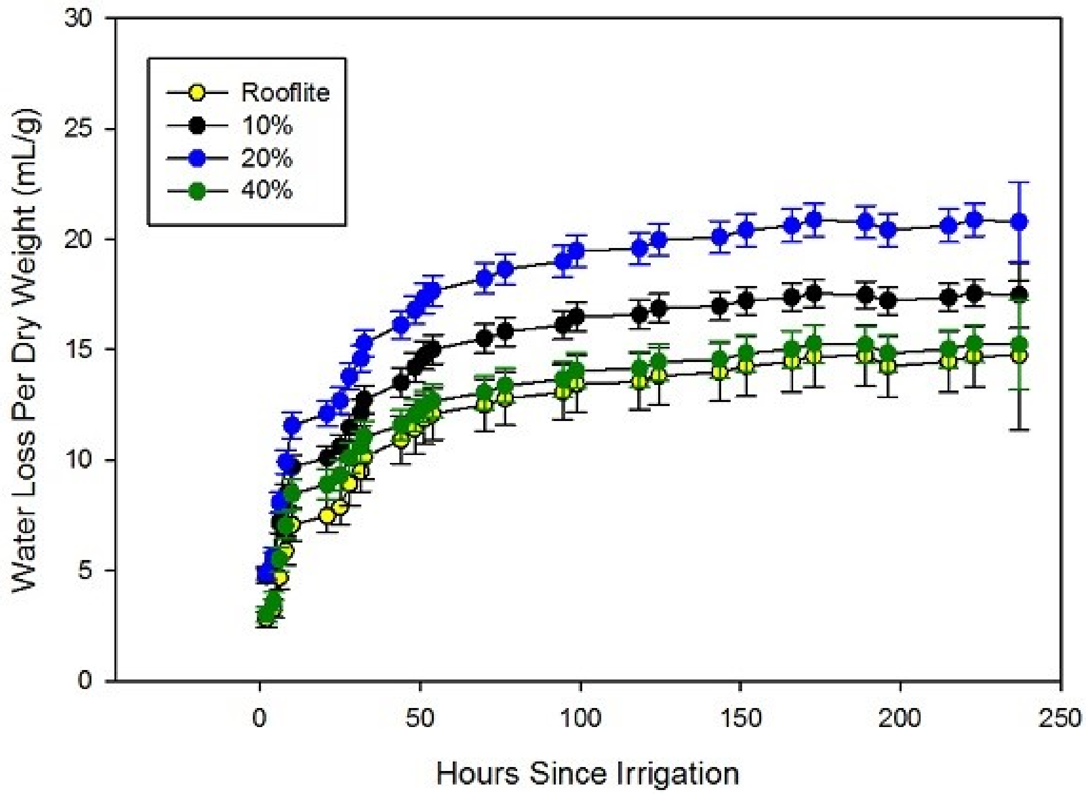
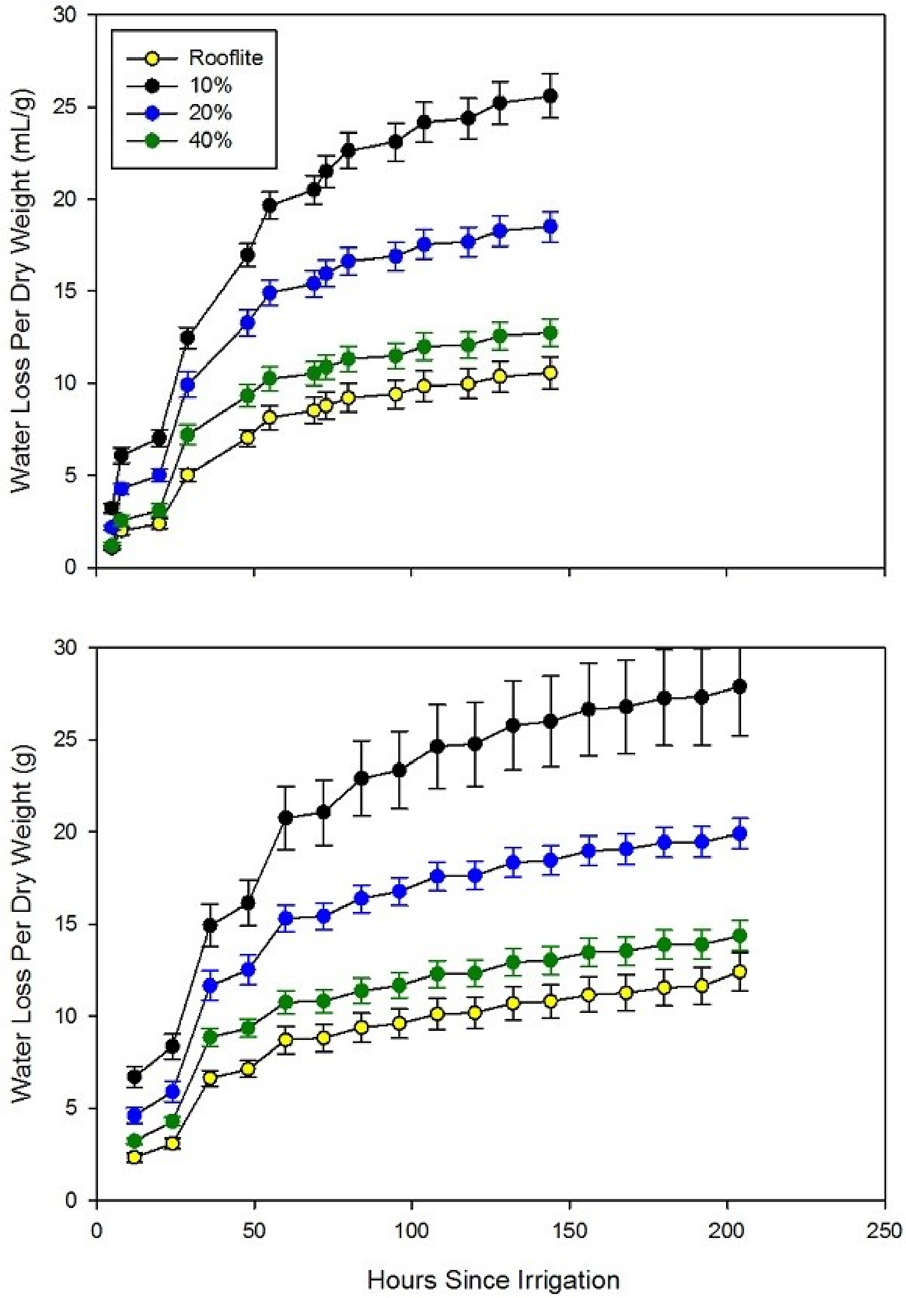


Fig. 4.10. Cumulative water loss per gram dry weight of plant biomass by container-grown *Sedum kamptschaticum* grown in three different green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry standard substrate (Rooflite™) for the second (top) and third (bottom) of three dry downs. Means (n = 6) are shown for each treatment at each measurement interval.



Interestingly, all replicates lost water more quickly at the beginning of the first dry-down as opposed to the second and third dry-down periods (Fig. 4.10). There are two possible explanations for this. Firstly, the 100 mL irrigation event which began the first dry down was applied all at once to each replicate pot while the second and third irrigation events were spread out to mimic a one-hour, 1.27 cm rain event. Secondly, the decreased rate of water loss for the second and third dry downs may indicate that plants had cycled into CAM. Until the beginning of the first dry down, plants were watered every third day with 100 mL of water and were watered in an identical fashion to begin the first dry down. They had therefore not been stressed and likely had not cycled into CAM before the beginning of the first dry down; however, by the beginning of the second dry down they had been 10 days without water and may have had their stomata closed during all or part of the day by the beginning of the second dry down. By the beginning of the third dry down, the plants had been over 20 days without water except for the 100 mL applied for the second dry down.

Because water loss is collectively attributed to evapotranspiration and transpiration, average per-treatment water loss at each time interval for unplanted treatments was subtracted from average per-treatment water loss for planted treatments (Figs. 4.11, 4.12, and 4.13) for each dry-down period. With the exception of the standard Rooflite™ media during the first dry down, evapotranspirational water loss from planted treatments surpassed evaporative water loss from unplanted treatments within the first 48 hours of the dry down.

Fig. 4.11. Cumulative water loss of unplanted pots with green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter subtracted from cumulative water loss of pots planted with *Sedum kamptschaticum* growing in the same experimental substrate blends for the first of three dry down periods. Means (n=3 for unplanted and n = 6 for planted treatments) are displayed.

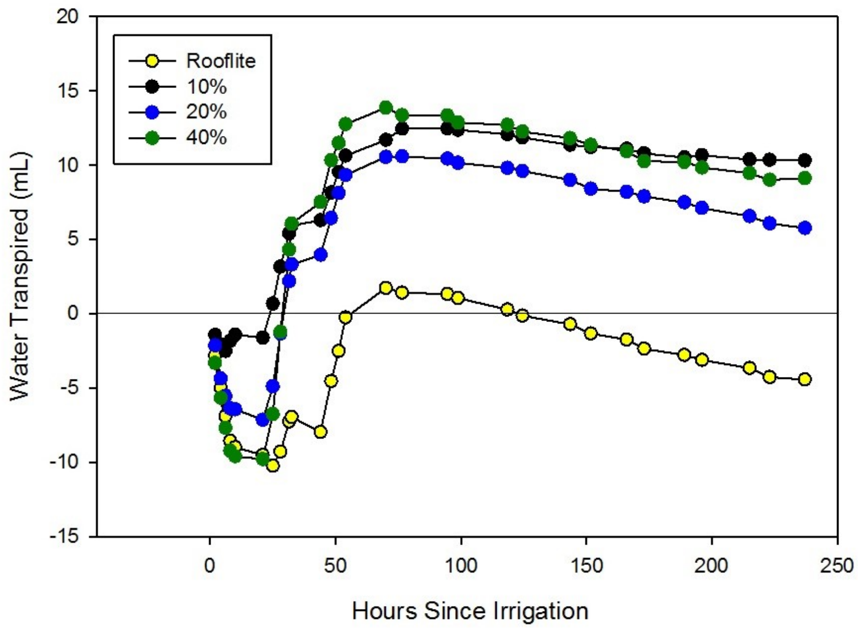


Fig. 4.12. Cumulative water loss of unplanted pots with green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter subtracted from cumulative water loss of pots planted with *Sedum kamptschaticum* growing in the same experimental substrate blends for the second of three dry down periods. Means (n=3 for unplanted and n = 6 for planted treatments) are displayed.

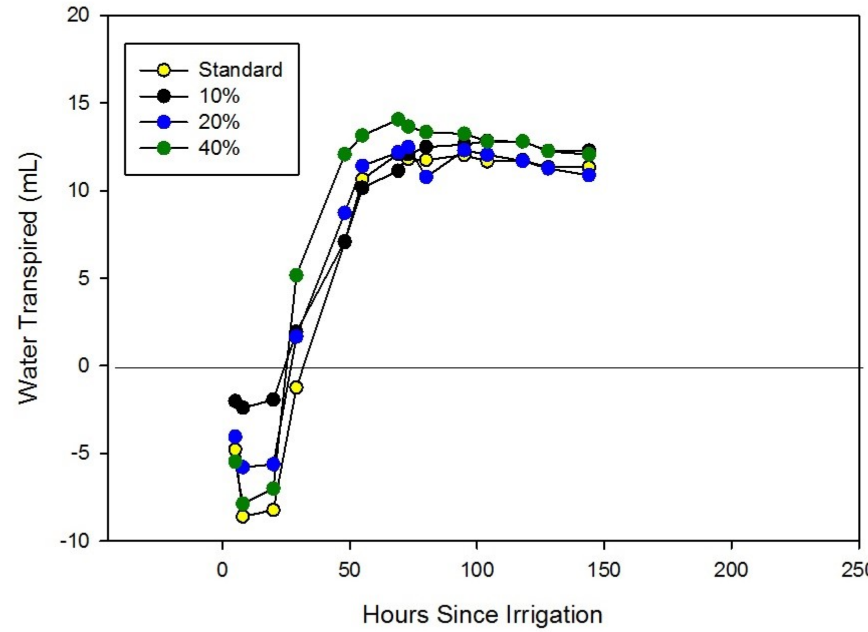
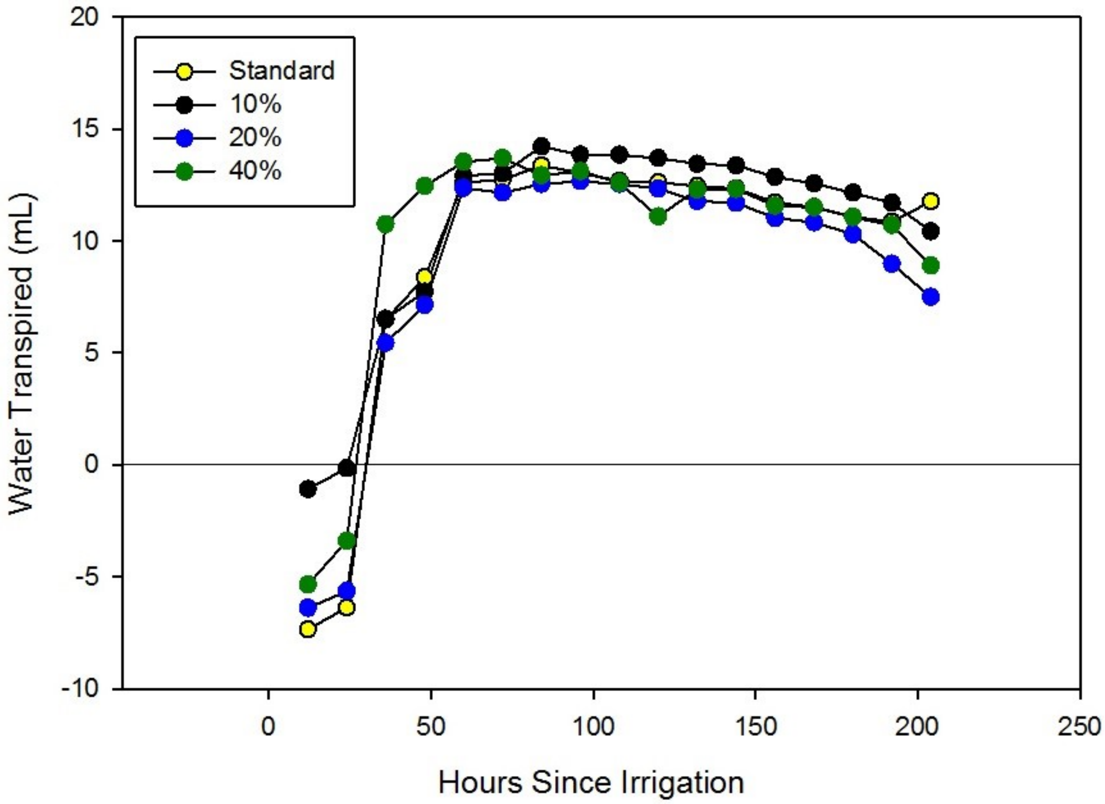


Fig. 4.13. Cumulative water loss of unplanted pots with green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter subtracted from cumulative water loss of pots planted with *Sedum kamptschaticum* growing in the same experimental substrate blends for the third of three dry down periods. Means (n=3 for unplanted and n = 6 for planted treatments) are displayed.



For the first dry down, the unplanted Rooflite™ treatment lost more water than the planted Rooflite™ treatment, which may indicate that plants in the Rooflite™ media had transitioned into CAM metabolism, with stomates closed during the day. If this was the case, then daytime water loss would be due to evaporation only, and planted pots would be expected to lose less water than unplanted pots due to the buffering effect of the plant canopy over the exposed media. These results indicate that when plants are actively evapotranspiring water, they are more effective at cycling stormwater back into the atmosphere than evaporation, confirming Starry's (2013) conclusion that *Sedum* plants are more effective at recharging green roof storage in C3 metabolism compared to CAM metabolism.

The substrate volumetric water content (VWC) was calculated for each replicate by accounting for the final plant fresh weight, substrate dry weight, and pot weight for each replicate over the course of the dry down (Figs. 4.14, 4.16, 4.18). Substrate VWC ranged from 22-25% to 3.5-5% over the course of the first dry down (Fig. 4.14). The second dry down VWC ranged from 18-22% to 4-5% (Fig. 4.16) while the third dry down VWC ranged from 20-23% to 2.5-4% (Fig. 4.18). The starting VWC was assumed to be container capacity (CC) for each substrate treatment, because each replicate produced leachate following each initial irrigation event. The final VWC at the end of each dry down indicates the plants were able pull nearly all of the water out of the substrate.

Cumulative water loss for each dry down was normalized by total plant leaf area (Figs. 4.15, 4.17, and 4.19). Similarly to the per gram dry weight water loss, normalized results indicate smaller plants may be more efficient; however, this is likely a result of the large difference in plant size between treatments. Interestingly, the rate of water loss leveled after about 60 hours for all three dry downs, which may indicate plants had transitioned to CAM to conserve water. Comparing the timing with the in-pot VWC graphs shows this transition (points of inflection) to occur around 8% VWC. Nevertheless, despite the extremely low water substrate VWC, the plants continued to transpire beyond this, albeit more slowly, further suggesting CAM activity – with stomata closed during the day, daytime water loss would be limited to evaporation and nocturnal water loss would be minimal during stomatal opening. In-pot VWC fell below 5% for all three dry downs, implying that *S. kamptschaticum* roots may have been accessing water previously assumed to be unavailable for plant uptake.

Fig. 4.14. In-pot volumetric water content for 500 mL containers planted with *Sedum kamptschaticum* in three different green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry standard control (Rooflite™) following the first of three 100 mL irrigation events. Means (n=6) are shown for each treatment at each measurement interval.

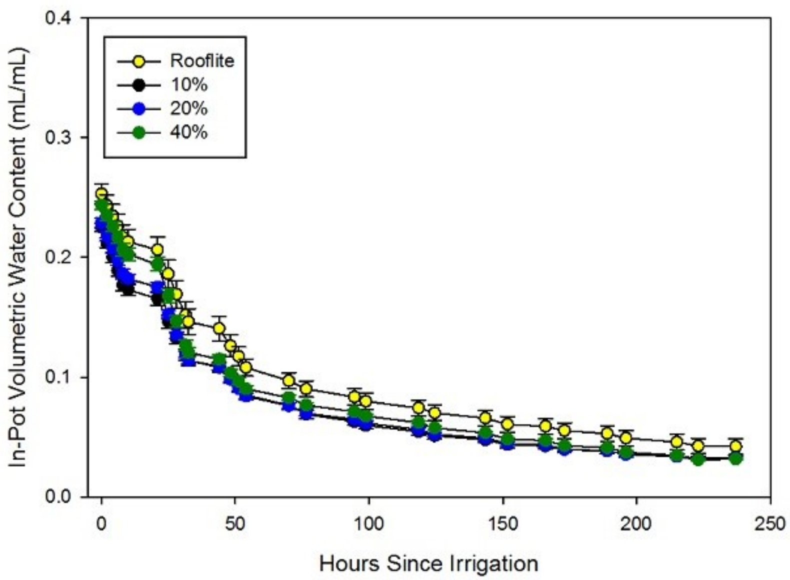


Figure 4.15. Water loss from containers planted with *Sedum kamptschaticum* in three different green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry control (Rooflite™) normalized by total replicate leaf area in the first of three dry downs. Means (n= 6) are shown for each treatment at each measurement interval.

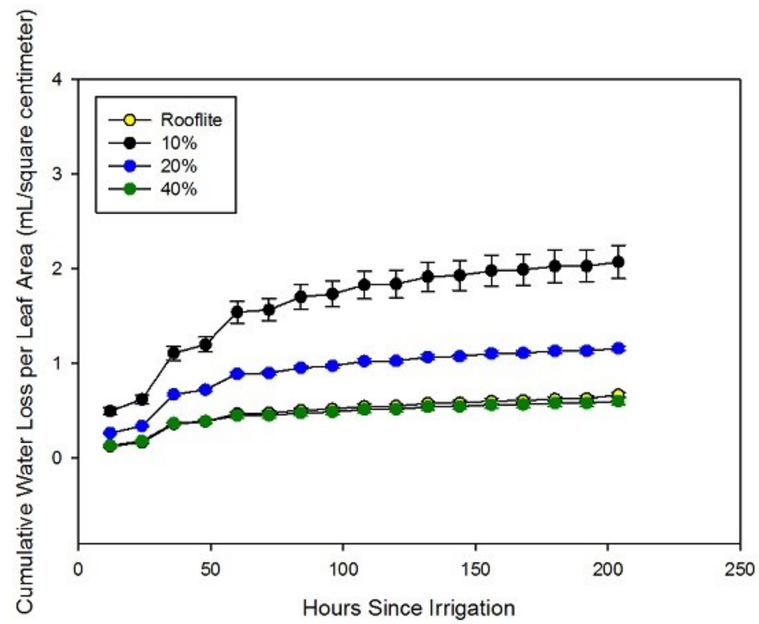


Fig. 4.16. In-pot volumetric water content for 500 mL containers planted with *Sedum kamptschaticum* in three different green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry standard control (Rooflite™) following the second of three 100 mL irrigation events. Means (n=6) are shown for each treatment at each measurement interval.

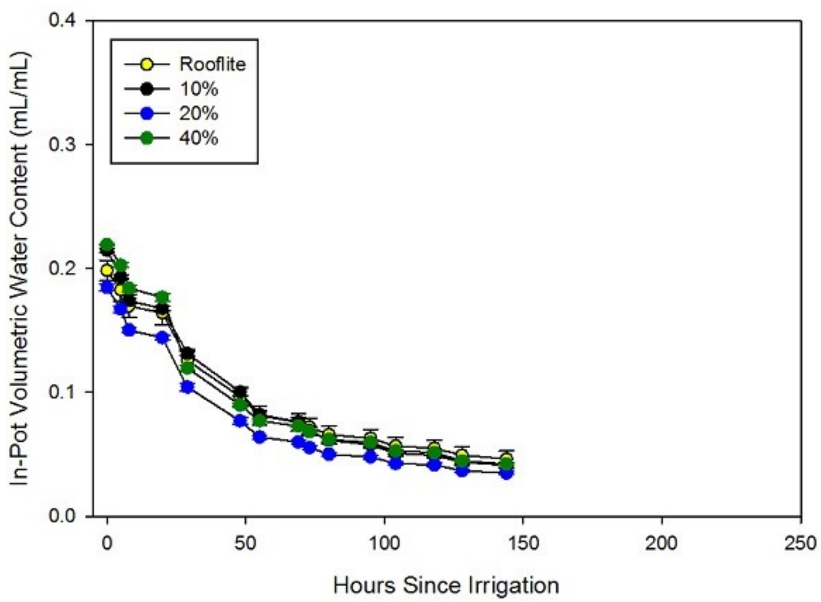


Fig. 4.17. Water loss from containers planted with *Sedum kamptschaticum* in three different green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry control (Rooflite™) normalized by total replicate leaf area in the second of three dry downs. Means (n= 6) are shown for each treatment at each measurement interval.

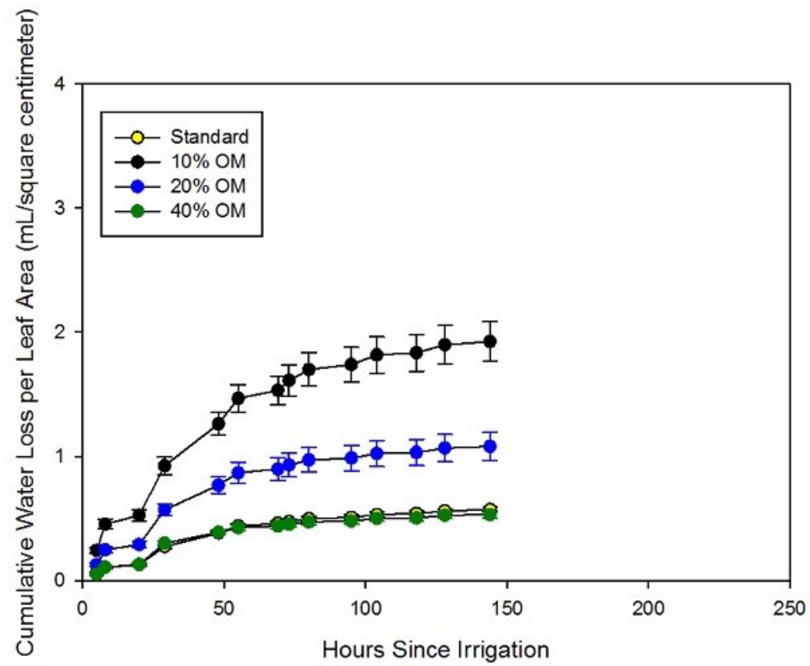


Fig. 4.18. In-pot volumetric water content for 500 mL containers planted with *Sedum kamptschaticum* in three different green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry standard control (Rooflite™) following the second of three 100 mL irrigation events. Means (n=6) are shown for each treatment at each measurement interval.

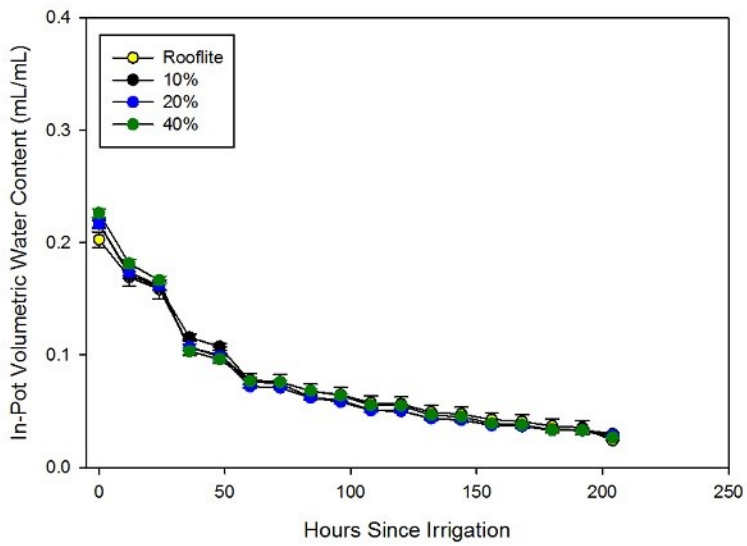
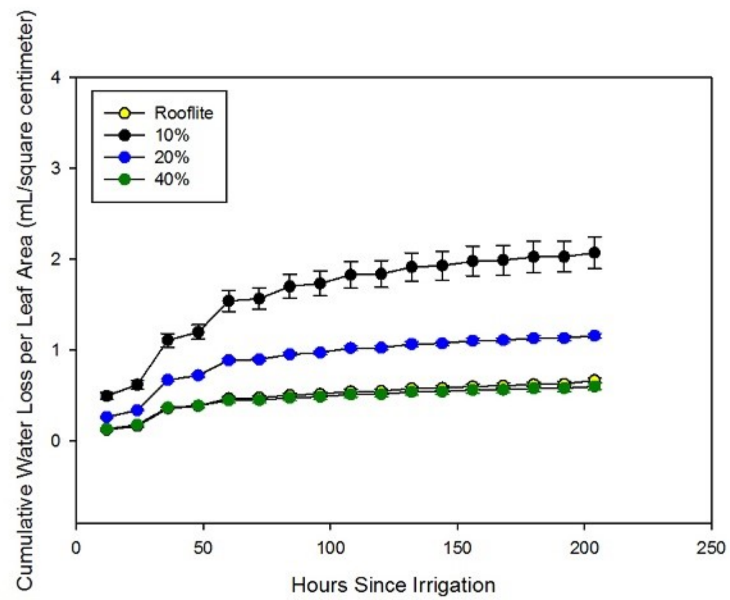


Fig. 4.19. Water loss from containers planted with *Sedum kamptschaticum* in three different green roof substrates with increasing volumetric proportions (10%, 20%, and 40%) of organic matter plus an industry control (Rooflite™) normalized by total replicate leaf area in the second of three dry downs. Means (n= 6) are shown for each treatment at each measurement interval.



4.4 Conclusions

As expected, increasing the volumetric proportions of organic matter in GRS results in plants with greater biomass and leaf area, likely due to increased water availability with increasing organic matter. Substrate composition did not affect the total volume of water removed from the containers over time; rather, the presence of larger plants resulted in greater transpirational water use (Fig. 4.7). Normalizing water loss by plant biomass dry weight and leaf area indicated a greater efficiency for smaller plants but it is assumed this is a misleading result based on the effect of smaller denominators for smaller plants. *S. kamptschaticum* plants grown in 10% organic matter had less biomass and leaf area than plants grown in 20% or 40% organic matter – dividing the cumulative water lost by a smaller denominator (dry biomass or leaf area, respectively) would have resulted in a larger normalized value than dividing by a larger denominator, i.e. for plants grown in 40% organic matter.

Perhaps the most interesting results of this experiment are the in-pot VWC reached during the course of the three dry downs, especially when compared to cumulative water loss, which typically asymptoted at approximately 8% VWC for all three dry-down periods (and substrates). Permanent wilting point is assumed to be -15 kPa matric potential (Keihl et al., 1992), which for horticultural substrates is around 40% VWC (Rodriguez 2009). These results indicate that *Sedum kamptschaticum* can access water previously assumed to be unavailable to plants. Clarifying the true VWC range at which green roof plants can successfully move water will allow for better estimation of stormwater mitigation potential of green roof systems and should be investigated more thoroughly.

Planted treatments lost more water than unplanted treatments cumulatively, and ET-T [evapotranspirational – evaporational] water loss during each dry down further demonstrates that plants are more effective at moving water into the atmosphere than evaporation. Applying these data to the roof- or even watershed-scale further confirms Starry's (2013) conclusions that planted rooftops are more effective stormwater mitigation tools than brown or unplanted rooftops. Furthermore, this study only spanned six months' time – the extrapolated stormwater retention potential over 30 years (assumed average lifespan of a green roof) of planted versus unplanted roofs is significant.

These results indicate growth differences from increasing the volumetric proportions of organic matter in an extensive green roof substrate may be due to differences in water availability than nutrient availability. The limited pot volumes (500 mL) resulted in a range of 0.19-0.76 g total N per pot with increasing proportions of mushroom content, indicating *Sedum kamptschaticum* plugs may have been more sensitive to the increased water holding capacity of organic matter than to the increased nutrient content. While this study served to quantify differences in *Sedum kamptschaticum* growth in experimental green roof substrates with increasing volumetric proportions of organic matter during establishment, the platform-scale field study presented in Chapter 5 provided data beyond the initial establishment period.

Chapter 5: A platform-scale study of the effects of green roof substrate organic content on the rate of substrate dry down following rain events, storm water retention, and growth of *Sedum kamptschaticum*.

5.1 Introduction

Although green roofs are becoming increasingly popular as storm water management tools, our understanding of the effects of green roof system design on storm water mitigation is still relatively poor, despite a growing body of literature. VanWoert et al. (2005) reported on the effects of roof surface, slope, and media depth on storm water retention, concluding from the platform-scale study that for all combined rain events, a 2% slope with 4 cm of substrate retained more storm water compared to 6.5% slope and 2 cm or 6 cm substrate. In a second, the authors concluded vegetated roof tops retain more storm water than gravel ballast or unplanted green roof media (VanWoert et al., 2005). The effects of substrate depth (12 cm and 20 cm, respectively) and vegetation type (herbaceous or woody shrubs) on temperature and storm water mitigation were reported by Nardini et al. (2011), where the authors found significant effects of substrate depth but no differences attributable to vegetation type. All vegetated modules retained more storm water than non-planted controls. Starry (2013) investigated the role of specific *Sedum* species on green roof storm water mitigation, reporting *Sedum kamptschaticum* and *S. sexangulare* to have the highest rates of evapotranspiration and storm water mitigation compared to *S. album*.

Looking beyond substrate depth and plant selection, the effects of substrate composition, specifically organic content, on storm water mitigation potential is not well understood. Voyde et al. (2010) investigated the effects of substrate composition and depth on storm water performance of green roofs in New Zealand and concluded that neither variable had a significant effect. Although the study did compare different compositions – the blends utilized zeolite, pumice, or expanded clay, respectively - each blend was a volumetric proportion of 80% mineral component and 20% composted bark fines. Molineaux et al. (2009) reported the effects of organic content and mineral composition on plant growth. The organic content portion of the study compared 15% (v:v) against 25% (v:v) and was independent of the study comparing mineral composition and particle size distribution. As expected, increasing the volumetric proportion of organic matter in a green roof substrate yielded larger plants; however, this was a trial study which took place in a greenhouse under well watered conditions. The effects of organic content on storm water mitigation were not investigated nor were the effects of organic content on rates of evapotranspiration reported.

Gaining a greater understanding of the effects of substrate organic content on storm water mitigation potential would better inform regulatory agencies, whose guidelines currently focus largely on substrate depth and water holding capacity (WHC) [Maryland (Maryland Department of Environment ESD Manual, 2011); Washington, DC (District Department of Environment SWM Guide, 2013); Auckland, New Zealand (Fassman-Beck and Simcock, 2013)]. Some organic matter (specifically, humic and fulvic acids) can hold up to nine times its dry weight in water (Hillel, 2004); increasing the volumetric proportions of organic matter in a green roof substrate may therefore have a significant effect on storm water retention potential. Most regulatory agencies base their substrate composition guidelines on the German Landscape Society's Manual for Green Roof Design, Installation, and Maintenance (FLL, 2008), which suggests ≤6.5g/L organic matter for an extensive green roof substrate. Given the differences in particle density between organic matter and the mineral component of a green roof substrate, volumetric organic content could range from 10-40% (APPENDIX C) and still fall within those guidelines. The study described herein served to answer the following research questions:

1. H_O: Green roof substrate organic content will not affect *Sedum kamptschaticum* growth and establishment in a platform-scale field study, as determined by canopy coverage, root fresh and dry biomass, and shoot fresh and dry biomass.

   H_A: Green roof substrate organic content will affect *Sedum kamptschaticum* growth and establishment in a platform-scale field study, as determined by canopy coverage, root fresh and dry biomass, and shoot fresh and dry biomass, because organic matter provides water holding capacity and cation exchange capacity and these will increase with increasing volumetric proportions of substrate organic content.

2. H_O: Green roof substrate organic content will not affect the substrate volumetric water content and rate of dry down following rain events in a platform-scale field study.

   H_A: Green roof substrate organic content will affect the substrate volumetric water content and rate of dry down following rain events in a platform-scale field study, because a pot-scale growth chamber experiment indicates substrate VWC during dry downs is the same for green roof substrates with 10%, 20%, and 40% organic matter.

3. H_O: Increasing the volumetric proportion of green roof substrate organic matter does not affect the percent volume of rainfall retained, when considering either total volume per rain event or intensity (volume per time).

   H_A: Increasing the volumetric proportion of green roof substrate organic matter will decrease the percent volume of rainfall retained, when considering either total volume per rain event or intensity (volume per time), because it is expected that root density in 10% organic matter substrates will be higher than 20% or 40% organic matter substrates because the plant roots will be searching for water and plant roots are the means by which plants uptake water and cycle it back into the atmosphere.

5.2 Materials and Methods

5.2.1 Platform Construction

Sixteen experimental green roof platforms [interior dimensions 113.5 cm X 113.5 cm] were constructed in May and June 2012 at the Research Greenhouse Complex at the University of Maryland in College Park, Maryland. The profile of each platform from bottom to top was as follows: 12 mm plywood decking, EPDM waterproofing membrane, drainage layer, filter fabric, experimental substrate blends, and plants (Fig. 5.1). The waterproofing membrane, plastic cup-type drainage layer, and filter fabric were obtained from Conservation Technology (Baltimore, MD). Platforms were constructed and maintained according to FLL standards (FLL, 2008). Platforms were with a 2% north-facing slope.

Fig. 5.1. Photograph of construction of the experimental green roof platforms at the Research Greenhouse Complex at the University of Maryland, College Park in May 2012.

Three different substrates were blended for the platform study. The inorganic portion was a 60:40 crushed recycled brick: scoria blend, which was blended with either 10%, 20%, or 40% (m^3/m^3) mushroom compost (Frey Brothers, Lancaster, PA). Particle size distributions of the mineral components and experimental blends are located in Appendix B, Table B.2. Four replicate platforms were installed with a 10 cm depth of each substrate blend (n=4). An additional four platforms were filled with 10 cm of the 10% organic matter blend and left unplanted to serve as a control (n=4). The four treatments were arranged in a randomized complete block design taking into account a potential climate gradient between the greenhouse range (to the NE) and an adjacent asphalt parking lot (to the SW).

The planted treatments were each planted on 4 July 2012 with 25 *Sedum kamptschaticum* plugs (Emory Knoll Farms, Street, MD) propagated in 72 plug trays. The roots of all plugs were washed completely of all propagation media prior to planting to avoid introducing additional non-plant organic matter into the substrate profile (Fig. 5.2).

Fig. 5.2. Photograph illustrating the removal of all propagation media from plug roots prior to planting.

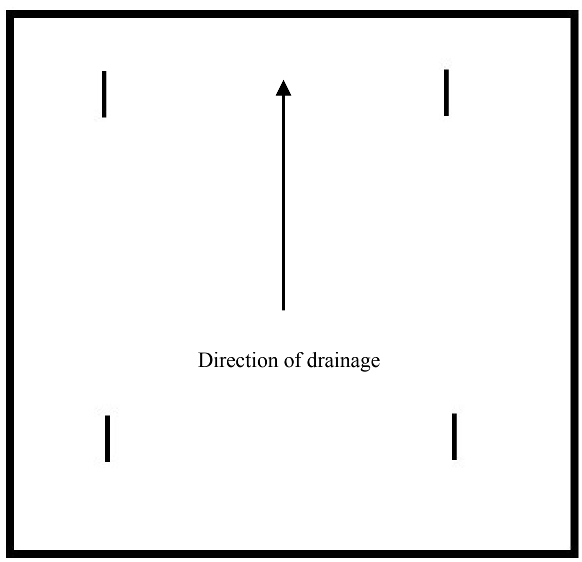
All sixteen platforms were hand-watered twice weekly to the point of drainage for two weeks following installation, after which time the study was solely dependent upon precipitation.

Per German guidelines (FLL, 2008), 15-10-15 Osmocote ® control release fertilizer was applied each spring at the recommended rate (5g N/m^2).

5.2.2 Environmental, Volumetric Water Content, and Runoff Data

Each platform was instrumented with four Echo-5TM moisture/temperature sensors (Decagon Devices, Inc. Pullman, WA) in October 2012 to measure substrate volumetric water content (VWC) and temperature data (Fig.5.3). Sensors were oriented horizontally, inserted into the substrate pointing towards the top of the slope to account for preferential water movement down the platform. Sensors were connected to Decagon nR-5 radio dataloggers, and set to average per-minute readings every five minutes.

Fig. 5.3. Diagram illustrating sensor placement for the sixteen experimental platforms.



Data were then transmitted to a base station and computer in the University of Maryland Greenhouse Range, and downloaded into DataTrac software (Decagon Devices, Inc., Pullman, WA). Sensors were calibrated to each of the three experimental blends for all VWC analyses.

In July 2013 each platform was instrumented with a double tipping bucket rain gauge (TB-4, Hydrological Services, New South Wales, Australia) (Fig. 5.4) to quantify platform runoff.

Fig. 5.4. Photograph illustrating a TB-4 rain gauge installed on one of the sixteen experimental platforms.

Runoff data were collected to a 1-minute resolution using a Campbell CR10X data logger (Campbell Scientific Inc. Logan, Utah) using a logger program that included a calibration to account for water loss during high intensity runoff events (Starry, 2013).

A weather station was installed adjacent to the platform study (Fig. 5.5). Rainfall (ECRN-100 tipping rain gauge), air temperature and humidity (ECT sensor), wind speed and direction (Davis cup anemometer), solar radiation (PYR, total radiation pyranometer), photosynthetic flux density (PPF, QSO-S PAR sensor), and leaf wetness (LWS-L) were all continuously collected using Decagon Devices (Pullman, Washington) instruments (Fig. 5.6). Environmental data were continuously collected using a Decagon Devices EM50R radio logger at 1-min resolution. (Figure 5.6).

I chose to designate a period of six hours without precipitation a separate rain event (Shamseldin, 2010; Voyde et al., 2010). Five rain events were selected from May 2013 and October 2013 and substrate volumetric water content (VWC) was plotted for the subsequent dry-down periods for each treatment (n=16).

Fig. 5.5. Photograph showing the orientation of the weather station in relation to the experimental green roof platforms at the University of Maryland Research Greenhouse Complex.

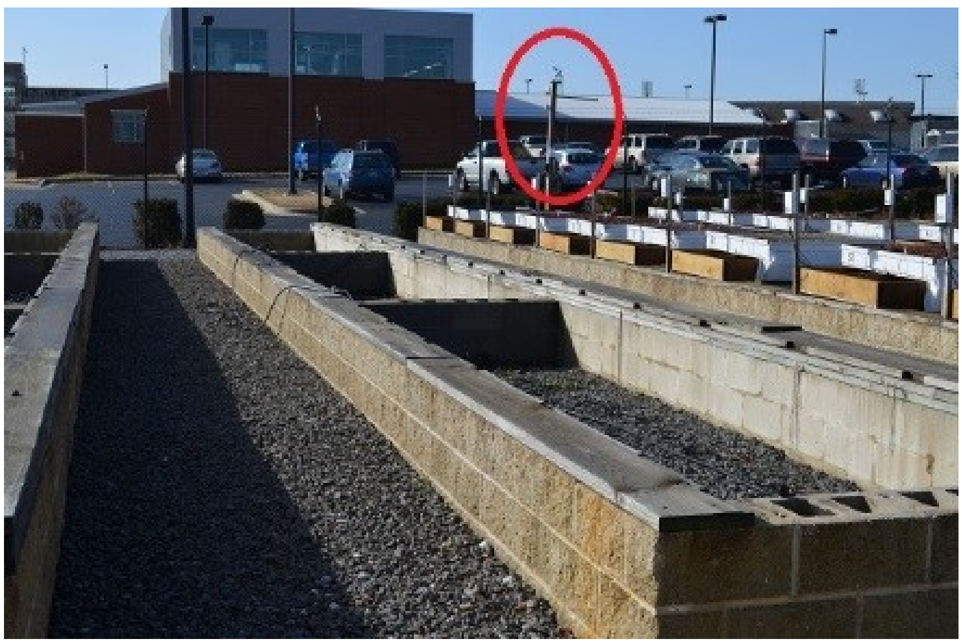
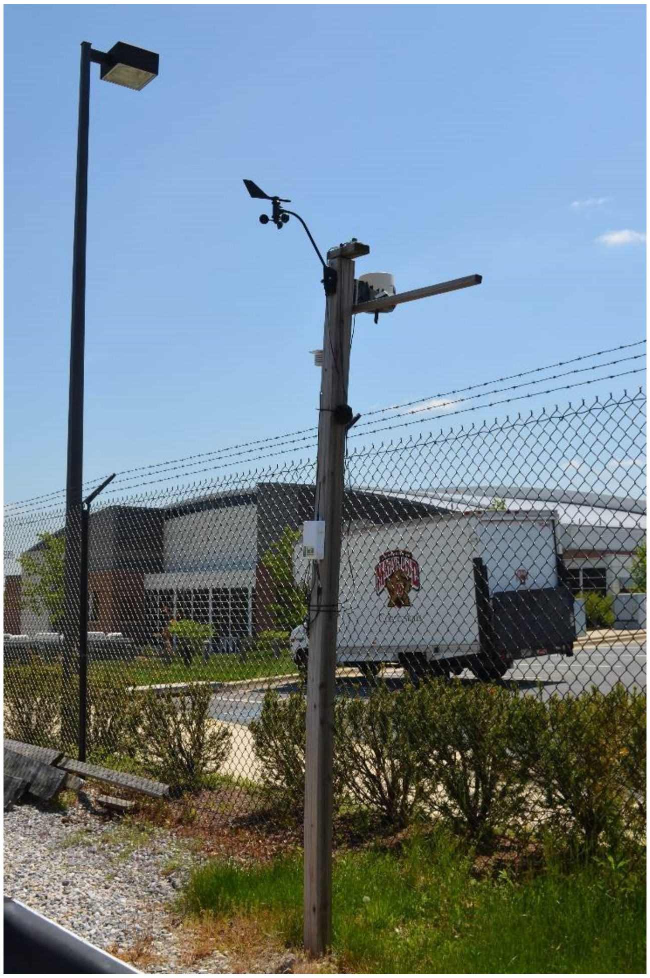


Fig. 5.6. Photograph of weather station detail.



5.2.3 Non-destructive Harvests

Platforms were sampled during October 2012, March 2013, July 2013, October 2013, and March 2014 for leaf area (Li-3100 Leaf Area Meter, Lincoln, Nebraska), shoot fresh and dry weight, root length, and root fresh and dry weight. Prior to sampling, photos were taken for canopy coverage analysis. Images were taken approximately 1.5 m above each platform using a Nikon D5100 and an iPad-based shutter control app (Figure 5.7).   Root length was quantified by hand-picking all visible roots out of each sample and measuring by hand (Figure 5.8). To determine canopy coverage, the number of pixels of plant canopy were divided by the total number of pixels of interior platform area using Adobe Photoshop CS6 (San Jose, California) following the procedure outlined by Kim et al. (2012) (Fig. 5.9). At each sampling date, three samples were randomly selected for each platform using a random number generator. Two random numbers indicated the location of each sample in a grid-based sampling pattern (Fig. 5.10).

Fig. 5.7. Photograph illustrating overhead picture-taking for canopy coverage analysis. October 2013.

Fig. 5.8. Photograph illustrating part of the method of measuring root length.

Fig. 5.9. An example of plant canopy coverage analysis using digital photography. The number of green pixels on the right would be divided by the total pixels on the left.

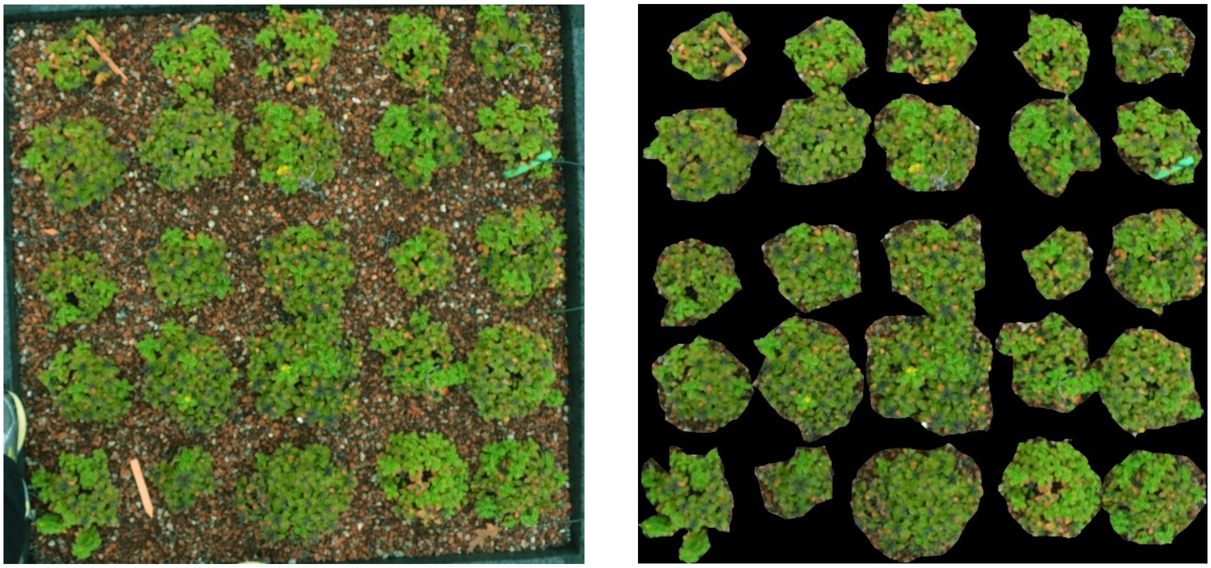


Fig. 5.10. Photograph of grid-based random sampling.

After a square was randomly selected, all plant biomass within the square and all of the substrate down to the filter fabric was sampled and processed for leaf area, shoot fresh and dry weight, root fresh and dry weight, root length, and substrate depth. After roots were hand-picked from cores all substrate material was collected, oven-dried at 110 C and ashed at 530 C for four hours using a muffle furnace to quantify the total mass of organic content (results in Appendix C).

5.2.4 Statistical Analyses

Harvest and storm water retention data were analyzed using repeated measures analysis in the MIXED procedure (SAS 9.3 SAS Institute, Inc., Cary, NC) There was no significant (α=0.05) effects by harvest date (repeated measure effect), so data were independently analyzed for each harvest date. Multiple means comparisons were performed using Scheffe's test where significant treatment differences were identified.

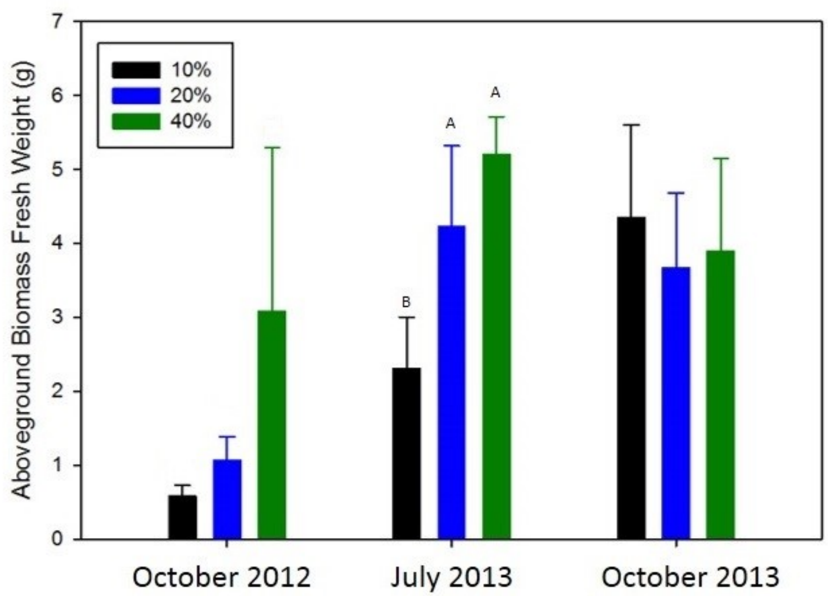
5.3 Results and Discussion

5.3.1 Non-destructive Harvests

Aboveground biomass was quantified for three of the five harvest dates – October 2012, July 2013, and October 2013, since *Sedum kamptschaticum* are deciduous and were dormant for both March harvests. Aboveground fresh and dry weights are reported in Figs. 5.11 and 5.12. The random nature of the sampling introduces a large amount of variability into the data, and may actually cause misleading results. The fresh and dry weight results for the July 2013 harvests are as expected, with plants grown in 40% organic matter producing more aboveground biomass than those grown in 10% or 20% organic matter, respectively. However, the October 2013 dry weights (Fig. 5.12) indicate greater biomass for plants grown in 10% organic matter. Thus the random nature of the sampling may introduce a large amount of variability into these data. Plant canopy coverage data using pixel analysis of digital photos offers a more accurate description of aboveground plant growth (Fig. 5.13), with increasing percentages of canopy cover as substrate organic content increases.

Fig. 5.11. Aboveground biomass fresh weight for *Sedum kamptschaticum* grown in a platform-scale green roof field study. Means (n = 4) are shown for each treatment, letters designate significance at α = 0.05, no letters indicate p>0.05.

Fig. 5.12. Aboveground biomass dry weight for *Sedum kamptschaticum* grown in a platform-scale green roof field study. Means (n = 4) are shown for each treatment, letters designate significance at α = 0.05.



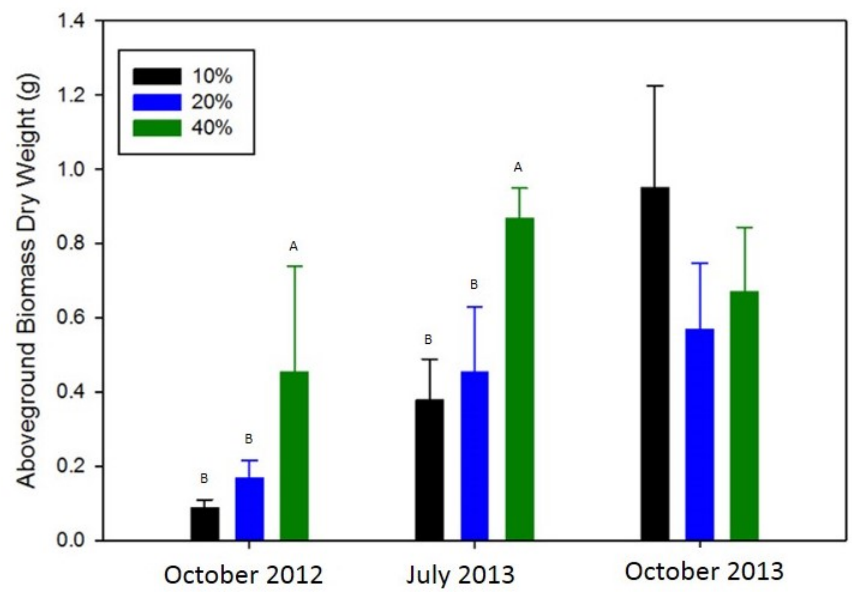


Fig. 5.13. Platform canopy coverage for *Sedum kamptschaticum* grown in a platform-scale green roof field study. Means (n = 4) are shown for each treatment, letters designate significance at α = 0.05.

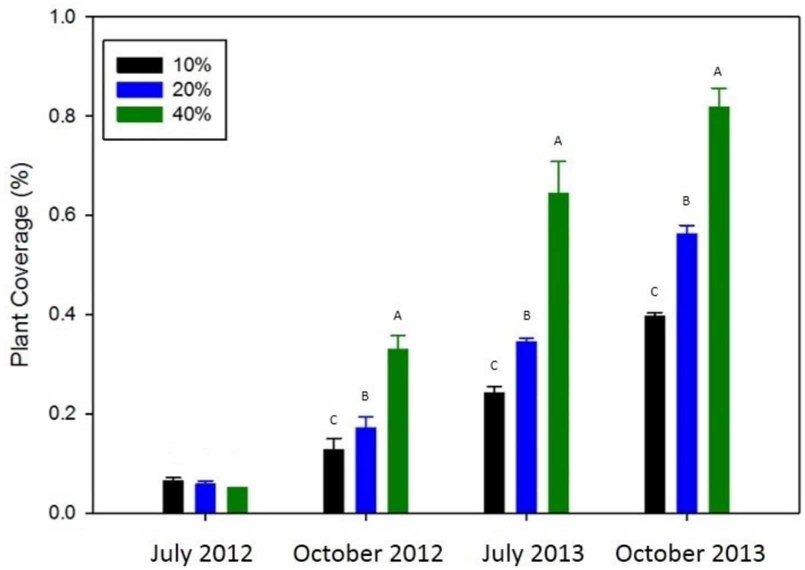
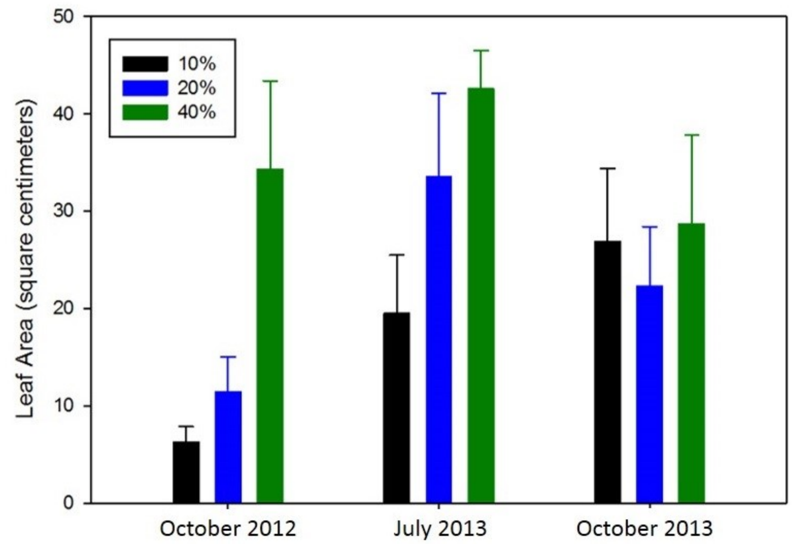
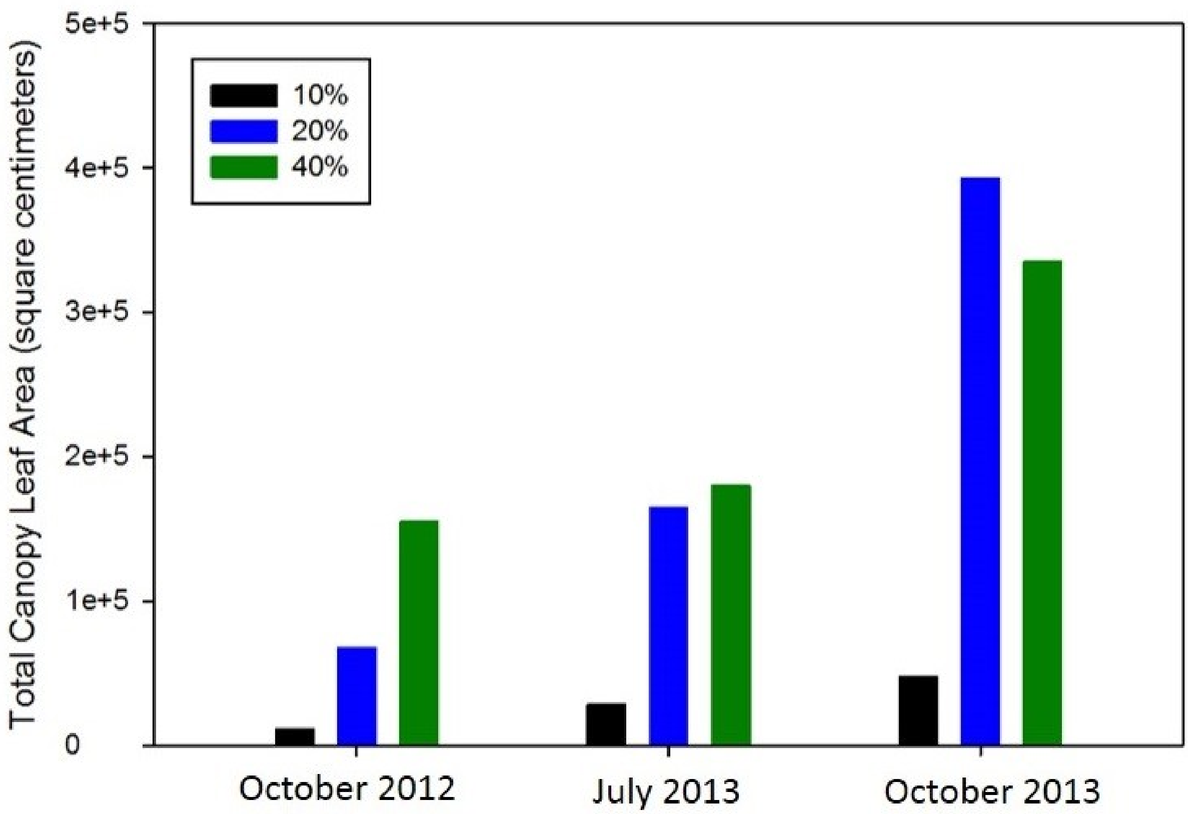


Fig. 5.14. Leaf area for *Sedum kamptschaticum* grown in a platform-scale green roof field study. Means (n = 4) are shown for each treatment.



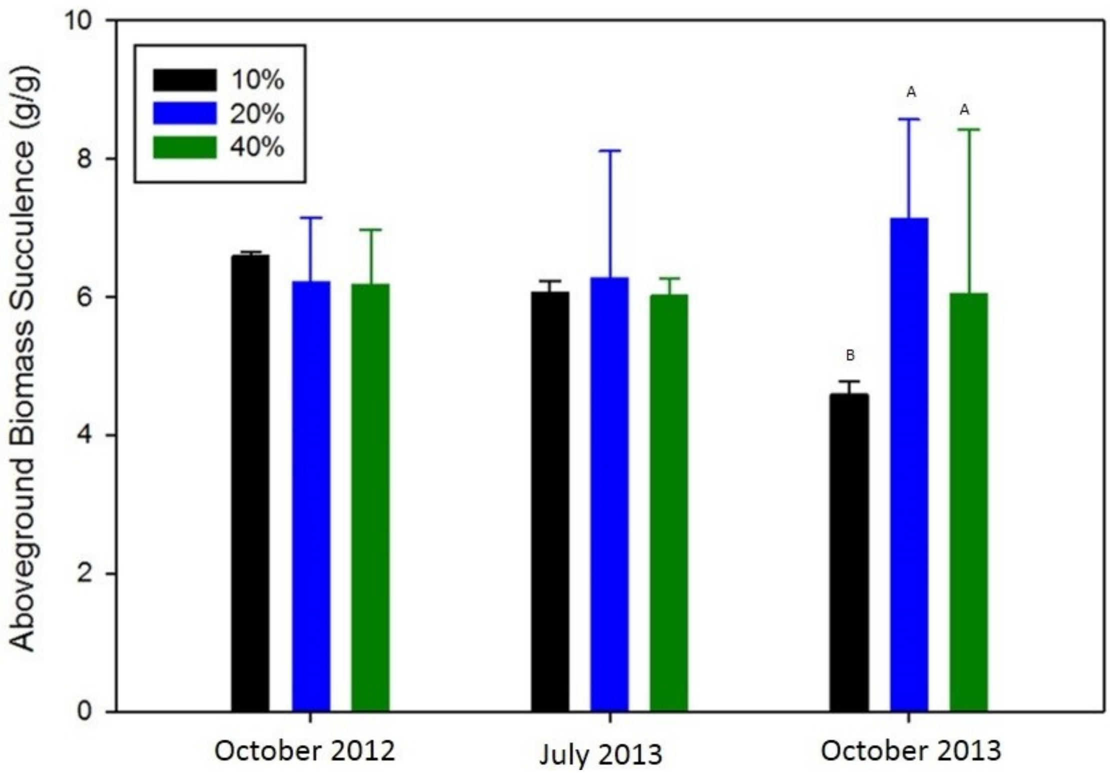
Plant canopy coverage data provides an excellent representation of two-dimensional shoot growth. Leaf area (Fig. 5.14) better describes three-dimensional shoot growth because all aboveground biomass within the sample area was quantified, particularly as leaves were often stacked vertically in the canopy. Thus total canopy leaf area was extrapolated by multiplying platform canopy coverage and leaf area data, presented in Fig. 5.15. These extrapolated data indicate a significant effect of substrate organic content on aboveground biomass.

Fig. 5.15. Total canopy leaf area of *Sedum kamptschaticum* grown in a platform-scale green roof field study. Results were extrapolated from the product of platform canopy cover and sample leaf area. Means (n = 4) are shown for each treatment.



Shoot succulence was determined by dividing aboveground fresh weight by above-ground dry weight (Fig. 5.16). Interestingly, differences were only detected for the October 2013 harvest date, when plants grown in 20% and 40% organic matter had a higher degree of succulence.

Fig. 5.16. Shoot succulence for *Sedum kamptschaticum* grown in a platform-scale green roof field study. Results were extrapolated from by dividing aboveground biomass fresh weight by aboveground biomass dry weight. Means (n = 4) are shown for each treatment, letters designate significance at α = 0.05, no letters indicate p>0.05.



Belowground biomass data were gathered for all five harvest dates. Again, random sampling may have introduced large amounts of variability into the data set; however, comparing the July 2013 fresh weight (Fig. 5.17) to July 2013 dry weight (Fig.5.18) indicates a large amount of water storage in the root system for all treatments. Root succulence was determined by dividing belowground biomass fresh weight by belowground biomass dry weight, presented in Figure 5.19.

Fig. 5.17. Belowground biomass fresh weight for *Sedum kamptschaticum* grown in a platform-

scale green roof field study. Means (n = 4) are shown for each treatment, letters designate significance at α = 0.05, no letters indicate p>0.05.

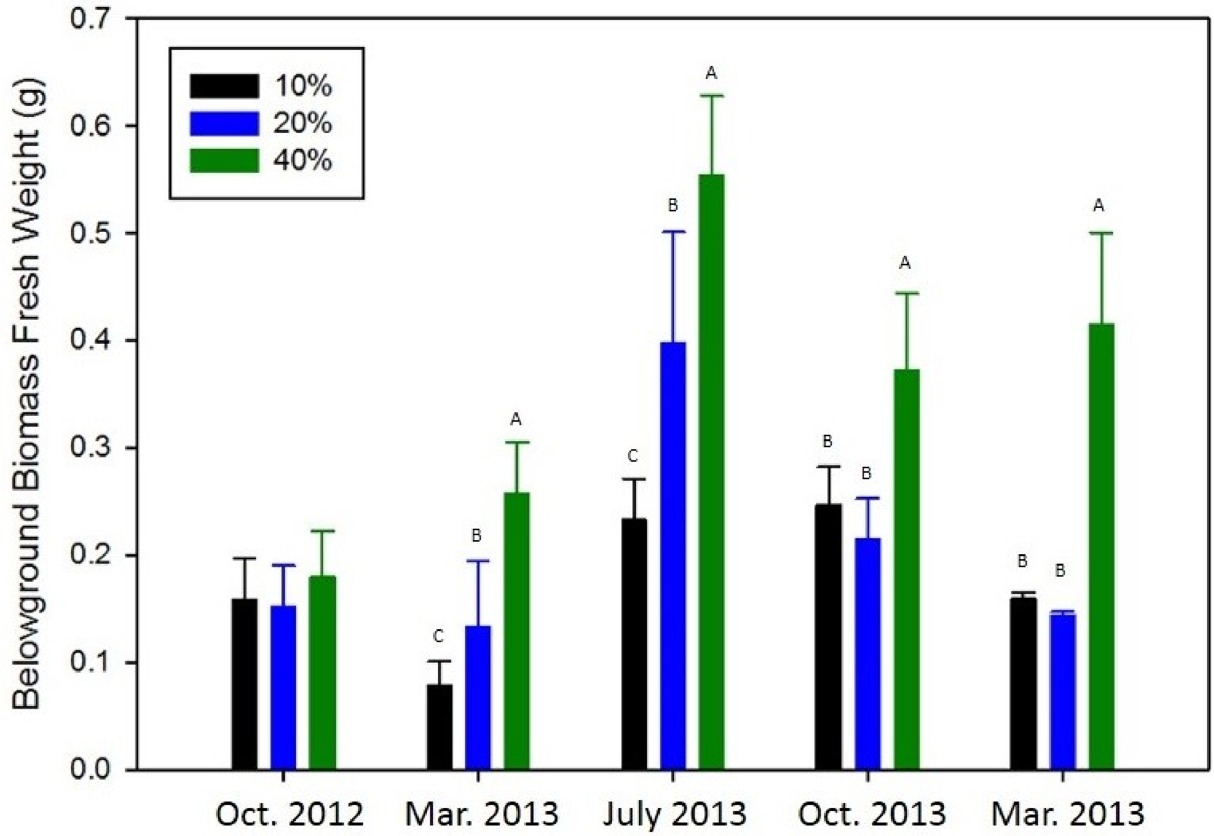


Fig. 5.18. Belowground biomass fresh weight for *Sedum kamptschaticum* grown in a platform-scale green roof field study. Means (n = 4) are shown for each treatment, letters designate significance at α = 0.05, no letters indicate p>0.05.

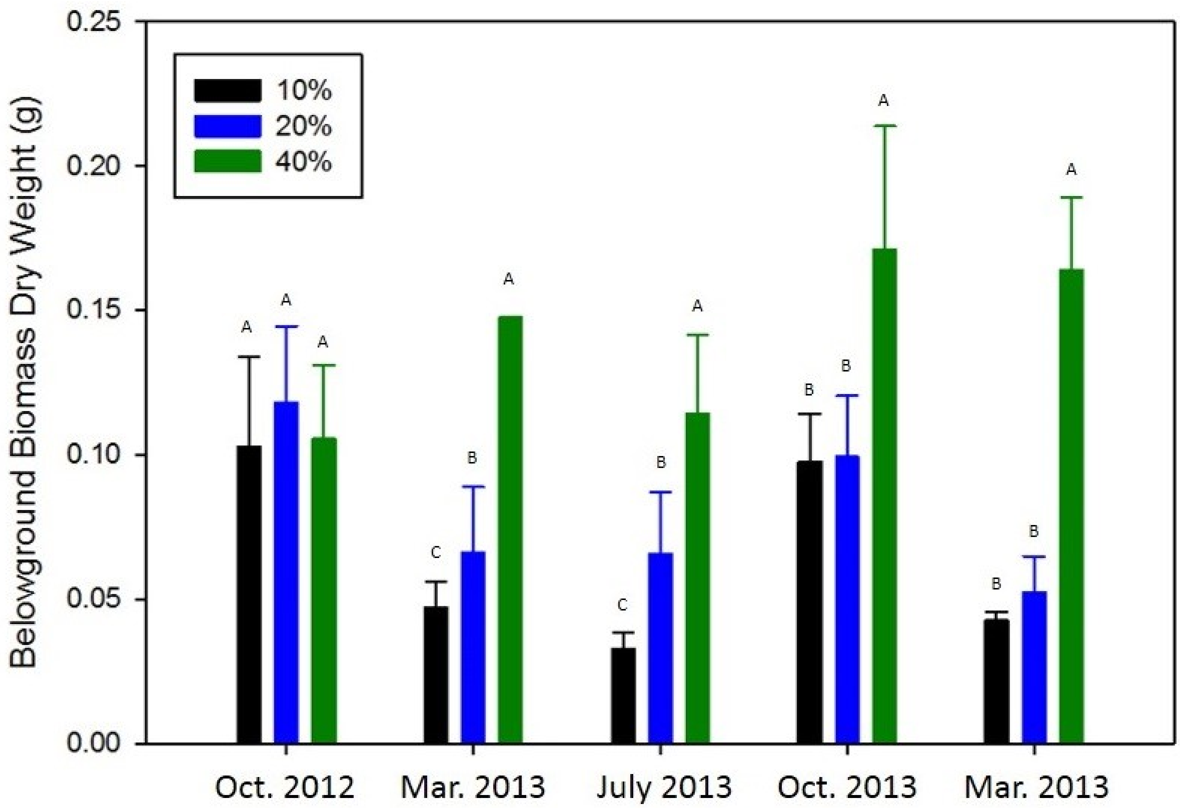
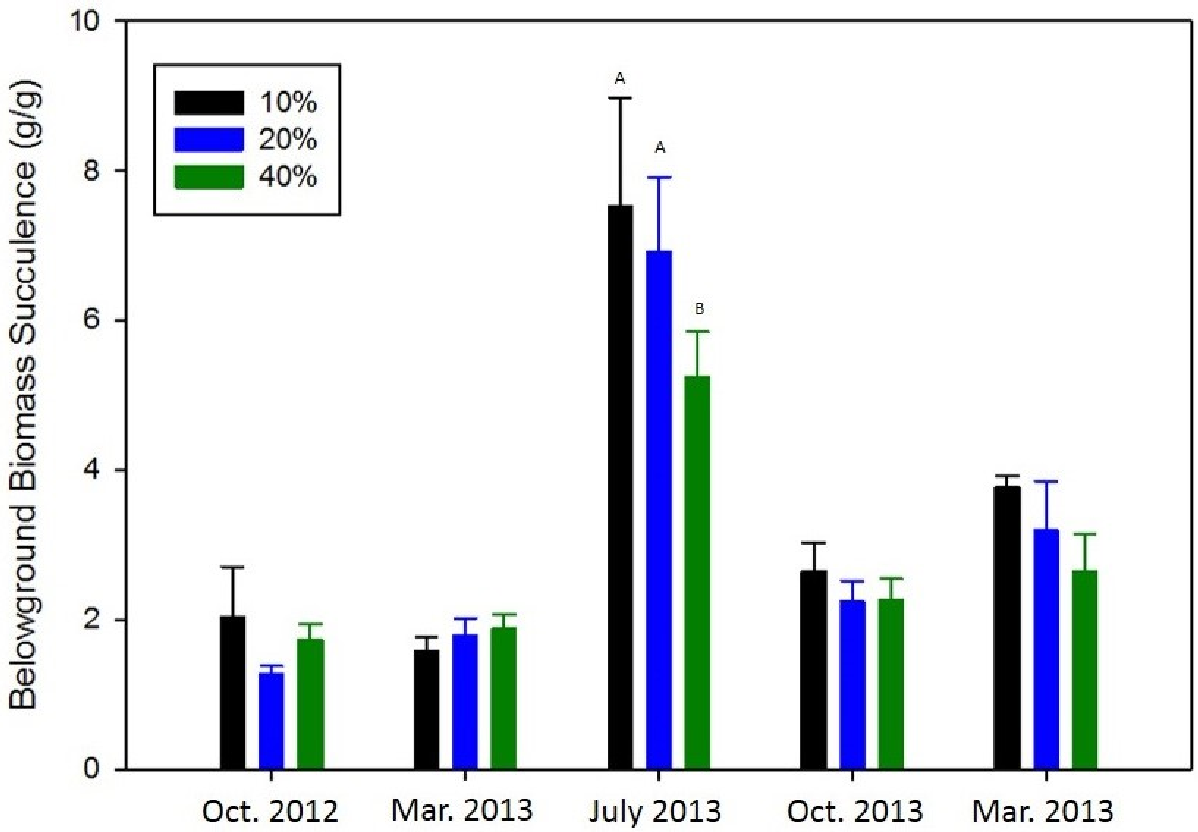


Fig.5.19. Root succulence of *Sedum kamptschaticum* grown in a platform-scale green roof field study. Means (n = 4) are shown for each treatment, letters designate significance at α = 0.05, no letters indicate p>0.05.



Total root length per sample demonstrated increased root growth with increasing proportions of substrate organic matter (Figure 5.20), but root density (fresh weight divided by sample volume) indicated no difference between plants grown in 10% and 20% organic matter, except for July 2013 (Figure 5.21). Root density was also highest for July 2013, attributed to the increased fresh weight.

Only the July 2013 harvest showed a significant effect of substrate organic content on root succulence. Interestingly, root succulence – or the amount of water stored in the roots – was far greater in July 2013 than for the other harvest dates. Even though 2013 was a fairly rainy year

– both in the total rainfall and number of events – it is not assumed that root succulence would be affected by substrate VWC or precipitation. Additionally, substrate VWC reached its peak in Fall 2013 (Figure 5.22), indicating that *Sedum kamptschaticum* may store more water in the root system during the summer months.

Fig. 5.20. Root length of *Sedum kamptschaticum* grown in a platform-scale green roof field study. Means (n = 4) are shown for each treatment, letters designate significance at α = 0.05, no letters indicate p>0.05.

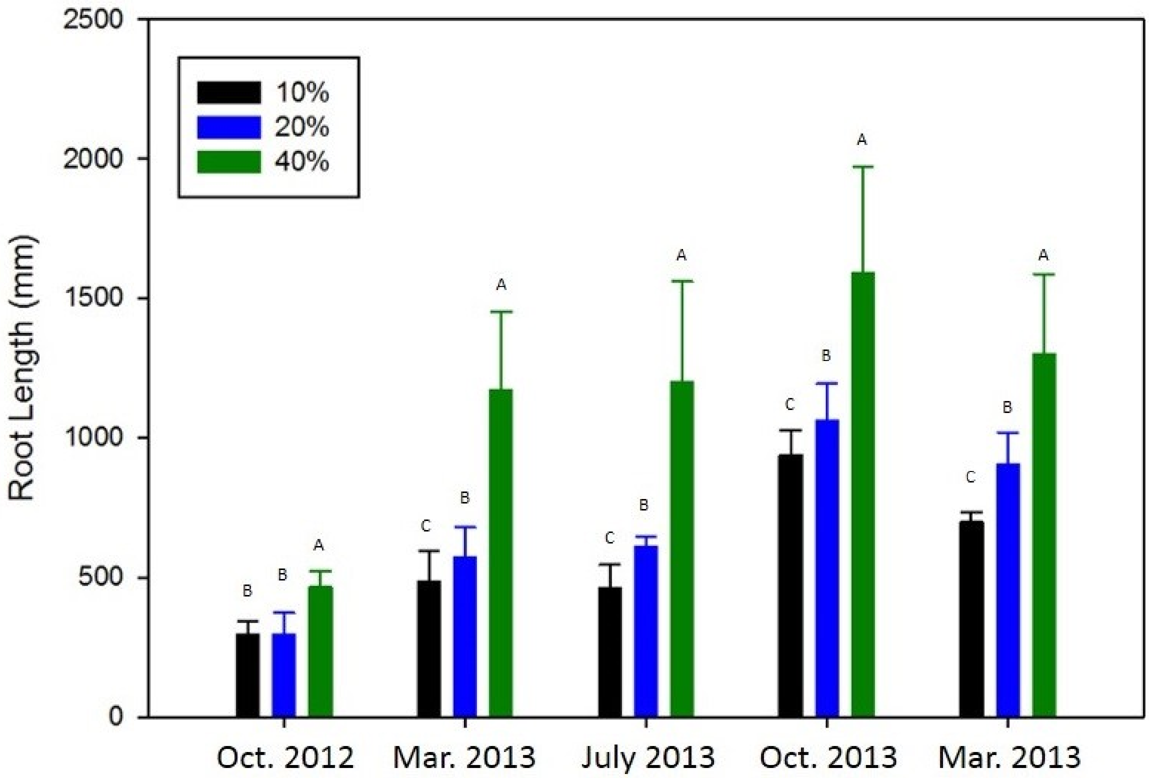
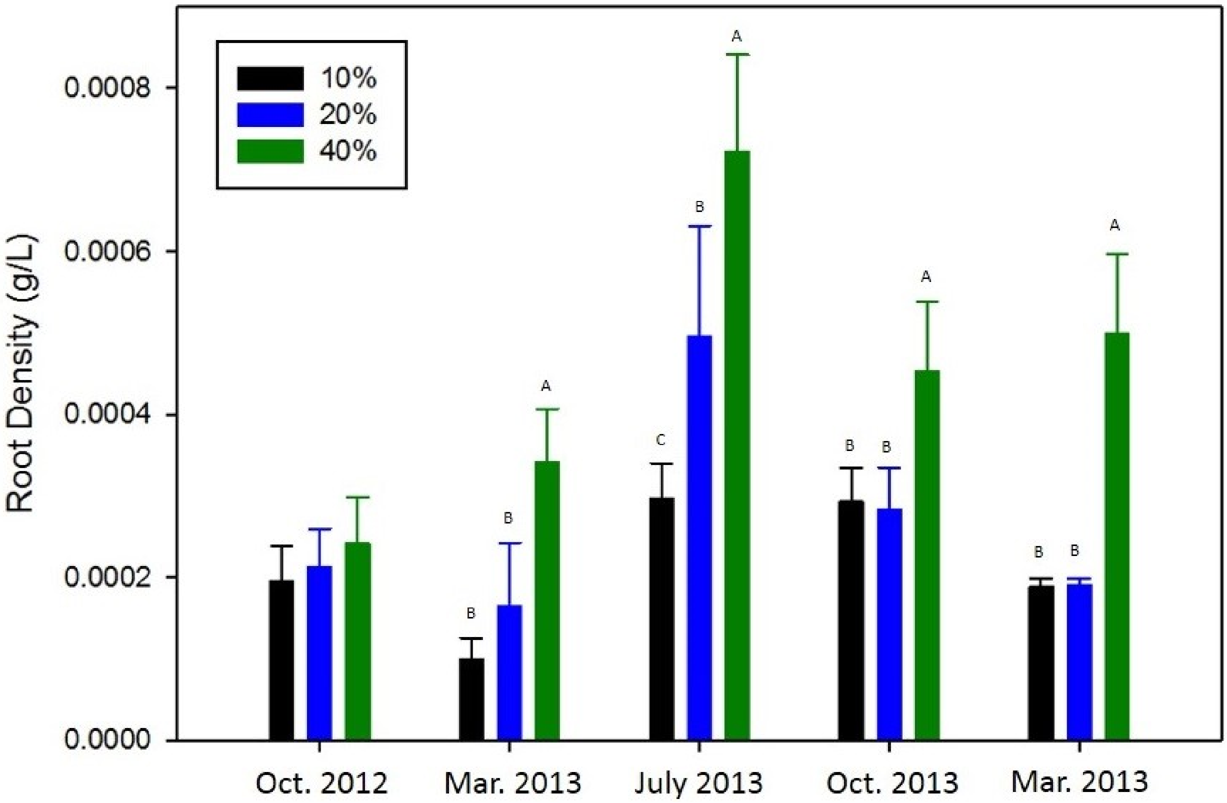


Fig. 5.21. Root density of *Sedum kamptschaticum* grown in a platform-scale green roof field study, determined by dividing belowground biomass fresh weight by total sample volume. Means (n = 4) are shown for each treatment, letters designate significance at α = 0.05, no letters indicate p>0.05.



5.3.2 Volumetric Water Content

The daily substrate VWC (n=16) was plotted for 2013 based on sensor readings at 5:00 AM as a means to normalize the data on a daily basis while avoiding potential climatic variability. These data are presented with daily rainfall totals in Figs. 5.22 and 5.23. Substrate volumetric water content for each treatment was plotted for five dry-down periods immediately following rain events (Figs. 5.24, 5.25, 5.26, 5.27, and 5.28). The longest dry period of 2013 was 15 days, and many rain events were small (less than 0.5 mm), so in some cases multiple dry periods were combined with intermittent rain for graphing purposes.

Fig. 5.22. Daily substrate volumetric water content (n=16) at 5:00 AM for experimental green roof platforms for 2013.

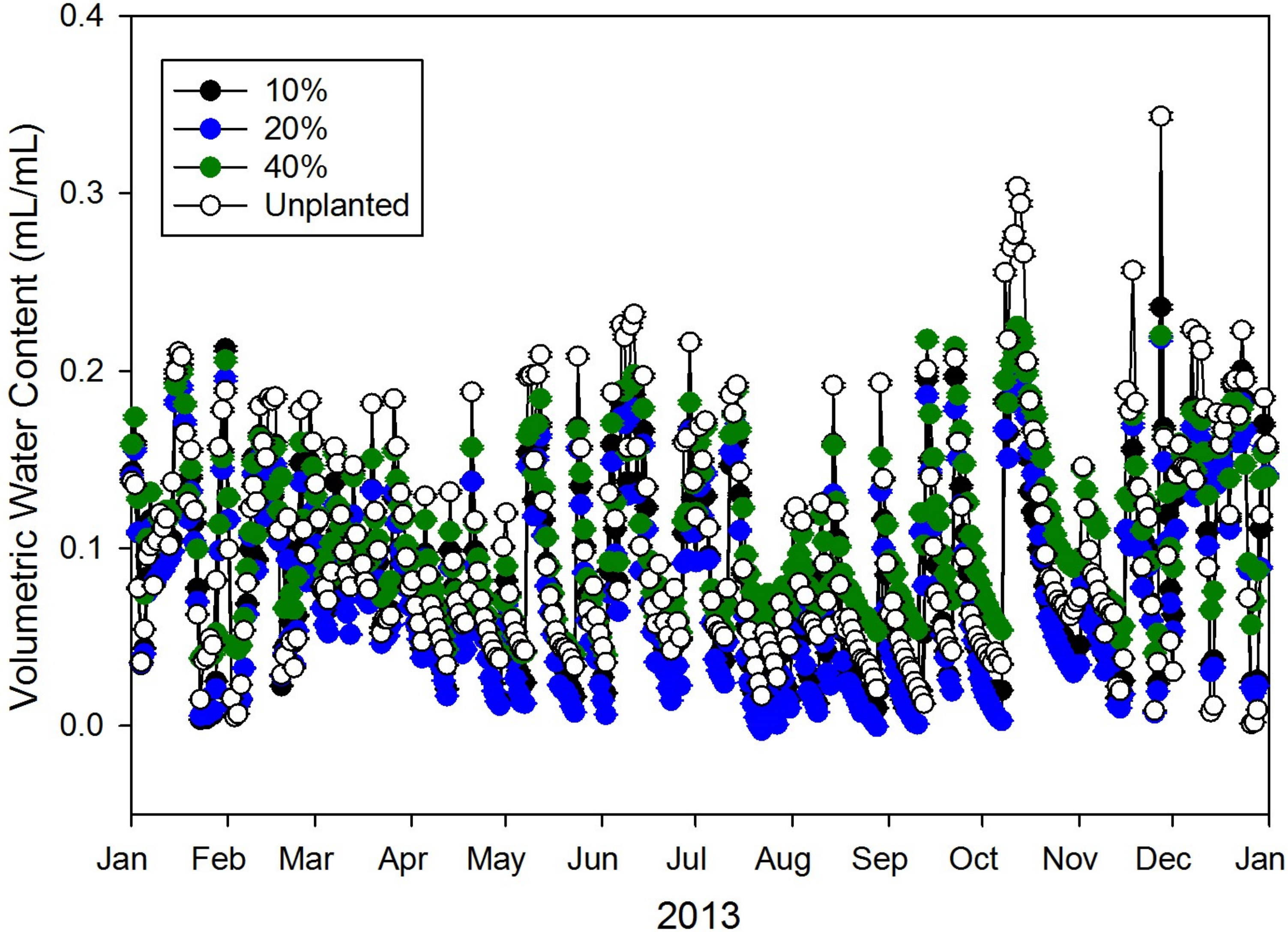


Fig. 5.23. Daily precipitation totals for 2013.

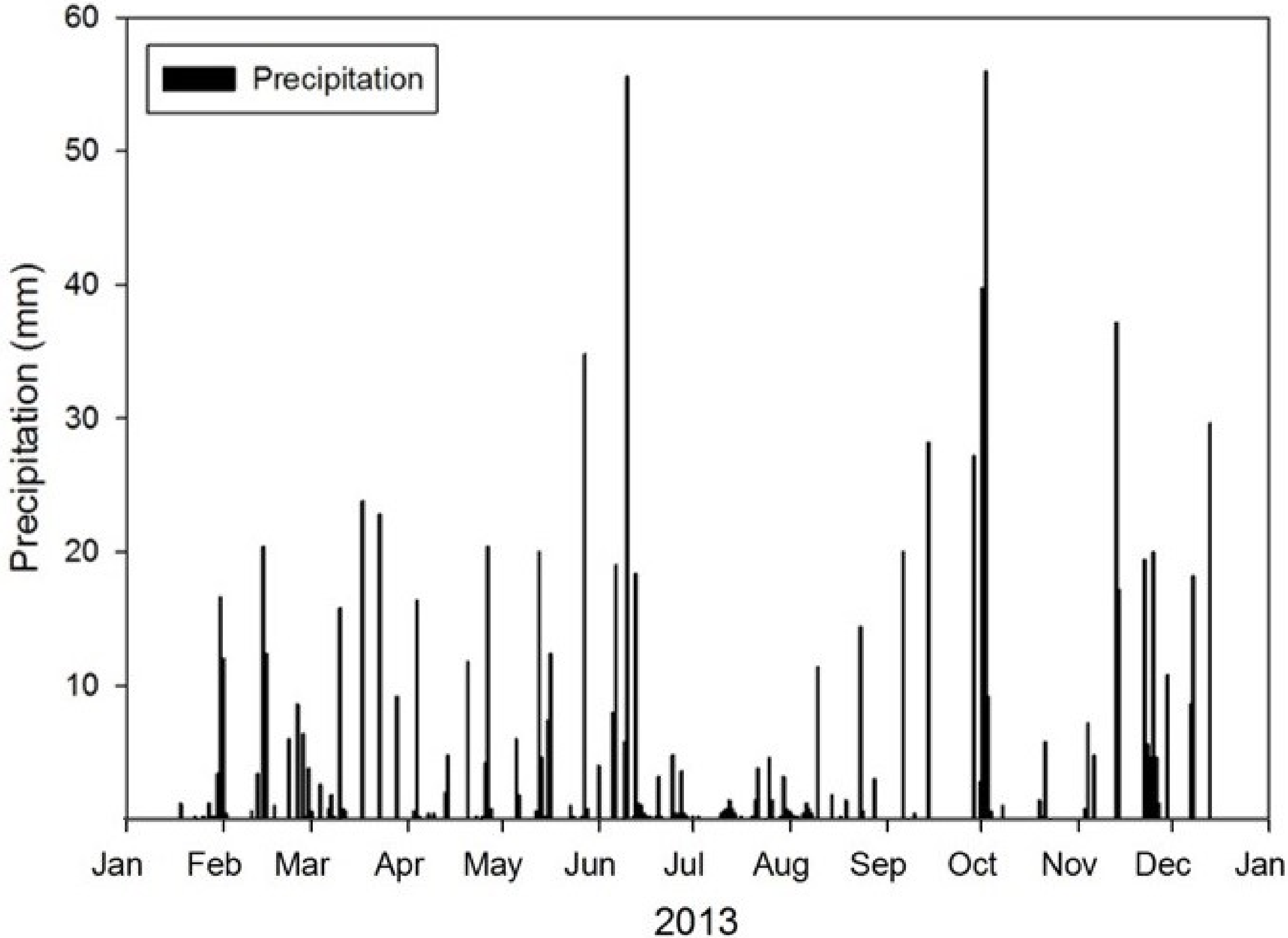


Fig. 5.24. Substrate volumetric water content of platform-scale experimental green roofs with increasing proportions of organic content following a 10.8 mm rain event which occurred over 4.5 hours on May 11. Means (n = 16) are shown for each treatment.

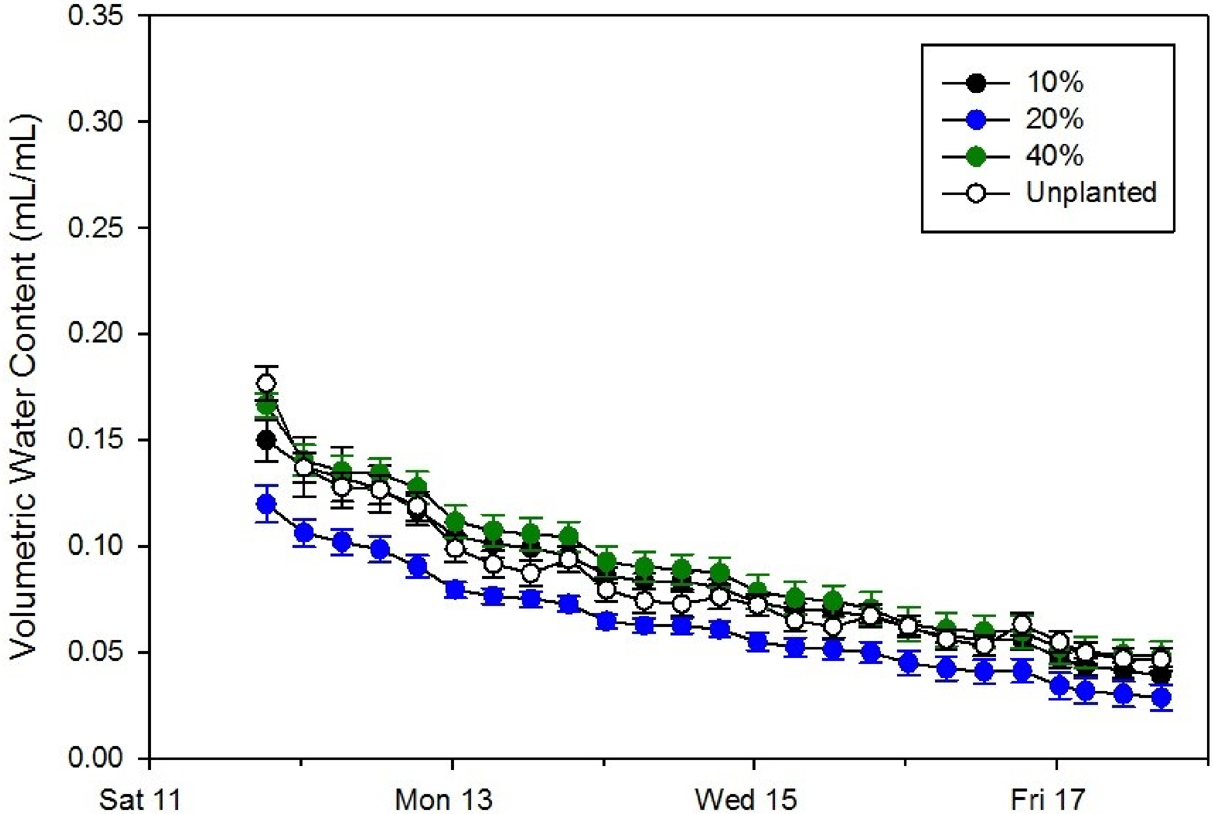


Fig. 5.25. Substrate volumetric water content of platform-scale experimental green roofs with increasing proportions of organic content following an 11.2 mm rain event which occurred on August 1 occurring over 9 hours, and a 3.6 mm rain event on August 3 occurring for 1.5 hours. Means (n = 16) are shown for each treatment.

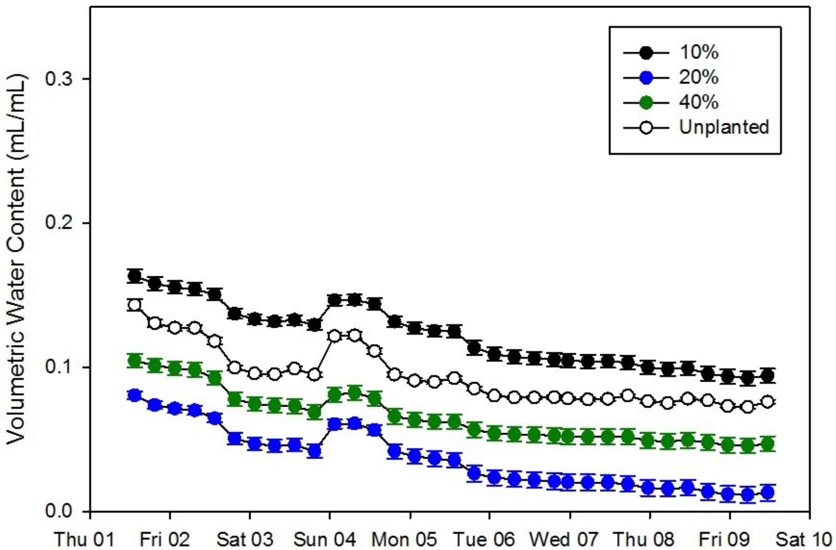


Fig.5.26. Substrate volumetric water content of platform-scale experimental green roofs with increasing proportions of organic content following an 18.4 mm rain event which occurred on August 13 which occurred over 24 hours, and a 2.2 mm rain event on August 16 which occurred over 7.25 hours. Means (n = 16) are shown for each treatment.

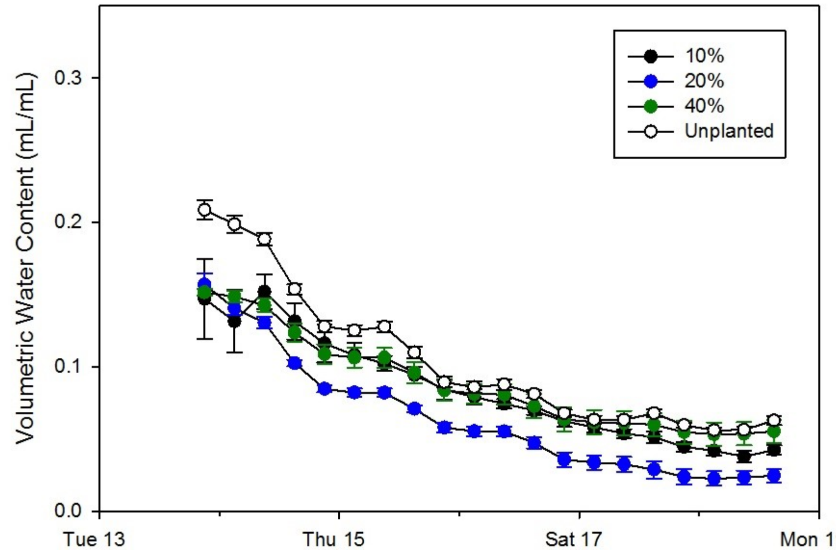


Fig. 5.27. Substrate volumetric water content of platform-scale experimental green roofs with increasing proportions of organic content following a 15.0 mm rain event which occurred over 12.25 hours on August 28, followed by 3 mm event lasting 7 hours on September 2, and a 20 mm event lasting 5 hours on September 12. Means (n = 16) are shown for each treatment.

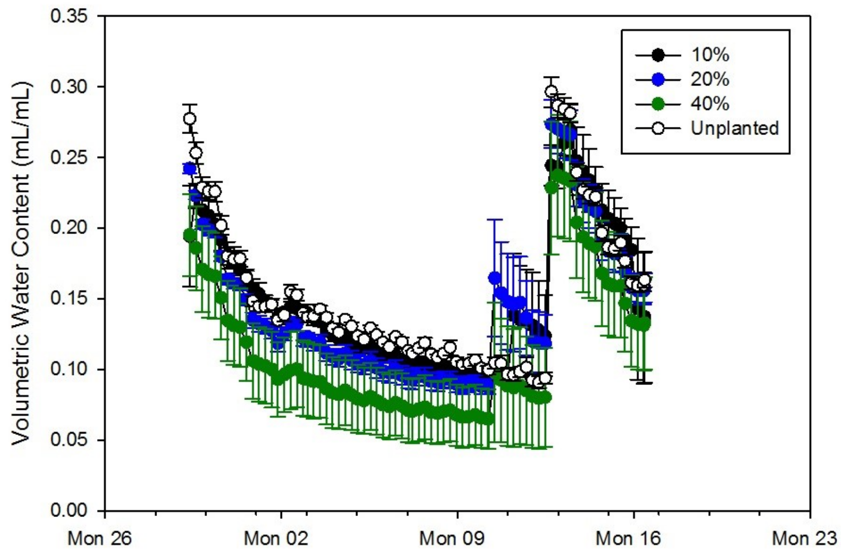
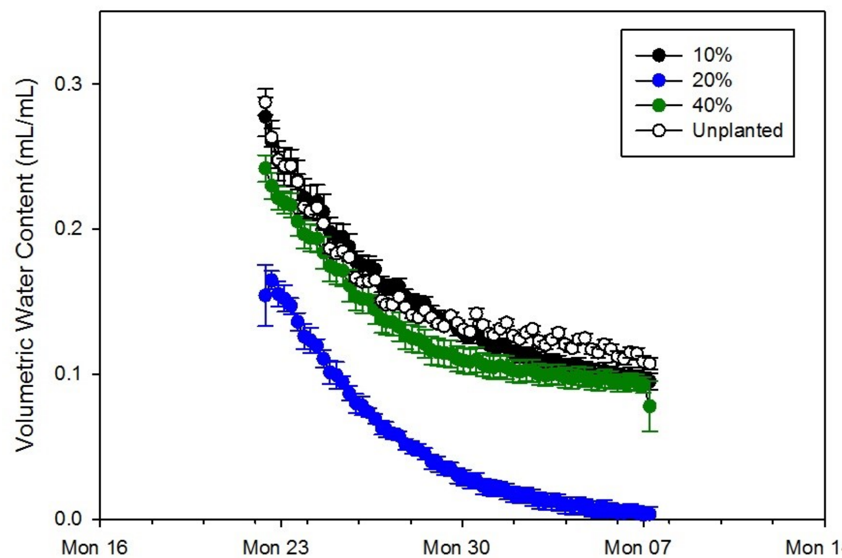


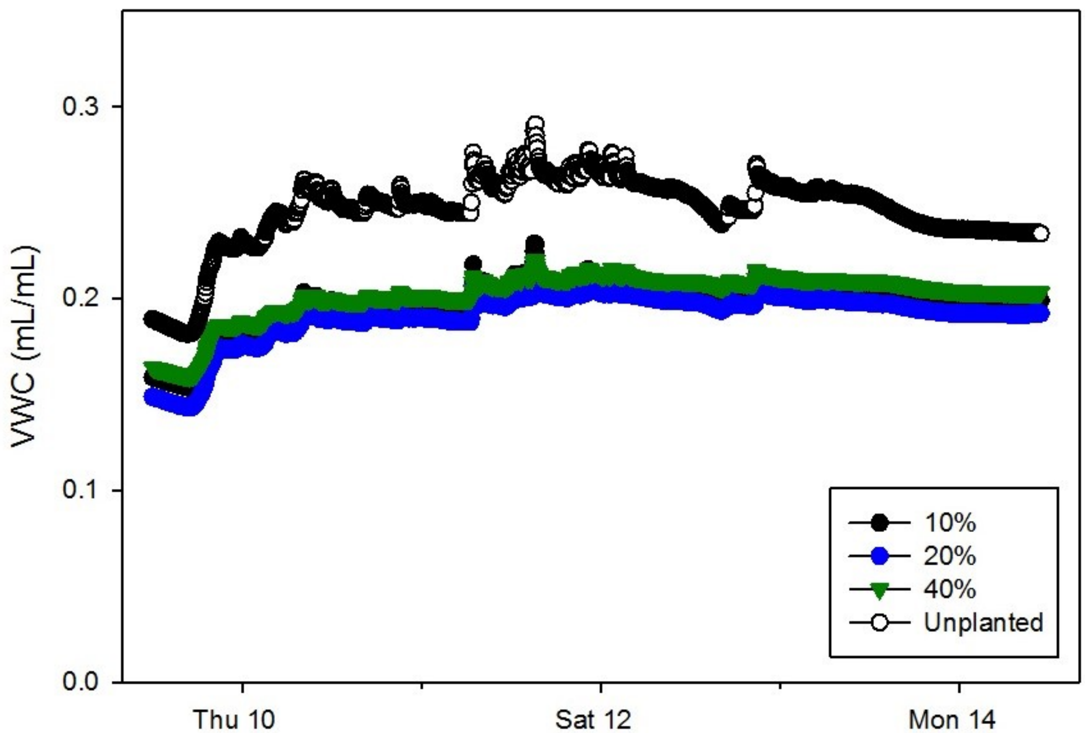
Fig. 5.28. Substrate volumetric water content of platform-scale experimental green roofs with increasing proportions of organic content following a 28.2 mm rain event which occurred over 7 hours on September 21. Means (n = 16) are shown for each treatment.



Interestingly, substrate VWC (starting immediately following the rain event, assumed to be FC_{unsat}) ranged from 18-22% for most dry downs; however, for the fourth dry down (Fig. 5.26), multiple dry periods were combined and the maximum substrate VWC reached almost 30% for the third rain event. This could be evidence of hydrophobicity or water repellency – substrate VWC reached 30% when a rain event started after only 3 dry days – the substrate VWC was above 8% at the start of the third rain event, which may have allowed for easier re-wetting. Hydrophobicity is primarily caused by the fulvic and humic acids in organic matter, although the amount of organic matter is not correlated to the degree of hydrophobicity (DeBano, 1981). The data may indicate that when substrate VWC falls below 8%, the ability to re-wet is hampered and therefore subsequent maximum VWC is closer to the 18-22% range. This field data further supports my delineation between FC_{sat} and FC_{unsat} as discussed in Chapter 4.

Substrate VWC in the 20% organic matter treatment was lower than all other treatments and reached a much lower VWC for the final dry down (Fig. 5.28). It is worth noting that this 15-day dry period was the longest dry period of the entire calendar year and occurred immediately prior to Hurricane Sandy. Substrate VWC during the four days of Hurricane Sandy is presented in Fig.5.29. Interestingly, substrate VWC during Hurricane Sandy was highest for the unplanted control, and the maximum VWC was around 30%. Planted treatments had similar VWC for the duration of the event, which ranged from 18-20%. Substrate VWC was expected to reach FC_{sat} values, or at least rise consistently above 30% during this extended rain event. One explanation could be the higher porosity of the media – green roof substrates are engineered to be rapidly draining to avoid ponding during intense rain events – in this case, ponding certainly never occurred. However, Figure 5.25 demonstrates substrate VWC did at times reach 30%. Another explanation for the lower maximum VWC during Hurricane Sandy could be hydrophobicity due to the 15-day dry period immediately preceding the precipitation event. Another interesting result is that planted treatments had consistently lower substrate VWC during Hurricane Sandy than the non-planted control. While the relationship between root density and substrate total VWC is not well understood, it is worth noting that VWC was more stable for planted versus non-planted treatments.

Fig. 5.29. Substrate volumetric water content of platform-scale experimental green roofs with increasing proportions of organic content during Hurricane Sandy, a 108.4 mm rain event which occurred over 4 days from October 9 to October 13. Means (n = 16) are shown for each treatment.



5.3.3 Stormwater Retention

Platform runoff was quantified for 21 rain events from July 2013 to November 2013, as summarized in Table 5.1. There were many small (<12.5 mm) events, contributing to 100% retention for many events. For several medium events (12.5-62.5 mm), the event duration was so long that retention was near 100%.

Table 5.1. Table of rain events for which runoff from experimental green roof platforms planted with increasing proportions of organic matter (10%, 20%, and 40%) was captured. Means (n=4) of retention percent are given. Rain events are delineated by size (small <12.5mm, medium 12.5-62.5mm, large >62.5mm).

Event Start	Depth (mm)	Event Duration (min)	Subsequent Dry Period Duration (min)	Event Size	10% Organic Matter		20% Organic Matter		40% Organic Matter		Unplanted (10%)	
					Estimate	SEM	Estimate	SEM	Estimate	SEM	Estimate	SEM
7/12/2013	23.20	980	1585	medium	62.3%	±0.015	66.0%	±0.052	72.6%	±0.071	71.4%	±0.153
7/13/2013	5.20	25	13,330	small	79.4	0.006	86.3	0.048	83.6	0.031	83.1	0.053
7/22/2013	5.00	60	6,775	small	100.0	0.000	100.0	0.000	100.0	0.000	100.0	0.000
7/27/2013	5.80	405	5,830	small	100.0	0.000	100.0	0.000	100.0	0.000	100.0	0.000
8/1/2013	11.20	545	2,805	small	99.9	0.001	99.6	0.004	99.9	0.001	99.9	0.001
8/3/2013	0.40	220	430	small	100.0	0.000	100.0	0.000	100.0	0.000	100.0	0.000
8/3/2013	3.60	80	3,640	small	100.0	0.000	100.0	0.000	100.0	0.000	100.0	0.000
8/6/2013	0.20	5	3,315	small	100.0	0.000	100.0	0.000	100.0	0.000	100.0	0.000
8/8/2013	0.20	5	1385	small	100.0	0.000	100.0	0.000	100.0	0.000	100.0	0.000
8/9/2013	5.60	10	5235	small	96.1	0.007	96.3	0.018	95.4	0.012	96.7	0.004
8/13/2013	18.40	1465	6310	medium	98.6	0.003	97.1	0.005	93.9	0.005	92.4	0.031
8/18/2013	2.20	470	4825	small	100.0	0.000	100.0	0.000	100.0	0.000	100.0	0.000
8/21/2013	0.20	5	2235	small	100.0	0.000	100.0	0.000	100.0	0.000	100.0	0.000
8/23/2013	1.40	120	7260	small	88.9	0.065	88.2	0.071	92.8	0.044	96.7	0.033
8/28/2013	15.00	735	5680	medium	83.8	0.011	81.3	0.011	82.3	0.004	76.2	0.027
9/2/2013	3.00	410	15120	small	100.0	0.000	100.0	0.000	100.0	0.000	100.0	0.000
9/12/2013	20.00	300	5190	medium	87.9	0.084	86.0	0.081	86.8	0.033	82.1	0.021
9/16/2013	0.40	45	7505	small	100.0	0.000	100.0	0.000	100.0	0.000	100.0	0.000
9/21/2013	28.20	425	22435	medium	60.6	0.017	61.9	0.010	56.9	0.016	46.2	0.035
10/7/2013	27.20	220	3045	medium	100.0	0.000	100.0	0.000	100.0	0.000	100.0	0.000
10/9/2013	108.40	5050	6245	large	35.4	0.021	34.9	0.057	30.1	0.010	39.4	0.041

Retention was plotted by storm size (depth) and intensity (depth per minute), and is presented in Fig. 5.30 and Fig. 5.31. There was no significant relationship between organic content storm water retention by storm size or intensity.

Fig. 5.30. Retention by storm size for experimental green roof platforms planted with substrates with increasing volumetric (10%, 20%, and 40%) proportions of organic matter. Events ranged from July 12 to October 9, 2013.

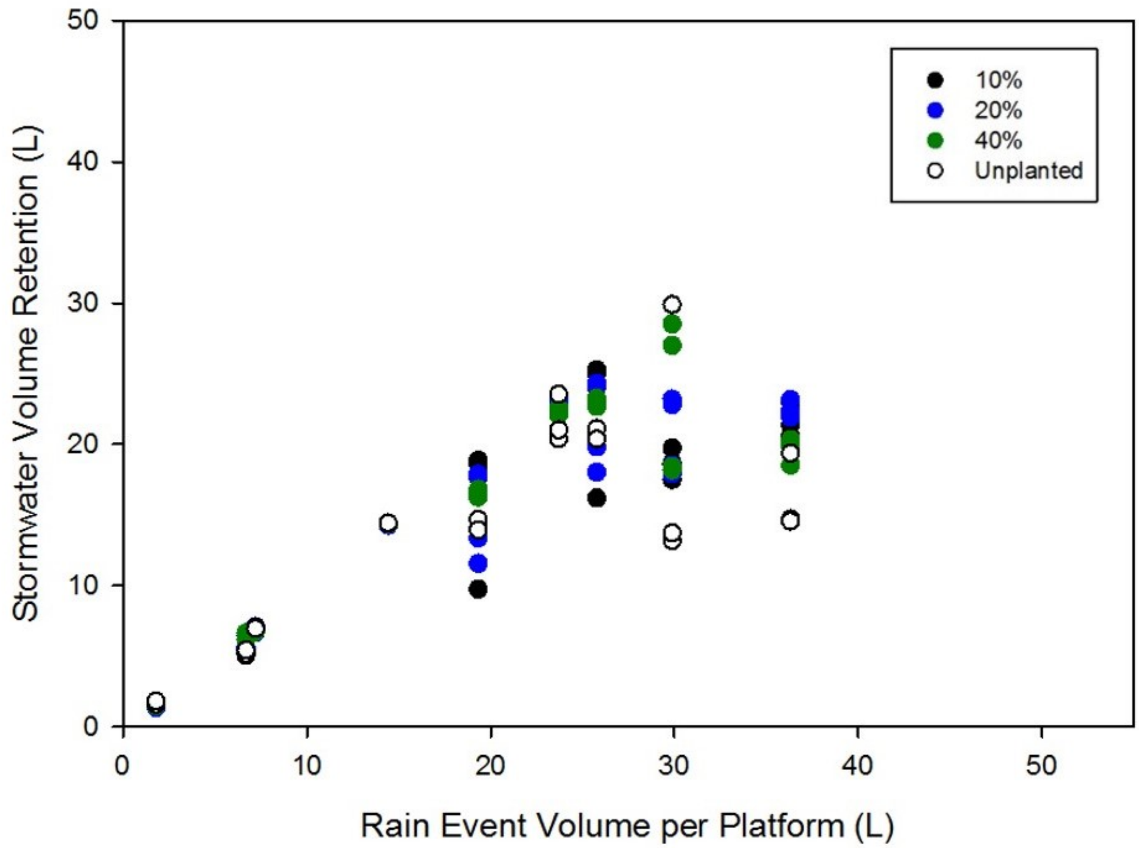
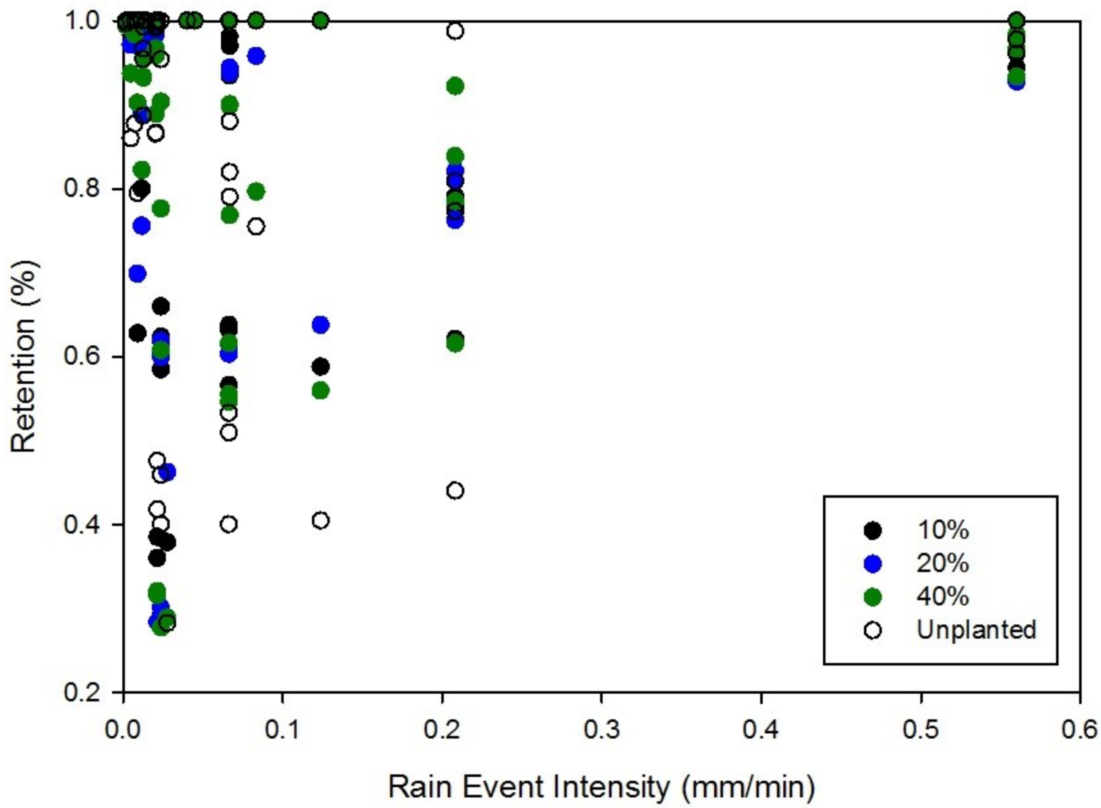


Fig. 5.31. Percent retention by intensity (total event volume divided by event duration) for experimental green roof platforms planted with substrates with increasing volumetric (10%, 20%, and 40%) proportions of organic matter. Events ranged from July 12 to October 9, 2013.



Due to the high proportion of events with 90% retention or better (14 of 21), runoff for four events were plotted for each treatment (n=4), for five events retaining less than 90% of a rain event (Figs. 5.32, 5.33, 5.34, and 5.35). Runoff from an August 13 event, in which 18.4 mm fell over the course of 24 hours, shows a higher peak runoff for unplanted treatments (Fig. 5.32). Runoff from a September 12 event peaked more rapidly than other events, which was expected due to the event intensity - 20 mm fell in only 5 hours (Figure 5.33) – although it is interesting that after approximately 2 hours, runoff had all but stopped, with only a single tip (0.04 L per tip) approximately every ten minutes.

Figure 5.32. Runoff from experimental green roof platforms planted with substrates with increasing volumetric (10%, 20%, and 40%) organic matter during a rain event occurring on August 13, 2013, in which 18.4 mm fell over 24 hours. Means (n = 4) are shown for each treatment.

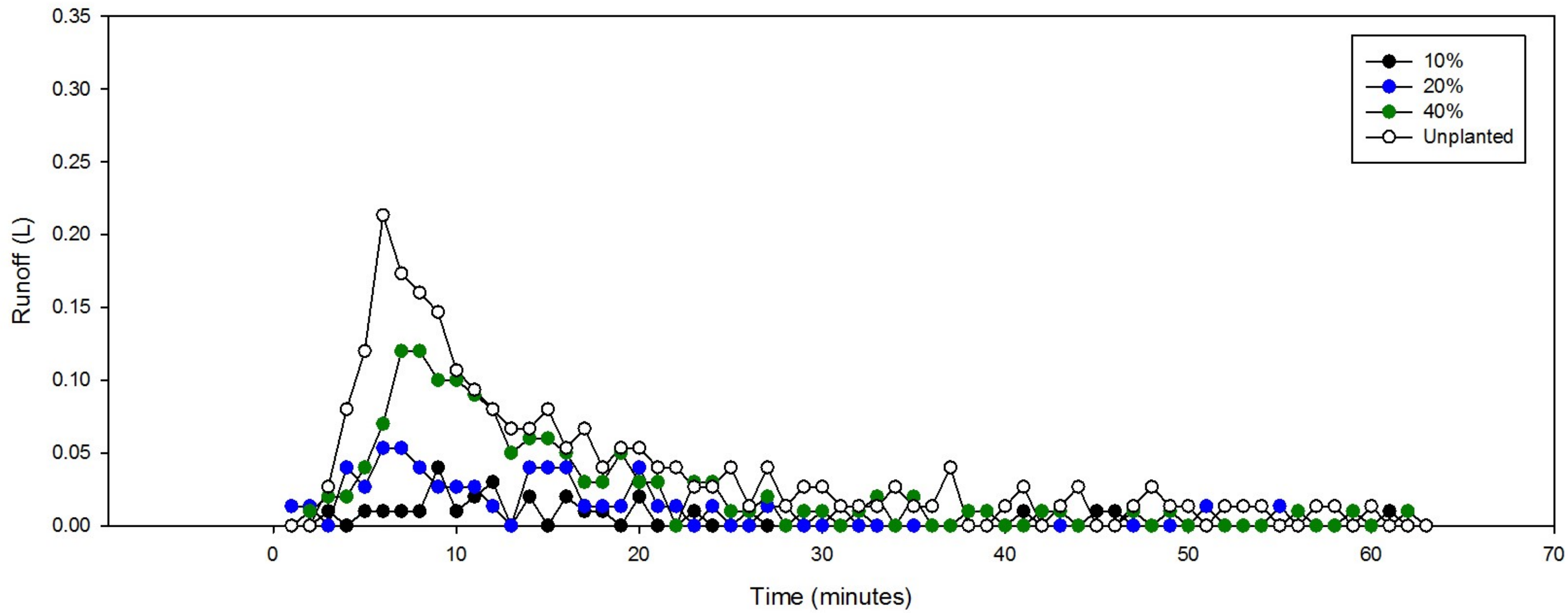
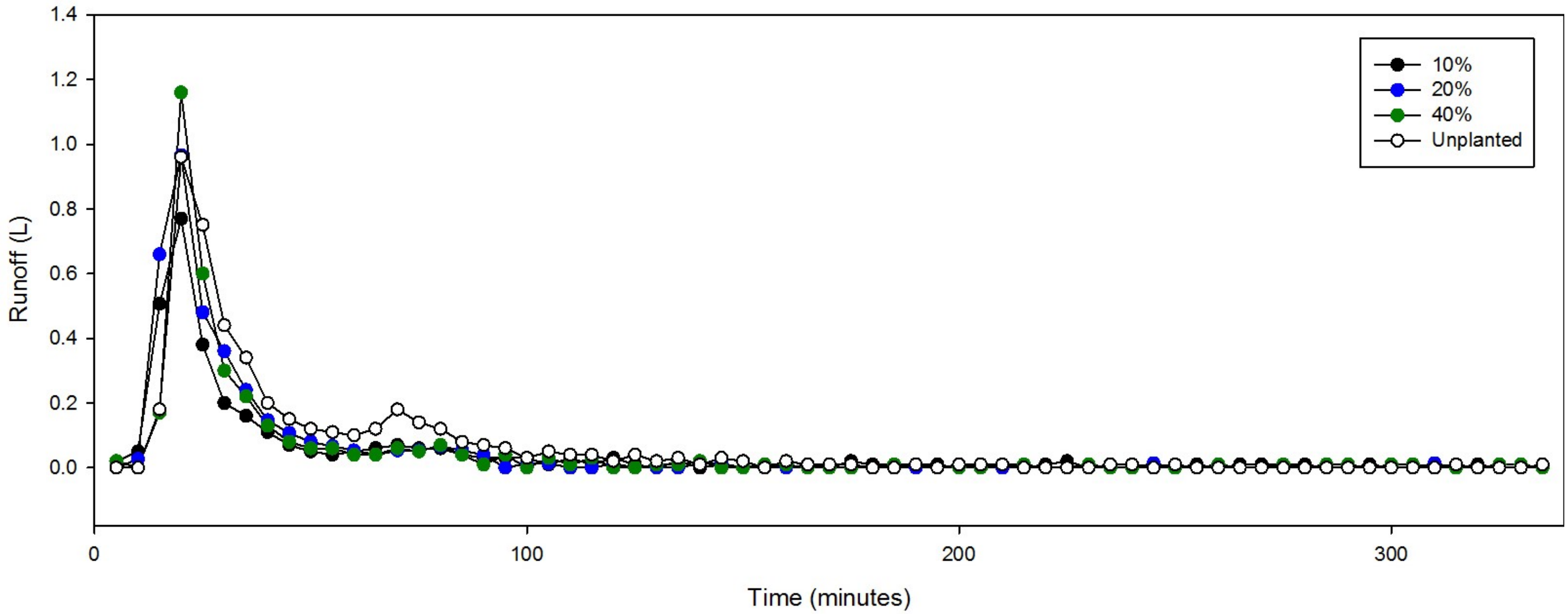


Figure 5.33. Runoff from experimental green roof platforms planted with substrates with increasing volumetric (10%, 20%, and 40%) organic matter during a rain event occurring on September 12, 2013, in which 20 mm fell over 5 hours. Means (n = 4) are shown for each treatment.



A September 21 event – 28.2 mm in only 7 hours – shows runoff occurring more rapidly for unplanted platforms, as well as a higher peak volume for unplanted platforms compared to planted treatments, although no treatment differences for planted platforms was detected (Fig. 5.34). Runoff from this event was more characteristic to Starry's (2013) results, which indicated planted platforms retain more stormwater than unplanted platforms. Finally, runoff during Hurricane Sandy, the largest event of 2013, is presented in Fig.5.35. Rain totals for the four day event reached 108.4 mm. As expected, planted and unplanted platforms performed similarly, as did all planted treatments. Again, these results confirm Starry's conclusions that green roof stormwater retention performance is largely dictated by storm characteristics – namely volume and intensity. Hurricane Sandy was an outlier event in terms of total precipitation volume. Nonetheless, the experimental green roof platforms did retain some storm water from the event – performance ranged from 30-40% depending on treatment (Table 5.1), although no significant differences for any treatment during any event were detected.   With the exception of the standard Rooflite™ media during the first dry down, evapotranspirational water loss from planted treatments surpassed evaporative water loss from unplanted treatments within the first 48 hours of the dry down.

Figure 5.34. Runoff from experimental green roof platforms planted with substrates with increasing volumetric (10%, 20%, and 40%) organic matter during rain event occurring on September 21, 2013, in which 28.2 mm fell over 7 hours. Means (n = 4) are shown for each treatment.

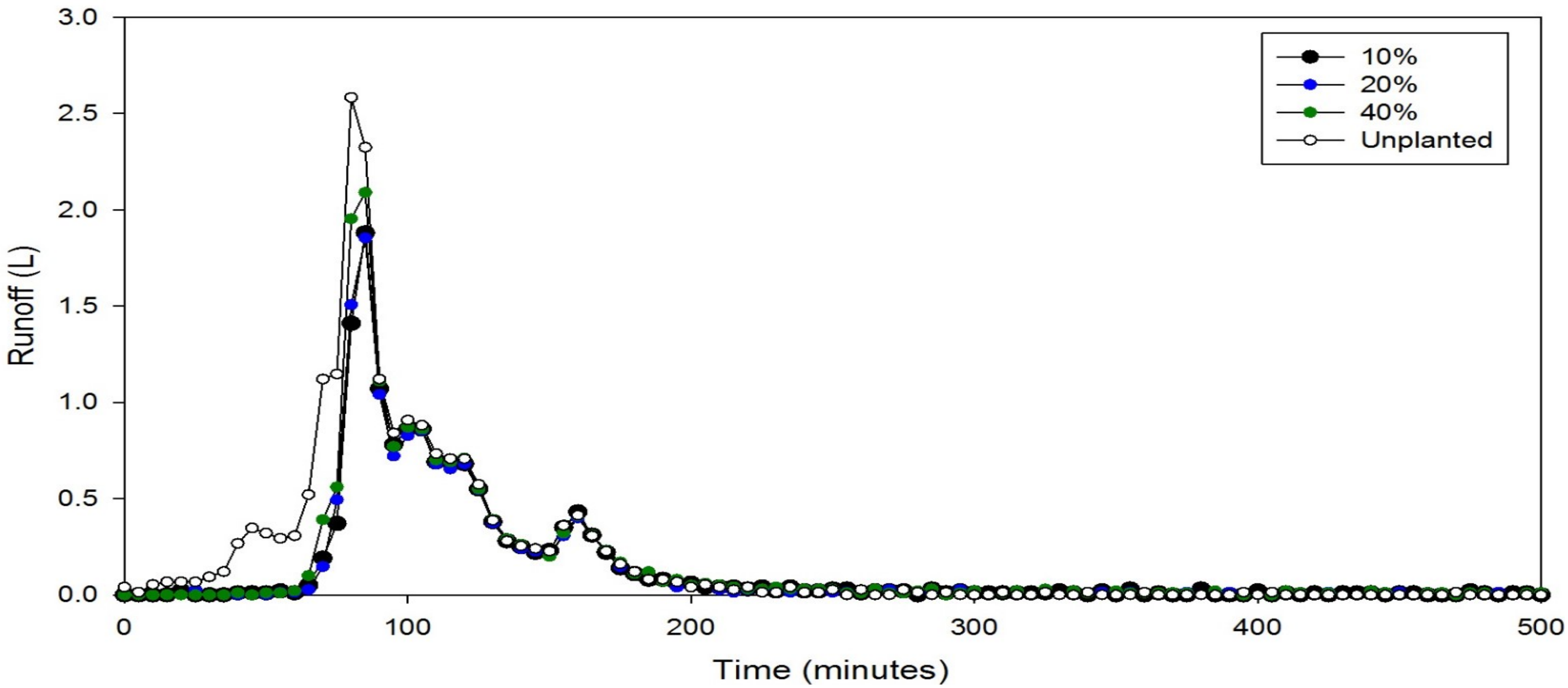
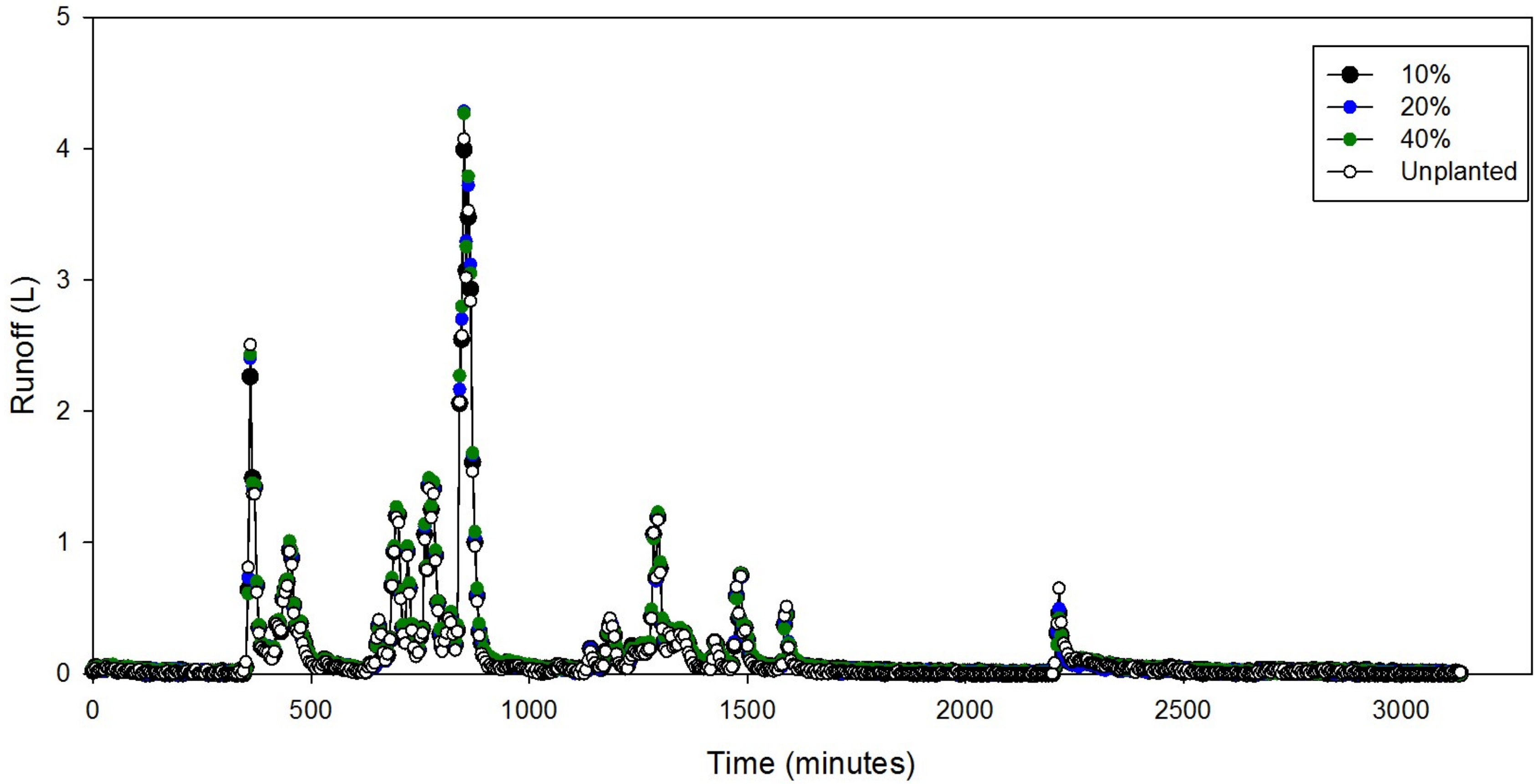


Figure 5.35. Runoff from experimental green roof platforms planted with substrates with increasing volumetric (10%, 20%, and 40%) organic matter during Hurricane Sandy, which lasted from October 9 to October 13, 2013, in which 108.4 mm fell. n = 4 for each treatment.



One limitation of field work is smaller sample size (in this case, n=4), so while this may have played a role, the results may also highlight an industry-wide issue: what defines a "successful" green roof? For many, a successful green roof is one which has green vegetation growing on it – the idea that "if it's green, it's good". But platforms planted with 10% organic matter performed equally as well as platforms planted with 40% organic matter, even with less plant coverage, giving credence to the idea regional performance-based (i.e. retention, not visible plant growth performance) metrics for green roofs should be developed. Please note that this is not a recommendation for adding 10% organic matter for green roof substrates – the growth chamber and destructive harvest data in Chapter 4 suggest more vigorous roots and shoots for plants grown in 20% organic matter. But with no retention differences between 20% and 40% despite differences in canopy cover, the motivation to choose 40% over 20% is at this point largely client-focused – reaching 100% coverage in a shorter amount of time to fulfill the expectation that "if it's green, it's good", although performance may be the same.

5.4 Conclusions

Random non-destructive sampling introduced large amounts of variability into the data, so it was difficult to draw informed inferences from the effects of substrate organic content on plant growth from the fresh and dry weight of *S. kamptschaticum*. The platform canopy coverage data, obtained through pixel analysis of digital photographs, was cleaner and allowed for extrapolation of data which confirms the expected result – increased substrate organic content leads to increased plant growth, which supports Chapter 4 destructive harvest findings. Dry mass data from one harvest date indicated greater shoot dry biomass for 10% organic matter, although pixel analysis showed otherwise. This is a direct result of the randomized sampling, because in no case was shoot biomass for 10% organic matter greater than that of plants grown in 20% or

40% organic matter. Random sampling will likely be a more effective methodology once all replicates reach at least 80% coverage, at which time differences in plant biomass will likely be identified through harvests as well as pixel analysis.

The effects of organic content on substrate VWC is still somewhat unclear. Because substrate VWC is largely affected by storm characteristics and antecedent moisture conditions, there is no clear conclusion; however, I assert that when substrate VWC falls below 8%, substrates will not hold as much water in subsequent rain events – the field capacity will be that of FC_{unsat} compared to lab-estimated FC_{sat} values, as discussed in Chapter 4.

Furthermore, the effects of organic content on storm water retention are difficult to discern due to the numerous rain events in 2013. Runoff data indicates platform discharge occurred more quickly for unplanted platforms compared to planted platforms for at least two events (Figs. 5.32 and 5.34), but there were no statistically significant differences in retention values for any treatment. Retention was above 90% for all but 5 of 21 measured storms, attributed to storm characteristics – most measured events were either small in volume, long in duration, or a combination of both. Also of importance is that runoff was not measured until one year post-installation – perhaps differences in retention would have been present during the first season's growth. Conversely, differences in retention performance due to substrate organic content may not be detectable until after several seasons. It is likely that data 3-5 years post-installation would provide a clearer picture of the effects of substrate organic content on stormwater retention.

In conclusion, the effects of organic content on storm water retention is a complex issue that should continue to be studied, and likely will not be understood without multiple seasons of data in order to account for climatic variability from year to year.

Chapter 6: Conclusions

As green roofs gain popularity as stormwater management tools, regulatory agencies are defining metrics and setting parameters for green roof performance around the world. Since these systems are dynamic, it is integral to better define the effects of components, specifically substrate, on plant growth, hydraulic properties, and stormwater retention.

The freeze-thaw analysis in Chapter 2 demonstrated firstly a need for greater accountability within the green roof industry, because none of the three commercial extensive green roof substrates met FLL particle size distribution guidelines as received direct from the manufacturer. Furthermore, all three blends showed significant ($p<0.05$) particle degradation when subjected to 30 freeze-thaw cycles, which speaks to the need for performance-based metrics. The freeze-thaw analysis also demonstrates that green roof system design, regulations, and performance metrics are likely to be most effective when developed on a regional basis. Not all regions experience the extreme temperature fluctuations and freeze-thaw cycles of the Mid-Atlantic; however, substrate analysis of established (3-7 years post-installation) green roofs in the region indicate that green roof substrates are not maintaining their physical properties, which may partially explain the number of green roof failures in the region.

Lab analysis of the matric potential and hydraulic conductivity of extensive green roof substrates in Chapter 3 failed to detect in significant differences based on substrate organic content, although the precision of the technique was excellent; however, the HYPROP© method may not be appropriate for extensive green roof substrates or other highly porous media. The system was developed for use with soils; the high porosity of the extensive green roof substrates led to tensiometer water column caviation at around -30 kPa. Similar values may have been attained using the tension table method; nonetheless, cavitation occurred outside of the range of plant unavailable water (-50 to beyond -500 kPa), which are the tensions at which organic matter is most likely to affect matric potential and hydraulic conductivity.

The results from Chapter 2 and Chapter 3 call into question the relevancy of component-based guidelines, such as those from the FLL and even ASTM. If stormwater retention is the driving force behind green roof design and installation, do particle size distribution and matric potential matter? These parameters may affect and likely do affect stormwater retention; however, current guidelines are based on lab analyses of components, a disjointed approach that apparently does not account for actual performance from the empirical data shown in Chapters 4 and 5, with regards to plant water extraction and the effects of rainfall intensity on efficiency. We need to delve beyond the basic assumptions that maximum water holding capacity will be achieved during each rain event. I assert that a more appropriate and accurate way of standardizing green roof design and estimating green roof performance is to shift the focus from lab-based component analysis to system-based stormwater performance analysis. Without actual performance data we cannot know how much stormwater a system will actually retain, and since current technologies allow for data collection there is no excuse not to expand the body of actual roof performance-based literature.

Growth chamber (Chapter 4) and platform-scale (Chapter 5) plant growth analyses using substrate moisture sensors may offer better predictions of plant water use in extensive green roof substrates with increasing (10%, 20%, and 40%) volumetric proportions of organic matter. *Sedum kamptschatcicum* grown in 40% organic matter were larger in both studies. The increased biomass with increasing volumetric proportions of organic matter for the platform-scale study in Chapter 5 may be due to increased nutrient content – as apparent in Appendix E, which indicates that, depending on treatment, these experimental platforms contained a range of 55-222 g N per platform. While every platform was fertilized each spring according to FLL guidelines, increased plant coverage in 40% organic matter may be attributed to nutrient availability, which is different from the pot-scale study in Chapter 4, when differences were more likely due to differences in water availability because od the limited rooting volume. For the pot-scale study, nutrient availability ranged from 0.19 to 0.76 g N per pot. These results demonstrate that water may be the more important resource during establishment (i.e. the first six months), but longer-term plant growth is more perhaps equally sensitive to nutrient availability.

Interestingly, substrate VWC reached below 5% during three consecutive dry down periods in the growth chamber study. Similar VWC was reported during post-rain event dry down periods for the platform analyses in Chapter 5. These data indicate plant roots are accessing substrate water previously assumed to be unavailable – Chapter 3 results demonstrate that defining plant unavailable water for green roof substrates is challenging due to limitations of current analytical laboratory tehcniques. Regardless of these issues, Chapters 4 and 5 illustrate clearly that plant roots are extracting water from substrates beyond substrate moisture contents that have been previously demonstrated.

While plant roots did evapotranspire a large proportion of the water held by the substrate, there were no treatment differences in stormwater retention. This could be an artifact of storm characteristics – most of the measured events were either small in size, short in duration, or a combination thereof. Another likely explanation is that the effects of substrate organic content on stormwater retention may not detectable until the systems are more mature – i.e., beyond three years post-installation. Retention data was based on the second growing season for the experimental platforms, so while plant growth differences were identifiable, these may not yet have a measurable impact on retention. The growth differences between treatments will only be compounded with each growing season – larger plants in 40% organic matter will build a thicker thatch layer, which will add even more organic matter back into the system through microbial degradation – I expect analysis of year 5 data will better elucidate the effects of substrate organic content on stormwater retention.

In addition to identifying the need for more rigorous performance-based guidelines and regulations regarding stormwater retention green roofs, my work demonstrates the ability of *Sedum kamptschaticum* to access substrate water previously assumed to be unavailable. While the volume of plant available water was not defined, these findings helps move forward the literature and should help inform policies with regards to green roof stormwater retention estimates. This work also clearly defines the need for delineation between lab-based maximum water holding capacity (i.e., FC_{sat}) and the more realistic field-based maximum water holding capacity (i.e., FC_{unsat}). Together these results offer more understanding to expected green roof retention and lay the foundation for more actual roof performance monitoring.

Appendix A.

A carbon cost analysis of local (Frederick, Maryland) crushed brick was completed to provide a basis of comparison for expanded mineral substrates. The brick are obtained direct from a brick manufacturer in Frederick, Maryland and are considered "seconds" – either due to imperfections in color or integrity of the structure (cracks, chips, etc.). These seconds are culled from the production line prior to shipment and historically are stored in bulk by the manufacturer indefinitely (Michael Furbish, Furbish, *pers. comm.*). The carbon cost analysis for crushed brick as a green roof substrate starts at the point the brick is obtained as seconds from the manufacturer for the purpose of crushing and blending into media. A portable crusher is used on-site at the brick factory, and the crushed material is then transported to the blending facility.

For the sake of simplicity, the carbon comparison does not account for transportation costs because expanded minerals also must be transported from the manufacturer to the blending facility. Therefore, the only carbon cost associated with the crushed brick is the actual crushing. The crusher used was a diesel-powered Eagle 1200 CC crusher, and yields about 225 tons/hour for particle sizes less than 1" (2.25 cm). For these particle sizes, one ton is roughly one cubic yard (based on bulk density of 1177 g/L). The crusher consumed 9.7 gal diesel fuel per hour. Burning one gallon of diesel fuel yields 22.38 lbs CO_2, coming to 201.42 lbs CO_2 per hour from the consumption of diesel fuel. Assuming a continuous 225 tons produced per hour, the total carbon cost comes to 1.12 lbs CO_2 per ton, equal to 0.5 kg CO_2 per ton (cubic yard). This is far below Elliot's (2007) and the Expanded Shale, Slate, and Clay Institute's (2011) reported 110 kg CO_2 per cubic yard expanded mineral.

Appendix B

Particle size distributions of mineral components (Figure A.1) and substrate blends used (Figure A.2) in Chapters 3, 4, and 5. n = 5 for each treatment; samples were oven-dried at 110 C for 48 hours prior to sieving using a Meinzer 11 shaker for 20 minutes and ASTM sieves 8, 16, 30, 45, 60, 100, and 200. Data are presented as percent weight of each diameter range per total sample weight.

Figure B.1. Particle size distribution of recycled brick and scoria which made up the mineral component of the experimental extensive green roof substrate blends. n = 5 for both treatments and differences determined by independent student's t test at each particle diameter with $\alpha = 0.05$. Significance indicated by **, $p<0.01$.

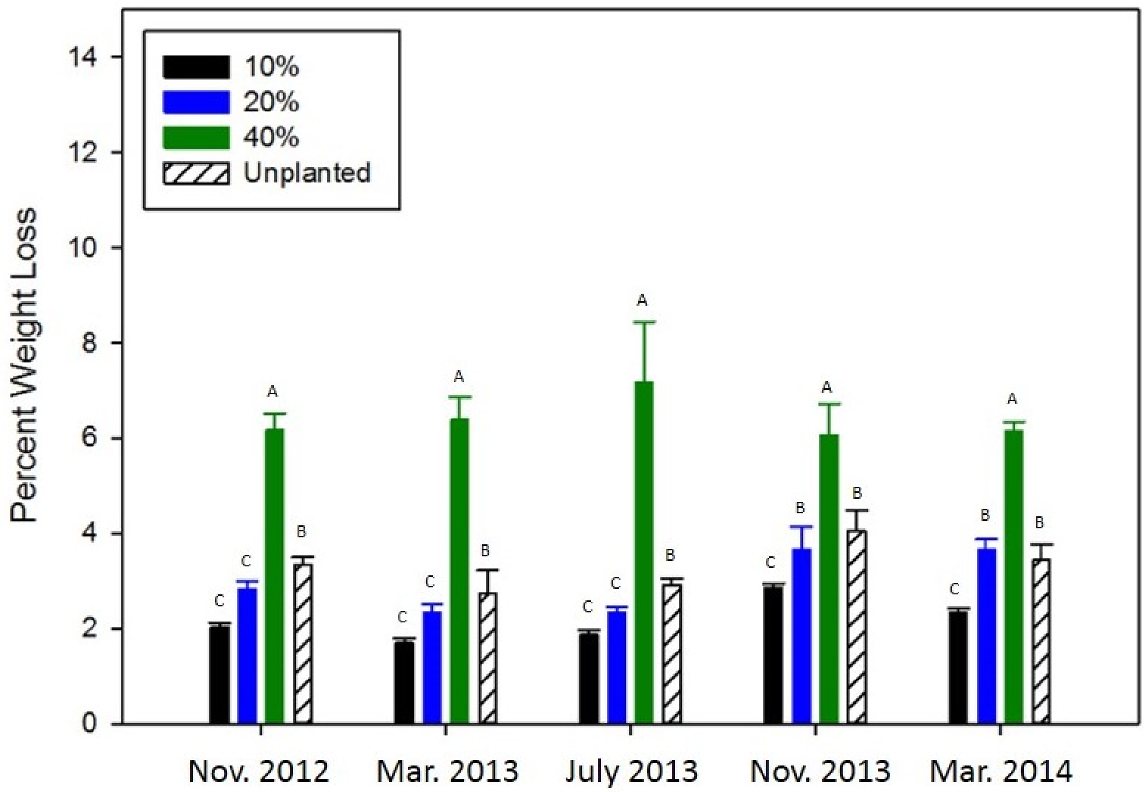
ASTM Sieve No.	Mesh size (mm)	Brick		Significance	Scoria	
		Percent	SEM		Percent	SEM
8	**>2.360**	84.98	±1.84	**	49.31244	±2.93
16	**1.180-2.360**	3.49	±0.56	**	12.45906	±0.24
30	**0.600-1.180**	1.84	±0.51	**	7.678015	±0.59
45	**0.355-0.600**	1.37	±0.22	**	6.565116	±0.51
60	**0.250-0.355**	1.26	±0.22	**	4.388538	±0.52
100	**0.150-0.250**	1.82	±0.23	**	6.717835	±0.44
200	**0.075-0.150**	2.49	±0.36	**	8.010246	±0.67
pan	**<0.075**	2.74	±0.19	**	4.868749	±0.31

Figure B.2. Particle size distribution of three experimental extensive green roof blends composed of 60:40 recycled brick:scoria and increasing volumetric proportions of organic matter plus Rooflite ™, an industry standard ready-to-plant blend. n = 5 for all treatments and differences were determined using Scheffe's adjustment for multiple means comparisons at α = 0.05.

ASTM Sieve No.	Mesh size (mm)	10% OM			20% OM			40% OM			Rooflite ™		
		Percent	SEM	Sig.	Percent	SEM	Sig.	Percent	SEM	Sig.	Percent	SEM	Sig.
8	**>2.360**	56.85	±2.74	A	59.61	±2.65	A	61.20	±1.05	A	54.89	±0.54	A
16	**1.180-2.360**	10.14	±0.46	B	9.80	±0.57	B	9.72	±0.49	B	21.83	±0.80	A
30	**0.600-1.180**	7.70	±0.54	B	7.21	±0.60	B	8.03	±0.29	C	11.80	±0.29	A
45	**0.355-0.600**	5.72	±0.37	A	6.03	±0.77	A	5.43	±0.34	A	4.37	±0.39	A
60	**0.250-0.355**	3.56	±0.25	A	3.32	±0.19	A	3.50	±0.25	A	2.10	±0.19	B
100	**0.150-0.250**	6.29	±0.59	A	5.46	±0.43	A	5.86	±0.17	A	2.15	±0.20	B
200	**0.075-0.150**	6.67	±0.46	A	5.44	±0.20	AB	3.79	±0.61	B	1.52	±0.16	C
pan	**<0.075**	3.08	±0.40	A	3.13	±0.44	A	2.47	±0.06	AB	1.35	±0.27	B

Appendix C.

Fig. C.1 Substrate organic content based on loss on ignition analysis. All roots were removed by hand from samples of planted treatments. The unplanted treatment was mixed with 10% organic matter initially. Loss on ignition was achieved by burning samples in a muffle furnace at 530 C for four hours, following the methodology outlined by Heiri et al. (2001).



Appendix D

Volumetric water content (mL^3/mL^3) of three experimental green roof substrates with increasing (10%, 20%, and 40%) volumetric proportions of organic matter was measured continuously by the HYPROP© method (Schindler et al., 2010) with Decagon Devices ECHO-5TM moisture sensors inserted into the cores (Fig. C.1). Substrate VWC values are actual weight-based values measured by loss of weight during evaporation. Substrate matric potential (VWC plotted against pF) is presented in subset A while substrate VWC is plotted against millivolts (moisture sensor output) in subset B. Maximum VWX captured by the sensors is a little less than the maximum HYPROP© VWC because the HYPROP© begins taking measurements immediately after the instrument is assembled; evaporative water loss had begun before and during sensor insertion. Core depth and sensor length are both 5 cm, so great care was taken not to disturb or damage the tensiometers or pressure transducers (Fig. C.2), so there was a time delay between the start of HYPROP© measurements and the start of sensor measurements. Moisture sensors captured substrate VWC beyond the measurement range for the HYPROP©, which stops at the point of tensiometer water column cavitation.

Fig. D.1. Particle size distribution of recycled brick and scoria which made up the mineral component of the experimental extensive green roof substrate blends. n = 5 for both treatments and differences determined by independent student's t test at each particle diameter with α = 0.05. Significance indicated by **, p<0.01.

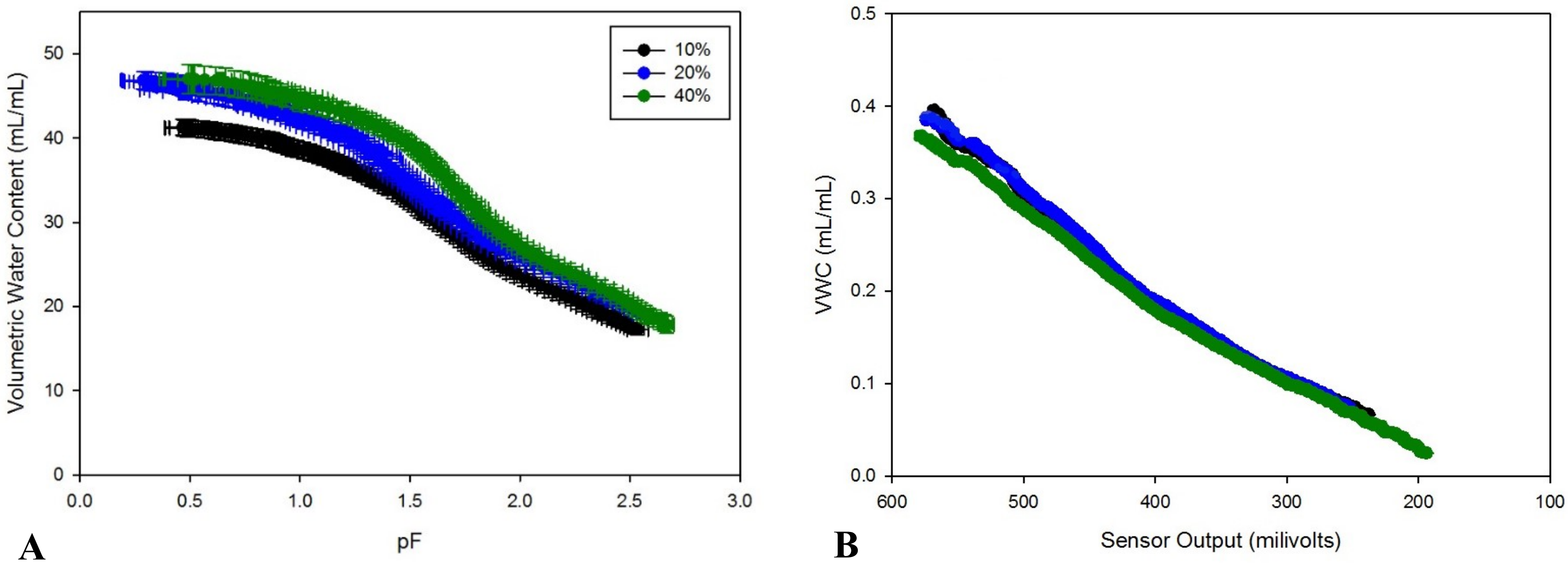
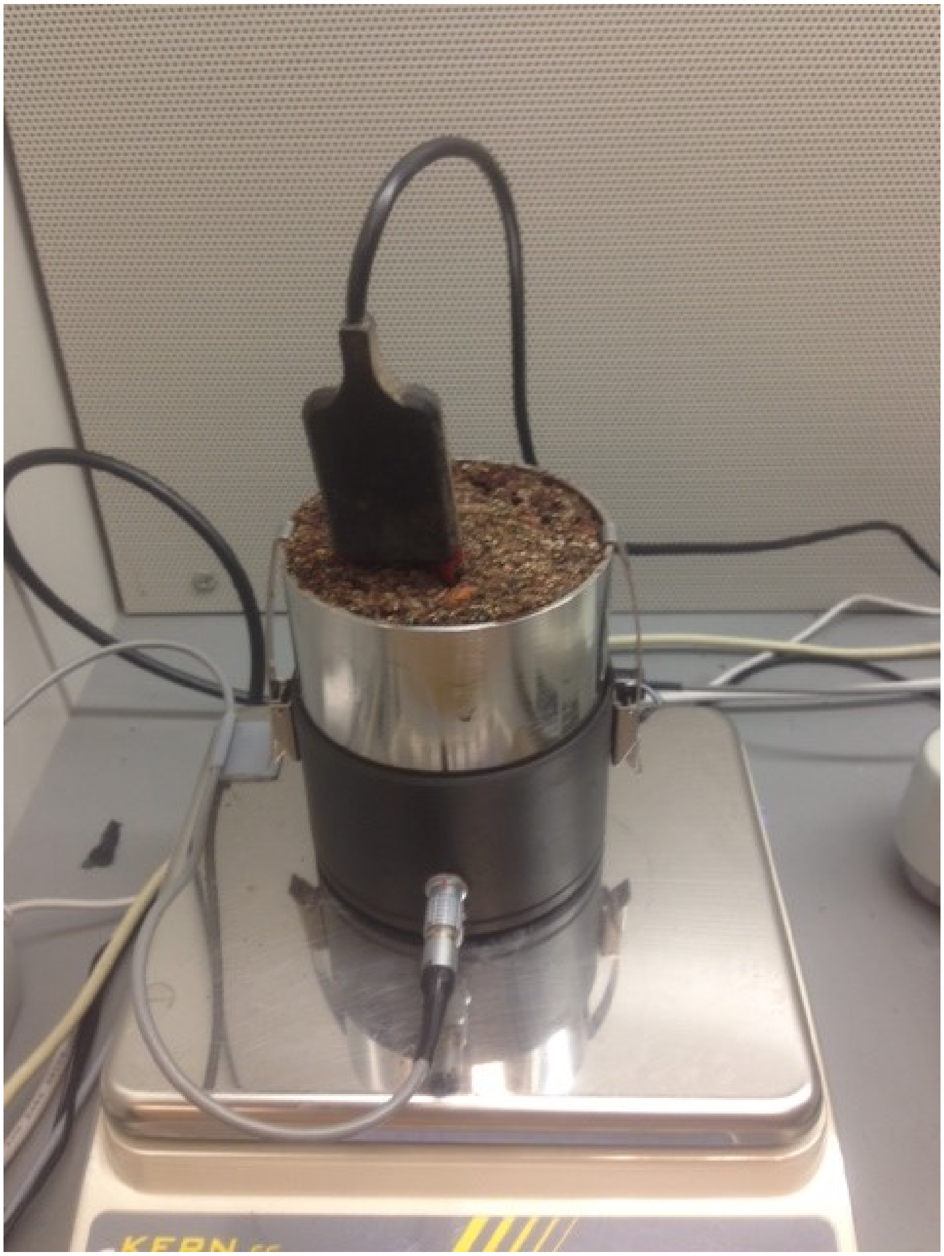


Fig. D.2. Photograph illustrating the HYPROP© measurement system being used in conjunction with Decagon Devices Echo-5TM moisture sensors, which are connected to an EM-50 data logger. The HYPROP© collected measurements at 10 minute intervals; the logger recorded by-minute averages every 5 minutes.



Appendix E.

Mushroom compost is a common horticultural substrate amendment and its nutritional content has been widely reported. Fidanza et al. (2010) reported the N-P-K values of mushroom compost from 30 mushroom compost facilities across Southern Pennsylvania. The authors reported total N to be 6.4 lbs/yd^3, total phosphorus (as P_2O_5) as 1.67 lbs/yd^3, and total potassium (as K_2O) to be 5.89 lbs/yd^3. Table X.1 presents extrapolated values for the growth chamber study in Chapter 4 (g per pot per treatment) and for the platform-scale field study in Chapter 5 (g per platform per treatment).

Fig E.1. Extrapolated nutrient availability (N,P,K) per gram for the pot-scale growth chamber study presented in Chapter 4 and the platform-scale field study presented in Chapter 5.

	Growth Chamber Study			Platform Study		
TRT	N (g/pot)	P (g/pot)	K	N (g/platform)	P (g/platform)	K(g/platform)
10%	0.19	0.05	0.17	55.60	14.51	51.17
20%	0.38	0.10	0.35	111.20	29.02	102.34
40%	0.76	0.20	0.70	222.40	58.03	204.68

Glossary

FC_{sat}: Field capacity as determined after saturating samples for a minimum of 24 hours and after gravitational drainage.

FC_{unsat}: Field capacity as determined without any extended saturation, after gravitational drainage.

pF: The base 10 logarithm of soil or substrate water potential in cm.

Bibliography

Anderson, D.C. 1970. Effects of Urban Development on Floods in Northern VA. U.S.G.S. Water Supply Paper 2001-C.

Arguedas-Rodriguez, F.R.A. 2009. Calibrating capacitance sensors to estimate water content, matric potential, and electrical conductivity in soilless substrates. Thesis, University of Maryland, College Park, Maryland. 137 pp.

Arnold, C.L. and C.J. Gibbons. 1996. Impervious Surface Coverage, the Emergence of a Key Environmental Indicator. J. Am. Planning Assn. 62: 247-258.

Beattie, D.J. and R. Berghage. 2004. Green roof media characteristics: the basics. Proc. 2nd North Amer. Green Roof Conf.: Greening Rooftops for Sustainable Communities, Portland, OR. 2-4 June 2004. Cardinal Group, Toronto.

Berndtsson, J.C. 2010. Green roof performance towards management of runoff water quantity and quality: a review. Eco.Eng.36:351-361.

Berndtsson, J.C., L. Bengtsson, K. Jinno. 2009. Runoff water quality from intensive and extensive vegetated roofs. Eco. Eng. 35:369-380.

Berndtsson, J.C., T. Emilsson, and L. Bengtsson. 2006. The influence of extensive vegetated roofs on runoff water quality. Sci. of the Tot. Env. 355:48-63.

Bengtsson, L., L.Grahn, J.Olsson. 2005. Hydrological function of a thin extensive green roof in southern Sweden. Nordic Hydrol. 36(3):259-268.

Bliss, D.J., R.D. Neufield, and R.J. Ries. 2009. Stormwater runoff mitigation using a green roof. Env. Eng. Sci. 26(2): 407-418.

Bibbiani, Carlo, Assistant Professor-Researcher, University of Pisa, Italy.

Borland, A.M., V.A.B. Zambrano, J. Ceusters, and K. Shorrock. 2011. The photosynthetic plasticity of crassulacean acid metabolism: an evolutionary innovation for sustainable productivity in a changing world. New Phytologist 191:619-633.

Canada Climate Data. 2013. Canadian climate normal 1971-2000. www.climate.weather.gc.ca/climate_normals/results_e.html?stnID=5097&autofwd=1 Last accessed 17 September 2013.

Canada Public Works Department. 2002. Introductory Manual for Greening Roofs for Public Works and Government Services. Version 1.1.

Carpenter, D. D. and P. Kaluvakolanu. 2011. Effect of roof surface type on storm-water runoff from full-scale roofs in a temperate climate. J. Irrig. Drain. Eng. 137:161-169.

Carter, T. and A. Keeler. 2008. Life cycle cost-benefit analysis of extensive vegetated roof systems. Journal of Environmental Management 87:350-363.

Casey Trees and LimnoTech. 2007. The Green Build-out Model: Quantifying the Stormwater Management Benefits of Trees and Green Roofs in Washington, DC.

Chesapeake Bay Foundation. www.cfb.org. 9 February 2011.

City of Los Angeles Environmental Affairs Department. 2006. Report: Green roofs – cooling Los Angeles.

Coffman, R.R. 2007. Vegetated roof systems: design, productivity, habitat, and sustainability in green roof and ecoroof technology. Dissertation, The Ohio State University, Columbus, Ohio. 227 pages.

Costanza, R. and H. E. Daly. 1987. Toward and Ecological Economics. Baton Rouge: Coastal Ecology Institute, Center for Wetland Resources, and the Department of Economics, Louisiana State University.

Currie, B.A., and B. Bass. 2005. Estimate of air pollution mitigation with green plants and green roofs using the UFORE model. In: Proceedings of Third Annual Greening Rooftops for Sustainable Communities conference. Washington, D.C. May 4-6 2005.

Davis, A.P. and R.H. McCuen. 2005. Stormwater Management for Smart Growth. Springer Publishing, New York. 367 pp.

DC Water and Sewer Authority. http://www.dcwasa.com/customercare/iab.cfm. 9 February 2011.

De Bano, L.F., S.M. Savage, and D.A. Hamilton. 1976. The Transfer of Heat and Hydrophobic Substances During Burning. Soil Sci. Am. J. 40:779-782.

De Bano, L.F. 1981. Water Repellent Soils: A State of the Art. Pacific Southwest Forest and Range Experiment Station, California.

De Boodt, M. and O. Verdonck. 1972. The physical properties of the substrates in horticulture. Acta Hort. 26:37-44.

Delong, C. P. 2014. Evaluation of plant species for survival, growth, and contribution to green roof function. *Thesis*. University of Maryland, College Park. 85 pages.

Deutsch, B., H. Whitlow, M.Sullivan, Savineau. 2005. Re-greening Washington, DC: A green roof vision based on quantifying stormwater and air quality benefits. http://www.greenroofs.org/resources/greenroofvisionfordc.pdf.

District Department of the Environment, Watershed Protection Division, District of Columbia. June 2013. Stormwater Management Guidebook.

Drzal, M.S., W.C. Fonteno, and D.K. Cassel. 1999. Pore fraction analysis: a new tool in substrate analysis. Acta Hort. 481:43-54.

Durhman, A.K. and D.B. Rowe. 2007. Effect of substrate depth on initial growth, coverage, and survival of 25 succulent green roof taxa. HortScience 42(3)588-595.

Durner, W. 1994. Hydraulic conductivity estimation for soils with heterogeneous pore structure. Water Resources Res. 30(2):211-223.

Elliott, Stephen. 2007. Embodied energy comparisons – light weight aggregates and pumice. http://www.greenroofs.com/pdfs/skytrenches=1107_stephanelliott.pdf.

Emilsson, T. 2008. Vegetation development on extensive vegetated green roofs: influence of substrate composition, establishment method, and species mix. Ecological Engineering 33(2008):265-277.

Erlichman, P. and S. Peck. 2013. Annual green roof industry survey for 2012. Available online at http://greenroofs.org/index.php/resources/2012-green-roof-industry-survey . Accessed 12 August 2013.

Expanded Shale, Clay, and Slate Institute. 2012. Embodied energy to manufacture expanded shale, clay, and slate (ESCSI) lightweight aggregate. Information sheet 9153.

Fassman, E.A. and R. Simcock. 2008. Development and implementation of locally-sourced extensive green roof substrate in New Zealand. World Green Roof Congress, London.

Fassman-Beck, E.A. and Simcock, R. (2013). Extensive Living Roofs: Review and Design Recommendations. Auckland UniServices Technical Report to Auckland Council. Auckland Council TR2012/010. Available at http://www.aucklandcouncil.govt.nz/en/planspoliciesprojects/reports/technicalpublications/Pages/home.aspx.

Fassman-Beck, E., E. Voyde, R. Simcock, and Y.S. Hong. 2013. 4 Living roofs in 3 locations: does configuration affect runoff mitigation? Journal of Hydrology 490:11-20.

Ferguson, B.K. 1994. Stormwater Infiltration. Boca Raton, FL. CRC Press. 288 pp.

Ferguson, B.K. 1996. Preventing the Problems of Urban Runoff. Renewable Resources Journal 13(4):14-18

Ferguson, B. Introduction to Stormwater: Concept, Purpose, Design. 1998. Wiley and Sons, Inc., New York. 255 pp.

Fidanza, M.A., D.L. Sanford, D.M. Beyer, and D.J. Aurentz. 2010. Analysis of fresh mushroom compost. HortSci. 20(2): 449-453.

Fonteno, W.C. and C.T. Harden. 2003. Procedures for determining the physical properties of horticultural substrates using the NCSU porometer. Available online at http://www.ncsu.edu/project/hortsublab/pdf/porometer_manual.pdf

Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau [FLL] Guideline for the Planning, Execution, and Upkeep of Green-Roof Sites. 2008.

Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau [FLL] Guideline for the Planning, Execution, and Upkeep of Green-Roof Sites. 2002.

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

Getter K.L., D.B. Rowe, G. P. Robertson, B.M. Cregg, and J. A. Andresen. 2009. Carbon sequestration potential of green roofs. Enviro. Sci. Technol. 43:7564-7570.

Gliessman, S.R. 1998. Agroecology: ecological processes in sustainable agriculture. Ann Arbor Press, Chelsea, Michigan. 357 pp.

Graham, P., M.Kim. 2005. Evaluating the stormwater management benefits of green roofs through water balance modeling. Green Roofs for Healthy Cities Conference Proceedings. May 2005. Washington, DC.

Gregoire, B. and J. Clausen. 2011. Effect of a modular extensive green roof on stormwater runoff and water quality. Eco. Eng. 37:963-969.

Groenevelt, P.H. and P.E. Gruntha. 1998. Utilization of crumb rubber as a soil amendment for sports turf. Soil & Tillage Research 47 (1998) 169-172.

Handreck, K. and N. Black. 2002. Growing media for ornamental plants and turf. Second Edition. University of New South Wales Press, Sydney, Australia. 483 pp.

Handreck, K. and N. Black. 2007. Growing media for ornamental plants and turf. Third Edition. University of New South Wales Press, Sydney, Australia. 542 pp.

Harmon, K.S. 2000. Characteristics of rotary kiln expanded slate lightweight aggregate, Proc. 2nd International symposium on structural lightweight aggregate concrete, Kristiansand, Norway. 18-22 June. Pp. 574-583.

Hathaway, A.M., W.F. Hunt, and G.D. Dennings. 2008. A field study of green roof hydrologic and water quality performance. ASABE 51(1): 37-44.

Hill, M.S. 1997. Understanding Environmental Pollution. Cambridge, UK. Cambridge University Press. 316 pp.

Hillel, D. 2004. Introduction to Environmental Soil Physics. San Diego, CA. Elsevier Academic Press. 494 pages.

Horton, T. 2003. Turning the Tide: Saving the Chesapeake Bay. The Chesapeake Bay Foundation. Island Press, Washington, DC. 387 pp.

Johnson, J. and J. Newton. 1996. Building Green, a Guide for using Plants on Roofs and Pavement. The London Ecology Unit, London.

Kiehl, P.A., J.H. Liehl, D.W. Buerger. 1992. Growth response of Chrysanthemum to various container medium moisture tension levels. J. Amer. Soc. Hort. Sci. 117(2): 224-229.

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

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

Kohler, M., M.Schmidt, F.W. Grimme, M. Larr, V.L. de Assuncao Paiva, S. Tavares. 2002. Green roofs in temperate climates and in the hot-humid tropics – far beyond the aesthetics. Environ.Manage.Health 13(4)382-391.

Kolb, W.. 2004. Good reasons for roof planting – green roofs and rainwater. Proc. IC on Urban Horticulture. Acta Hort 543:295-300

Kosareo, L. and R. Ries. 2007. Comparative environmental life cycle assessment of green roofs. Build. Environ. 42:2606-2613.

Leopold, L.B. 1968. Hydrology for Urban Planning – a Guidebook on the Hydrologic Effects of Urban Land Use. USGS Circular 554. Washington, DC. U.S. Geological Survey.

Lubowski, R.N., M. Vesterby, S. Bucholtz, A. Baez, and M.J. Roberts. 2006. Major Uses of Land in the United States, 2002. United States Department of Agriculture Economic Research Service Summary Report. May 2006. www.usda.gov/publications/eib14.

Lundholm, J.T., J.S. MacIvor, M.A. Ranalli. 2009. Benefits of green roofs on Canada's east cost. In: Proc. 7th North American Green roof Conference: Greening Rooftops for Sustainable Communities. Atlanta, GA. The Cardinal Group, Toronto.

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

Maryland Department of the Environment Environmental Site Design (ESD) Process and Computations. 2010. Prepared by MDE. Available online at http://www.mde.state.md.us/programs/Water/StormwaterManagementProgram/MarylandStormwaterDesignManual/Pages/programs/waterprograms/sedimentandstormwater/stormwater_design/index.aspx

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

Miller, Charlie, P.E. Owner, Roofmeadow, Philadelphia, PA.

Molineux, C.J., C.H. Fentiman, A.C. Gange. 2009. Characterising alternative recycled waste materials for use as green roof growing media in the U.K. Ecological Engineering 35(2009):1507-1513.

Monterusso, M.A., D.B.Rowe, and C.L. Rugh. 2005. Establishment and persistence of *Sedum spp.* and native taxa for green roof applications. HortScience 40(2):391-396.

Monterusso, M.A., D.B. Rowe, C.L. Rugh, and D.K. Russell. 2004. Runoff water quantity and quality from green roof systems. Acta Hort 639:369-376.

Mualem, Y. 1976. A New Modelfor Predicting the Hydraulic Conductivity of Unsaturated Porous Media, Water Resources Research 12(3):513-522.

Nardini, A., S. Andri, and M. Crasso. 2012. Influence of substrate depth and vegetation type on temperature and water runoff mitigation by extensive green roofs: shrubs vs. herbaceous plants. Urban Ecosyst. 15(3): 697-708.

National Institute of Standards and Technology. 2012. Time of Wetness and Freezing Predictions. http://ciks.cbt.nist.gov/bentz/nistir6551/node10.htm. Last accessed 31 July 2012.

Newman, S., K. Panter, and M. Roll. 1997. Growth and nutrition of geraniums grown in media developed from waste tire components. HortScience 32:674-676.

Nobel, P.S. 1996. High productivity of certain agronomic CAM species. In: Winter K. and J.A.C. Smith. Crassulacean acid metabolism: biochemistry, ecophysiology, and evolution. Berlin, Germany. Springer-Verlag, 255-265.

Oberlander, C.H., E. Whitelaw, E. Matsuzaki. 2002. Introductory manual for greening roofs for public works and government services Canada. Version 1.1 published 13 December 2002.

Palla, A., L.G. Lanza, and P. La Barbera. 2008. A green roof experimental site in the Mediterranean climate. Proc. 11th Annual Conf. on Urban Drainage, Edinburgh, Scottland, UK.

Peck, Steven. 2013. Annual Green Roof Industry Survey. Green Roofs for Healthy Cities Report April, 2013. http://www.greenroofs.org/resources/GreenRoofIndustrySurveyReport2013.pdf

Peters, A. and W. Durner. 2008. Simplified evaporation method for determining soil hydraulic properties. Journal of Hydrology 356:147-162.

Portland Bureau of Environmental Services (PBES). 2006. Combined Sewer Overflow Program Progress Report. http://www.portlandonline.com/shared/cfm/image.cfm?id=113677.

Prodgers, R.A. 2009. Revegetating topsoil, scoria, and spoil in Montana. Proc. 2009 National Meeting of American Society of Mining and Reclamation. Billings, MT. May 30 – June 5, 2009.

Quyum, Abdul. 2000. Water Migration Through Hydrophobic Soils. *Dissertation*. University of Calgary. 157 pages.

Raviv, M., R. Wallach, A. Silber, and A. Bar-Tal. 2002. Substrates and their Analysis. Chapter 2, *Hydroponic production of vegetables and ornamentals*. Embryo Publications, Athens, Greece. Pp. 25-101.

Rivera, Leo. Decagon Devices, INC. Pullman, WA.

Rowe, D.B., M.A. Monterruso, and C.L. Rugh. 2006. Assessment of heat-expanded slate and fertility requirements in green roof substrates. HortTechnology 16(3): 471-477.

Schindler, U., W. Durner, G. von Unold, L. Müller, and R. Wieland. 2010. The evaporation method: extending the range of soil hydraulic properties using the air-entry method of the ceramic cup. J. Plant Nutr. Soil Sci. 173:563-572.

Schindler, U., W. Durner, G. von Unold, and L. Müller. 2010b. Evaporation method for measuring unsaturated hydraulic properties of soils: extending the measurement range. Soil Sci. Soc. Am. J. 74:1071-1083.

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

Seattle stormwater code. 2009. Director's rules, client assistance memos, green stormwater infrastructure and flow control calculators. Last accessed March 3 2011. http://www.seattle.gov/dpd/codes/stormwatercode/overview/default.asp

Seattle Green Stormwater Infrastructure Manual. 2010. Volume 3, Section 4.4.8.

Shamseldin, A.Y., 2010. Analytical Probabilistic Models for Low Impact Development (LID) Stormwater Management Planning, Progress Report. Auckland, Waitakere City Council.

Snodgrass, E. and L. Snodgrass. 2006. Green roof plants. A resource and planting guide. Timber Press, Inc. Portland, Oregon. 203 pp.

Solano, S.L. 2010. Investigating crumb rubber amendments for extensive green roof substrates. Thesis, University of Maryland, College Park, Maryland. 150 pp.

Solano, L., A.R. Ristvey, J.D. Lea-Cox, and S.M. Cohan. 2012. Sequestering zinc from recycled crumb rubber in extensive green roof media. Eco. Eng. 47:284-290.

Starry, O. 2013. The comparative effects of three sedum species on green roof water retention. Dissertation, University of Maryland, College Park, Maryland. 157 pp.

Sydney City Council. 2010. Green Roof Resource Manual. Sydney, Australia. http://www.cityofsydney.nsw.gov.au/__data/assets/pdf_file/0006/109383/Green-roof-resource-manual-full-version.pdf

Taiz, L. and E. Zeiger. 2010. Plant Physiology Fifth Ed. Sinauer Associates, Inc. Sunderland, Massachusetts.

Tan, P. and A. Sia. 2005. A pilot green roof research project in Singapore. Ini: Proc. of 3rd North American Green Roof Conference: Greening Rooftops for Sustainable Communities, Washington, DC. 4-6 May 2005. The Cardinal Group, Toronto.

Teemusk, A. and U. Mander. 2007. Rainwater runoff quantity and quality performance from a green roof: the effects of short-term events. Eco. Eng. 30:271-277.

United States Environmental Protection Agency National Pollutant Discharge Elimination System. http://cfpub.epa.gov/npdes/hom.cfm?program_id=5 9 February 2011.

United States Environmental Protection Agency. Greenhouse gas equivalency calculator. http://www.epa.gov/cleanenergy/energy-resources/calculator.html Accessed 1 February, 2012

United States Environmental Protection Agency. 2010. Green Infrastructure Case Studies: Municipal Policies for Managing Stormwater with Green Infrastructure. Bulletin No. EPA-841-F-10-004.

United States Geological Survey. Volcanic Glossary: Scoria. http://volcanoes.usgs.gov/images/pglossary/scoria.php 8 July 2011.

van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44(5):892-898.

Van Renterghem, T. and D. Botteldooren. 2009. Reducing the acoustical façade load from road traffic with green roofs. Building and Environment 44:1081-1087.

Van Renterghem, T. and D. Botteldooren. 2011. In-situ measurements of sound propagating over extensive green roofs. Building and Envionment 46:729-738.

VanWoert, N.D., D.B. Rowe, J.A. Andresen, C.L. Rugh, and L. Xiao. 2005a. Watering regime and green roof substrate design affect *Sedum* plant growth. HortScience 40(3):659-664.

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

Villarreal, E.L. and L. Bengtsson. 2005. Response of a Sedum green-roof to individual rain events. Eco. Eng. 25:1-7

Voyde, E., E. Fasman, and R. Simcock. 2010. Hydrology of an extensive living roof under sub-tropical climate conditions in Auckland, New Zealand. J. Hydrol. 394:384-395.

Wallis, M.G., D.R. Scotter, and D.J. Horne. 1991. An Evaluation of the Intrinsic Sorptivity Water Repellency Index on a Range of New Zealand Soils. Austr. J. Soil Res. 29: 353-362

Wang, L., J. Lyons, P. Rasmussen, P. Simons, T. Wiley, and P. Stewart. 2003. Watershed, reach, and riparian influences on stream fish assemblages in the Northern Lakes and Forest Ecoregion. Canadian Journal of fisheries and Aquatic Science 60:491-505.

Wong, N.H., P.Y. Tan, Y. Chen. 2007. Study of thermal performance of extensive rooftop greenery systems in the tropical climate. Build. Environ. 42:25-54.

Wuerthner, George. "The Truth About Land Use in the United States". 2002. Watersheds Messenger, Vol. 9, No. 2.