DISSERTATION

EXTENSIVE GREEN ROOFS IN COLORADO: PLANT SPECIES PERFORMANCE, GROWING MEDIA MODIFICATIONS, AND SPECIES RESPONSE TO GROWING MEDIA DRY DOWN

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY JENNIFER MCGUIRE BOUSSELOT ENTITLED EXTENSIVE GREEN ROOFS IN COLORADO: PLANT SPECIES PERFORMANCE, GROWING MEDIA MODIFICATIONS, AND SPECIES RESPONSE TO GROWING MEDIA DRY DOWN BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

EXTENSIVE GREEN ROOFS IN COLORADO: PLANT SPECIES PERFORMANCE, GROWING MEDIA MODIFICATIONS, AND SPECIES RESPONSE TO GROWING MEDIA DRY DOWN

Green roofs provide many benefits and are often used to help alleviate the negative effects of urbanization. In order to provide these benefits, green roofs should remain alive and viable. Therefore, a series of studies were performed to elucidate some performance characteristics of extensive (shallow) green roofs.

Plant area covered was examined for six plant species on an existing modular extensive green roof in semi-arid Colorado. Species evaluated were *Antennaria parvifolia* Nutt., *Bouteloua gracilis* (Kunth) Lag., *Delosperma cooperi* (Hook. f.) L. Bol., *Eriogonum umbellatum* Torr. *aureum* 'Psdowns', *Opuntia fragilis* Nutt. and *Sedum lanceolatum* Torr. Most reported methods for measuring plant area covered (plant cover) are subjective and not based on quantitative measurements. This study compared digital image analysis data (DIA) to manually collected converted two-dimensional data (C2D) for plants grown on an extensive green roof. For each plant in the study, digital images and manual two-dimensional measurements were taken on four dates (at six week intervals) in 2008 and on four dates (at six week intervals) in 2009. Using SigmaScan Pro

5.0 image analysis software, DIA was performed on these images. Additionally, comparisons between DIA data and final biomass, and C2D and final biomass, were performed. Plant cover increased for all six species during the 2008 growing season. However, *E. umbellatum aureum* 'Psdowns' had a low overwintering rate (12.5%) and was removed from analysis in 2009. In the spring of 2009, four of the five remaining species exhibited decreased plant cover due to winter dieback; the one exception was *O. fragilis*. In terms of plant cover, both quantification methods (C2D and DIA) revealved that *B. gracilis* and *D. cooperi* out performed *A. parvifolia*, *O. fragilis* and *S. lanceolatum*. Thus, five of the six species evaluated in this study are appropriate for use in extensive green roof applications. High levels of correlation were found between the DIA and C2D data sets ($r = 0.77$) averaged over the five species on all eight data collection dates. The groundcover species (*A. parvifolia*, *D. cooperi* and *S. lanceolatum*) had a higher correlation on average ($r = 0.83$) than the upright (*B. gracilis*, $r = 0.70$) and decumbent (*O. fragilis*, $r = 0.65$) species. Additionally, DIA and final biomass correlations showed parallel trends with groundcovers averaging $r = 0.83$, upright $r = 0.64$ and decumbent $r = 0.41$. Therefore, using DIA to evaluate plant cover and biomass accumulation is especially appropriate for groundcover species.

Success of an extensive green roof is primarily dependent on plant species ability to survive the low moisture content of the growing media. Due to the well-drained nature of the growing media, plants adaptable to dry, porous soils are primarily used in extensive green roof applications. Although *Sedum* species have dominated the plant palette for extensive green roofs, there is growing interest in expanding the plant list for extensive green roof systems. In order to effectively select suitable plants, species need to

be evaluated in terms of their response to gradual and prolonged dry down of the growing media. A study to determine the relative rates of dry down for fifteen species was conducted in greenhouse and outdoor trials. During dry downs that extended over five months, succulent and herbaceous species dried down at different rates. Although, not all succulent or herbaceous plants had consistent moisture contents during the initial 18 days of dry down. Despite differences in dry down, the succulent species, as a group, maintained viable foliage for over five times longer than the herbaceous species. The revival rates of the succulent species were nearly double those of the herbaceous species. Therefore, not only are succulent species more likely to be longer-lived during periods of drought, but these species are more likely to resume growth soon after water is made available. Based on these results, irrigation frequency is recommended for succulent species at a maximum of 28 day intervals and herbaceous species at maximum of 14 day intervals.

Soilless green roof growing media blends were examined on an existing modular extensive green roof in Denver, Colorado. Growing media blends evaluated include a typical extensive green roof growing media, GreenGrid® and GreenGrid® plus varying percentages of ZeoPro™ H-Plus. Plant taxa used included *Sedum acre* L., *Sedum album* L., *Sedum spurium* Marsch-Bieb. 'Dragons Blood' and S. spurium 'John Creech', all which were already in use on the green roof. Growing media blends were evaluated based on plant taxa growth performance. Data collected included digital images to measure plant area covered using digital image analysis (DIA) and growing media volumetric moisture content (VMC). The DIA data were analyzed using the GLIMMIX procedure in SAS as multiple comparisons of growing media blends for each taxa from eight dates over two growing seasons. The VMC data were analyzed using the GLIMMIX procedure from seven dates over two years. The addition of zeolite to the typical extensive green roof growing media improved establishment year plant cover for *S. acre* and *S. album* but hindered overwintering. Conversely, the two cultivars of *S. spurium* did not show a benefit of plant cover from the addition of zeolite in the first year but did the second year. As the percentage of zeolite in the growing media increased, VMC also increased, despite the fact that laboratory results showed decreasing water holding capacity as zeolite percentage increased.

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Chapter 1. Introduction and Literature Review

As expanding urbanization consumes more land area, the amount of impervious surfaces also increases. As a result, many issues emerge which previously were insignificant: the need to manage stormwater, the urban heat island effect and loss of arable land (Getter and Rowe, 2006). One way to mitigate the negative impacts of urbanization is to vegetate impervious surfaces. Therefore, green roofs help to mitigate the negative impacts of urbanization and beautiful urban rooftop landscapes (Monterusso et al., 2004).

There are two main types of green roofs: extensive and intensive. Extensive green roofs are characterized by shallow growing media, usually less than 15 cm deep, while intensive green roofs are characterized by deep growing media, from 15 cm up to 1 m (Getter and Rowe, 2006). The shallower extensive green roofs are better suited structurally to existing buildings and are therefore utilized more often. However, the root zone limitations traditionally have not supported a large diversity of plant species. Intensive green roofs are more like rooftop gardens or raised beds because the deeper rooting depths support a wider variety of plants. Although intensive green roofs can be aesthetically similar to at-grade gardens, the weight bearing capacity of most buildings limits their use. Therefore, most intensive green roofs are installed on newly constructed buildings.

Historically, green roofs have been used for centuries in Europe, especially as sod roofs when other materials were not available to construct buildings (Monterusso et al., 2005). Furthermore, modern green roof research began in Europe, specifically Germany, in the last two decades of the twentieth century. More recently in Germany, there has been research on stormwater retention and species mixes for extensive green roofs (Kircher, 2004; Kolb, 2004). In Switzerland, modeling has been used to determine the environmental impact of greening 70% of the flat roofs of Basel (Brenneisen, 2004). Recent efforts in the United Kingdom have looked at growing media depth, species selection and the ecology of green roofs (Dunnett, 2006; Dunnett and Kingsbury, 2004; Dunnett et al., 2008; Dunnett et al., 2005).

Since the turn of the twenty-first century, North American researchers have investigated green roofs as well. Research in the United States has taken place at the Pennsylvania State University (Beattie and Berghage, 2004; Beattie, 2003; Berghage et al., 2007; DeNardo et al., 2005; Gaffin et al., 2006; Gaffin et al., 2005; Rezaei, 2005; Vidmar et al., 2007) and Michigan State University (Durhman et al., 2006; Durhman et al., 2007; Durhman et al., 2004; Getter and Rowe, 2007; Getter and Rowe, 2008; Getter et al., 2007; Monterusso et al., 2005; Monterusso et al., 2004; Rowe et al., 2005; Rowe et al., 2006a; Rowe et al., 2006b; VanWoert et al., 2005a; VanWoert et al., 2005b). Additionally, research has been reported from Southern Illinois University Edwardsville (Gibbs et al., 2006; Retzlaff et al., 2009; Sidwell et al., 2008), the University of Nebraska Lincoln (Sutton, 2008), the University of Texas at Austin (Simmons et al., 2008; Simmons et al., 2007), North Carolina University (Hathaway et al., 2008; Moran et al., 2004) and Colorado State University (Bousselot et al., 2009).

In order to provide the many benefits of green roofs, green roofs have to remain alive. Until just recently, green roofs have not previously been tested in the semi-arid, high elevation environment of the Front Range of Colorado. The low annual precipitation, low average relative humidity, high solar radiation due to elevation, high wind velocities and predominantly sunny days create extremely stressful conditions for long term survivability and adaptability for plants. Even plants that are adapted to extensive green roofs in other regions where environments are more suited to ideal plant performance (i.e. high moisture, high humidity and more cloud cover), may not survive in the challenging conditions characteristic of Colorado's Front Range region.

1.1 Plant Species for Green Roofs

Sedum species are often used on green roofs because of their low moisture requirements,their low-growing, mat-forming growth habit and some species are evergreen. Colorado native plants that inhabit areas with shallow, rocky, well-drained soils may be ideal candidates for including in green roofs. Researching additional plant species not already in use on extensive green roofs will expand the number of plant species available and will help to prevent *Sedum* species from becoming a monoculture on green roofs. A monoculture has a higher probability of pest problems than a system that has diversity because most pests are host specific and if there is plenty of their food available, pest populations tend to increase dramatically.

Selection of plants for use on extensive green roofs should be based on the following criteria: tolerant of soil moisture deficit, low-growing growth habit (beneficial for extensive green roofs to obtain good coverage) evergreen foliage, and a long period of bloom. Plants with erect growth habit can be used as accent plants (good for contrast with groundcovers in heights and bloom times). Since the largest limiting factor for plant growth on a green roof is water, plants that can maintain life with low moisture levels are the species most applicable for green roof systems. Species which are native to areas in Colorado dominated by shallow, rocky, well-drained soils are important because they are adapted to the extreme climactic conditions.

Crassulacean acid metabolism (CAM) plants are tolerant of soil moisture deficit conditions because they keep their stomata closed during the day when transpiration rates are high, and open them at night when transpiration rates are lower (Ting, 1985). Carbon is needed while photosynthesis is taking place during the daytime so CAM plants convert CO_2 into malic acid over night for use during the day. Winter-hardy CAM plants, such as many of the *Sedum* species, have proven to be ideal for green roof systems (Dunnett and Nolan, 2004; Durhman et al., 2006; Monterusso et al., 2005; Rowe et al., 2006b; VanWoert et al., 2005a).

CAM plants have higher water use efficiency (WUE) when compared to plant species that fix carbon through other metabolic pathways, such as C3 and C4 plants (Durhman et al., 2006; VanWoert et al., 2005a). CAM plants had better WUE than non-CAM plants when grown on an irrigated green roof where irrigation events were greater than two days apart (Durhman et al., 2006). In a study consisting of only *Sedum* species, it was hypothesized that non-CAM plants would suffer severely if they were subjected to the 0 $m^3 \cdot m^{-3}$ soil moisture content conditions that occurred in their study as soon as one day after watering (VanWoert et al., 2005a).

Despite how well-suited many CAM plants are for green roofs, a few of the most acclaimed benefits of green roofs are reduced when using CAM plants. Green roofs are supposed to act as insulators for the buildings below them, thus helping with indoor cooling during the summer months of the year. This cooling is accomplished is through evapotranspiration (ET), the process through which water is moved from the rhizosphere through the plant, and released to the surrounding atmosphere through the stomata on the surfaces of leaves. However, because CAM plants rarely open their stomata during the day, transpiration, and therefore the cooling effect, is significantly reduced (Durhman et al., 2006). In addition, due to the fact that CAM plants use less water, they leave more moisture in the growing media, which means they do not use as much of the stormwater as other plants. Therefore, there is a strongly supported hypothesis that more precipitation will leave as runoff when CAM plants are used on green roofs (Durhman et al., 2006; Miller, 2003).

Sedum species are CAM plants that consistently perform well in green roof experiments (Dunnett and Nolan, 2004; Durhman et al., 2006; Monterusso et al., 2005; Rowe et al., 2006b; VanWoert et al., 2005a), and are frequently used in green roof applications all over the world. To avoid *Sedum* monocultures, other plants will need to be incorporated into the extensive green roof plant palette (Durhman et al., 2006; Getter and Rowe, 2006; Rowe et al., 2006b).

Not all *Sedum* species are equally suited for green roof use. Several *Sedum* species were evaluated in a Michigan study; while all species performed well, *S. acre* and *S. album* grew more rapidly than *S. kamtschaticum*, *S. ellacombeanum*, *S. pulchellum*, *S. reflexum* and *S. spurium* 'Coccineum' (Monterusso et al., 2005). In a study conducted in

Europe, it was found that *S. album* established more quickly compared to *S. sexangulare* and *S. reflexum* (Kircher, 2004).

Although many researchers are interested in finding alternatives to *Sedum* species; very few have had much success. Researchers have investigated plants from semi-arid and arid environments with some of these plants being native to areas with shallow soil depths (Dunnett and Nolan, 2004). Some researchers suggest that appropriate native plants should be found near where the green roof will be located (Durhman et al., 2006). However, researchers who have evaluated native plants in their region have found little success (Dunnett and Nolan, 2004; Durhman et al., 2006; Kircher, 2004; Monterusso et al., 2005). This could be because the properties of the green roof growing media (depth, composition, water holding capacity, etc. discussed below) vary significantly from the soil in which these plants have evolved. Some researchers have specifically named Colorado as a place to find native plants that have shallow root systems and are adapted to low annual precipitation (Getter and Rowe, 2006).

Soil moisture deficit stress caused by the well-drained green roof growing media is the most limiting factor to plant performance. Survival as well as growth habit are important criteria for green roof plants. Although *Potentilla anserina* and *Fragaria virginiana* are stoloniferous plants, they did not provide even plant coverage when evaluated for green roof performance in Michigan (Monterusso et al., 2005). *Allium cernuum* has little above-ground biomass and is not a groundcover. However, *A. cernuum* was recommended for use on green roofs, due to its moisture deficit resistance, but only when combined with other species (Monterusso et al., 2005).

Similarly, growth rate can affect how suitable a plant is for green roof use. Even though *Opuntia humifosa* is a succulent and also very soil moisture deficit resistant, it does not spread or reproduce quickly and was not recommended for green roof culture (Monterusso et al., 2005).

Future research should be focused on fast growing succulent plants. Researchers have hypothesized that of the non-succulents which have been evaluated, most need more inputs, such as 1) larger rooting zones, 2) more frequent irrigation and 3) higher organic matter content in the growing media, to be successful (Rowe et al., 2006a). Of all the non-succulents, grasses are generally less recommended due to fire hazard (Kircher, 2004; Monterusso et al., 2005; Monterusso et al., 2004). However, this is a point that has yet to be debated thoroughly.

1.2 Green Roof Growing Media

The success or failure of a green roof is primarily dependent on a plant species' ability to grow in the highly porous growing media with low water holding capacity (Dunnett and Nolan, 2004). Many environmental factors affect the moisture content of the growing media such as surface temperature, ambient air temperature, intensity and duration of solar radiation, relative humidity, rate of air movement (wind), as well as growing media depth and composition.

Most extensive green roof growing media is predominantly composed of expanded slate, shale or clay. These materials are very well-drained, lightweight (but not so light that they blow away), and are not easily broken down (unlike organic materials). However, these expanded materials do have some limitations. The high amount of macro-pore space and low amount of micro-pore space cause these materials to drain very quickly, sometimes, too quickly and the low cation exchange capacity (CEC) of these materials results in a media that does not hold nutrients very well (Beattie and Berghage, 2004; FLL, 2008; Friedrich, 2005; Miller, 2003; Rowe et al., 2006b).

The growing media used on a green roof has to meet several requirements: light in weight (Getter and Rowe, 2006; Panayiotis et al., 2003; Rowe et al., 2006b), adequate nutrient holding capacity without leaching (Rowe et al., 2006b), a narrow range of organic matter content (Getter and Rowe, 2006; Rowe et al., 2006b), and a balance between drainage and water retention (Getter and Rowe, 2006; Panayiotis et al., 2003). Each of these attributes needs to be considered depending on the goal of the green roof (Getter and Rowe, 2006).

In order to diversify plant species on a green roof, modifications to the growing media may be required. Various percentages of expanded slate have been investigated for use in green roof growing media and their affect on plant growth (Rowe et al., 2006b). Generally, as the percentage of expanded slate went up, plant vigor decreased. However, for *Sedum* species to survive, a growing media with up to 80% heat-expanded slate still performed well (Rowe et al., 2006b).

Depth of the green roof growing media can also limit the variety of plant species that can be grown on the green roof. The importance of growing media depth in determining weight loading and therefore green roof type (extensive versus intensive), has been recently investigated (Dunnett and Nolan, 2004; VanWoert et al., 2005a; VanWoert et al., 2005b). The weight of green roof growing media is very important because of structural load limitations of a building's roof. If conventional roofs are to be retrofitted to an extensive green roof, then a lightweight growing media material is necessary. If the growing media is more lightweight, then a deeper growing media can be used so plants have a larger volume of rooting zone per unit of area (Boivin et al., 2001; Panayiotis et al., 2003).

Deeper growing media (6cm) has been shown to produce faster growth and canopy coverage than shallower growing media (2cm) (VanWoert et al., 2005a). Additionally, flowering periods for some plant species are longer with increasing growing media depth (Dunnett and Nolan, 2004). Deep growing media alone did not significantly benefit plants independent of irrigation in a United Kingdom study (Dunnett and Nolan, 2004), but did in North America (VanWoert et al., 2005a). However, both groups of researchers agreed that growing media moisture content and watering frequency are more important to the success of green roofs than growing media depth.

Compared to shallow growing media, deeper growing media provide better protection to plant roots from freezing temperatures (Boivin et al., 2001), although the effect of a building underneath the green roof will help maintain higher winter temperatures (Monterusso et al., 2005; Rowe et al., 2006b). Increased growing media depth will moderate stormwater runoff for longer periods than shallow growing media; however, once the growing medium is saturated, runoff will occur independent of depth (VanWoert et al., 2005b).

Organic matter content in the soil profile is important to the healthy root growth and maintenance of plants. It is logical that organic matter should be a component of green roof growing media. However, organic matter breaks down and needs to be replenished. This is not an easy or cost-effective management option for most green roof systems (Rowe et al., 2006b). If the organic matter breaks down and is not replaced, the growing media depth will shrink, reducing water holding capacity and rooting zone area as well as increasing runoff with excess nutrients (Getter and Rowe, 2006; Rowe et al., 2006b).

Maintaining moist growing media while allowing free drainage is ideal for green roof applications. One possible way to retain moisture is water retention fabric (VanWoert et al., 2005a). Researchers found that an extra water retention fabric layer did not significantly affect plant biomass accumulation in the first season of growth (VanWoert et al., 2005a). However, they hypothesized that later, when the roots of the plants had become established, the water retention fabric would be more useful at supplying the required moisture.

High water holding capacity growing media is not necessarily ideal either. If too much moisture is held without free drainage, then root (and therefore shoot) growth were limited (Panayiotis et al., 2003). The growing media should have macro pore spaces to allow for adequate oxygen in the rooting zone. A growing media with low water holding capacity may provide long term success if there is adequate moisture applied allowing only short periods of wilt when temperatures are the greatest (Panayiotis et al., 2003).

1.3 Moisture Management in Green Roof Growing Medias

Green roof plants do best with supplemental water during establishment (Dunnett and Nolan, 2004). Since the growing media has to be well-drained to prevent anaerobic conditions, the shallow growing media depths on green roofs means moisture content is typically low.

With higher wind speed and solar radiation evident on the tops of roofs than at ground level, ET is increased. Many microclimates are also created on green roofs, which typically mean increased temperatures and greater ET rates (Getter and Rowe, 2006). ET on a green roof plays an important role in how well a green roof system performs, especially in environments like Colorado, where low relative humidity, intense solar radiation, wind and high temperatures. In semi-arid Colorado, this is especially important and long term success may depend on continual irrigation.

Sedums have variability in soil moisture deficit resistance between species. It has been found that *S. acre* was more resistant to soil moisture deficit conditions than *S. kamschaticum ellacombianum* or *S. reflexum* (Durhman et al., 2006). The researchers attributed this to the lower height and smaller leaf area of *S. acre* compared to *S. kamschaticum ellacombianum* and *S. reflexum*.

In greenhouse studies, ET rates where highest on the day of watering for green roof systems (Durhman et al., 2006; VanWoert et al., 2005a). The growing media on green roofs drain quickly, not leaving much plant available water for the next day. On a green roof, without the controlled environment of a greenhouse, ET rates would be much higher than in either of these studies due to the *in situ* environmental effects, such as increased wind and solar radiation (Durhman et al., 2006; VanWoert et al., 2005a). The presence or absence of vegetation also affects the amount of moisture in green roof growing media. Researchers in Michigan found that treatments without vegetation lost water at a faster rate than vegetated treatments (VanWoert et al., 2005a). Although they did not speculate on why, this could be due to the low transpiration rates of the *Sedum* species used in the study. The bare growing media must have had a higher evaporative rate than the ET rate from the vegetated pots.

Evapotranspiration rates are important in terms of stormwater use (Kolb, 2004). Plants are imperative for removing larger quantities of moisture faster through transpiration. In this German study, it was found that annual ET rates can reach up to 45-70% of total precipitation (Kolb, 2004). That means only 30-55% of the precipitation left as runoff, a significant reduction when compared to a conventional roof.

Green roofs retain stormwater better than conventional roofs (Beattie, 2003; Bucheli, 1998; Carter and Jackson, 2007; DeNardo et al., 2005; Deutsch et al., 2007; Getter et al., 2007; Hilten et al., 2008; Hutchinson, 2003; VanWoert et al., 2005b; Villarreal et al., 2004), which is the biggest economical reason green roofs are installed. Results have varied but researchers in Michigan have found that green roofs retained an average of 83% of annual precipitation compared to conventional roofs that only retained 49% (VanWoert et al., 2005b). Growing media had the biggest impact on stormwater retention rate although having vegetation with the growing media did improve the retention slightly more (VanWoert et al., 2005b).

If the growing media is the most important factor in stormwater retention, then the depth of growing media would also affect the degree of retention (Monterusso et al., 2004). A deep green roof can retain a larger precipitation event (amount and duration) than a shallower one (VanWoert et al., 2005b). Regardless of depth, moisture content of the growing media will affect how much of the rain will be retained and therefore how much will run off (Monterusso et al., 2004).

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Chapter 2. Two Methods of Quantifying Plant Cover for Evaluating Species for Extensive Green Roof Culture

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2.0.1. Abstract. This research examined plant area covered for six plant species on an existing modular extensive green roof in semi-arid Colorado. Species evaluated were *Antennaria parvifolia* Nutt., *Bouteloua gracilis* (Kunth) Lag., *Delosperma cooperi* (Hook. f.) L. Bol., *Eriogonum umbellatum* Torr. *aureum* 'Psdowns', *Opuntia fragilis* Nutt. and *Sedum lanceolatum* Torr. Most reported methods for measuring plant area covered (plant cover) are subjective and not based on quantitative measurements. This study compared digital image analysis data (DIA) to manually collected converted two-dimensional data (C2D) for plants grown on an extensive green roof. For each plant in the study, digital images and manual two-dimensional measurements were taken on four dates (at six week intervals) in 2008 and on four dates (at six week intervals) in 2009. Using SigmaScan Pro 5.0 image analysis software, DIA was performed on these images.

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Additionally, comparisons between DIA data and final biomass, and C2D and final biomass, were performed. Plant cover increased for all six species during the 2008 growing season. However, *E. umbellatum aureum* 'Psdowns' had a low overwintering rate (12.5%) and was removed from analysis in 2009. In the spring of 2009, four of the five remaining species exhibited decreased plant cover due to winter dieback; the one exception was *O. fragilis*. In terms of plant cover, both quantification methods (C2D and DIA) revealved that *B. gracilis* and *D. cooperi* out performed *A. parvifolia*, *O. fragilis* and *S. lanceolatum*. Thus, five of the six species evaluated in this study are appropriate for use in extensive green roof applications. High levels of correlation were found between the DIA and C2D data sets ($r = 0.77$) averaged over the five species on all eight data collection dates. The groundcover species (*A. parvifolia*, *D. cooperi* and *S. lanceolatum*) had a higher correlation on average ($r = 0.83$) than the upright (*B. gracilis*, $r = 0.70$) and decumbent (*O. fragilis*, $r = 0.65$) species. Additionally, DIA and final biomass correlations showed parallel trends with groundcovers averaging $r = 0.83$, upright $r = 0.64$ and decumbent $r = 0.41$. Therefore, using DIA to evaluate plant cover and biomass accumulation is especially appropriate for groundcover species.

2.1. Introduction

Green roofs are used to mitigate the environmental effects of urbanization worldwide (Getter and Rowe, 2006; Oberndorfer et al., 2007; Vidmar et al., 2007). There are several types of green roof systems; extensive green roofs are characterized by shallow growing media, generally less than 15cm deep (Getter and Rowe, 2006).

Extensive green roofs have not been scientifically evaluated in the high elevation, semi-arid climate of Colorado. Elsewhere in North America, research on species that can survive and thrive on extensive green roofs has revealed that succulents, predominantly *Sedum* taxa, out-perform most non-succulents (Durhman et al., 2007; Monterusso et al., 2005; Rowe et al., 2006). However, the non-succulents tested were typically native to areas with high annual precipitation and relatively deep soil profiles. Plants native to the Rocky Mountain region, especially those that inhabit areas with shallow, rocky, well-drained soils, may be more suited for use in extensive green roof systems (Getter and Rowe, 2006).

Many plant-related research projects require quantification of plant area covered (plant cover) or, more specifically, rate of change in plant cover over time. Quantification of plant cover is valuable for studies pertaining to green roof plantings because plant species that can cover an area quickly are preferred for green roof applications for both aesthetics and performance (White and Snodgrass, 2003). The use of such species can reduce the cost associated with denser plantings of species that grow slower and cover less area.

There are several methods for quantifying plant cover and rate of change in plant cover. However, most reported methods are subjective and not based on quantitative measurements. Typically, visual assessment or visual ratings are used to evaluate plant cover (Olmstead et al., 2004; Richardson et al., 2001). Visual estimation of plant cover has previously been used in green roof research (Moran et al., 2004).

Manually measured plant growth indices are frequently used as a measure of plant performance. Typically, two plant diameters and plant height are used to estimate plant cover. For example, in the context of green roof research, an average of the three measurements has been used to yield a plant growth index for comparisons between plant species (Gibbs et al., 2006; Monterusso et al., 2005). Manual measurements have been used before to predict biomass accumulation, as was the case by using shoot height for *Arundo donax* (Spencer et al., 2006). The current research converts the two plant diameters into the area of a circle to estimate plant cover (C2D).

Digital image analysis (DIA) is one method used for quantification of plant area. The process of gathering DIA data requires periodic photographing of plants and then digitally analyzing the images to quantify plant cover. Traditionally, DIA has been used to quantify plant cover in several plant science disciplines, including turf sciences (Karcher and Richardson, 2003; Richardson et al., 2001), soil erosion prevention (Olmstead et al., 2004), range management (Bennett et al., 2000) and green roofs (Durhman et al., 2007).

Digital image analysis can also be used to estimate or validate biomass accumulation in plants. Vertical silhouette DIA of grass plants has been used to predict biomass accumulation (Tackenberg, 2007). It has also been used to estimate above ground legume contribution in grasslands and later validated by biomass data (Himstedt et al., 2009).

During 2008 and 2009, two methods of quantifying plant cover were utilized to evaluate the performance of the six species on an extensive green roof located in a semi-arid, high elevation region. For each of the six species in the study, approximate plant cover was obtained by manually measuring diameters of each plant and then converting those diameters (C2D) into approximate plant cover. In addition, digital images of these same plants were taken periodically throughout the growing season; these images were then digitally analyzed (DIA) to quantify plant cover. The DIA data were compared to the C2D data. The specific objectives of this research were to 1) determine species plant cover via DIA and C2D methods, 2) determine the correlation between the DIA and C2D methods, 3) determine the correlation between DIA and plant biomass, and 4) determine the correlation between C2D and plant biomass.

2.2. Materials and Methods

2.2.1. Plant material. Species used in this study were selected based on the following criteria: ability to grow in semi-arid, high elevation conditions (high light intensity, low relative humidity, limited soil moisture, and extreme temperature fluctuations), relatively low growing growth habit, aesthetics, and shallow or fibrous root systems (Getter and Rowe, 2006; White and Snodgrass, 2003) (Table 2.1). In a study conducted on a non-irrigated extensive green roof in Michigan, *Opuntia humifosa*, a relative of *O. fragilis*, was shown to survive the challenging conditions characteristic of extensive green roofs (Monterusso et al., 2005). The species selected for this study, with the exception of *D. cooperi*, are currently not widely used in green roof applications (Bousselot et al., 2009).

The six plant species (Table 2.1) were planted in a Colorado State University greenhouse as monocultures in 0.61m x 1.22m x 10cm black plastic modules filled with a proprietary blend of green roof growing media. The growing media used is very well-drained and designed for use in the GreenGrid® modular green roof system. The growing media contained various percentages of expanded clay, peat, perlite and vermiculite with a pH of 7.0, organic matter content of 4.9% and NPK values of 105, 19 and 251 ppm, respectively.

Table 2.1. Plant species evaluated in the study.

Species	*Antennaria parvifolia*	*Bouteloua gracilis*	*Delosperma cooperi*	*Eriogonum umbellatum aureum* 'Psdowns'	*Opuntia fragilis*	*Sedum lanceolatum*
Common Name	small-leaf pussytoes	blue grama	hardy ice plant	Kannah Creek® buckwheat	brittle pricklypear	spearleaf stonecrop
Growth Habit	groundcover	upright (grass)	groundcover	groundcover	decumbent (cactus)	groundcover

Five of the six species were produced in 128-cell plug trays; the remaining species (*O. fragilis*) was produced in a 72-cell plug tray because the cactus pads were too large to be propagated in the smaller cells of the 128-trays. For each plant species, five modules were filled with growing media and each planted with eight propagules on 06-February-08 in a greenhouse. Individual propagules were placed at 30.5 cm centers so growth could be measured without competition from nearby plants; planting densities on green roof applications are traditionally denser. Planted modules were hand watered every 48 hr and maintained at 23.9°C day and 18.3°C night temperatures until 20-March-08 when they were moved outdoors for hardening off. Fertilizer (Scotts Osmocote® Pro 19-5-8, Marysville, OH) was applied at 83 g per module on 21-March.

On 26-March-08 the modules were transported to and installed on the green roof above the 8th floor of the building that houses the EPA Region 8 Headquarters (1595 Wynkoop Street, Denver, CO). The research modules were placed among existing modules on the green roof. The climate conditions on the EPA Region 8 green roof during the 2008 and 2009 growing seasons are reported in Table 2.2 with graphs in Appendix 1.

Table 2.2. Mean monthly weather data for the 2008 and 2009 growing seasons.

Weather	May		June		July		August		September	
	2008[1]	2009[2]	2008[1]	2009[2]	2008[1]	2009[2]	2008[2]	2009[2]	2008[2]	2009[2]
Min. temp. (°C)	6.7	10.7	11.9	13.5	16.8	16.3	16.7	15.9	11.3	11.8
Max. temp. (°C)	22.6	24.7	29.4	28.3	34.4	31.8	31.7	32.0	26.5	27.6
Precip (mm)	64.3	56.4	16.8	41.3	3.8	63.5	8.4	21.8	16.0	17.5

[1]National Weather Service station (ID: 052223) at Denver Water (1600 W. 12th Avenue, Denver, CO) collected 2.6 km away from green roof.

[2]Campbell Scientific (Logan, UT) weather station located on the EPA Region 8 green roof (1595 Wynkoop Street, Denver, CO).

During the 2008 growing season, irrigation was supplied by 3.5 lph drip emitters. At initiation of the study, irrigation was provided at 18.7 mm/week and then reduced to 8.0 mm/week on 15-August -08. In order to provide more uniform coverage of water, the irrigation system was changed to an overhead rotator system during the 2009 growing season. Irrigation was provided at 6.4 mm/week starting 09-July-09. Irrigation initiation in 2009 was delayed due to an unusually moist spring, with precipitation 81.3%, 14.2%, and 64.4% above normal for April, May and June, respectively.

2.2.2. Data collection. Two methods of quantifying plant cover were used for this study: 1) Converted two-dimensional (C2D) and 2) DIA. Converted two-dimensional (C2D) data were derived from manual measurements (using a ruler) of plant width and length. Based on the assumptions that the plants were roughly circular and symmetrical, plant width (w) and length (ℓ) were converted to plant area (A) by the equation for the area of a circle:

$$A = \pi r^2 \quad \text{where } r = (w + \ell) \div 4$$

Digital image analysis required taking digital images and then determining plant cover using image analysis software. Images were taken using a FujiFilm FinePix S3000 (6x optical zoom 3.2 mega pixels lens) camera that was mounted on a Bogen Manfrotto 190xprob tripod (Ramsey, NJ, USA) with an extendable horizontal arm. A hand held bubble level rested on the back of the camera to ensure that the camera angle relative to the plants remained constant. A portable wire frame with an attached ruler was placed on the planter tray and was used for every photograph.

Two digital images were taken for each module, with four plants per image. Images were captured between 1230-1600 hours during each date data was collected to minimize the influence of the angle of the sun. Images were downloaded from the camera as 1536x2048 in JPEG (joint photographic experts group, .jpg) format. Photos were then saved in 24-bitmap format to ensure ease of use in the DIA program.

Some colors of the growing media were found to be similar to some of the colors of the plant foliage, thus the growing media was removed from each image prior to DIA using the free-form select tool in Microsoft® Paint (Microsoft Corporation, Redmond, WA, USA). Visual determination between growing media and plants was clear despite some overlap in color.

Digital image analysis was performed on adjusted images using SigmaScan Pro 5.0 (Systat Software Inc., San Jose, CA, USA) image analysis software to yield plant cover. Each image was two-point calibrated in SigmaScan using the ruler present in the image. This calibration quantifies the area per pixel so results can be analyzed in common area units (i.e. cm^2). Each plant (four per image) was individually evaluated after cropping to remove all additional growing media in the image.

The color spectrum in SigmaScan had a hue range of 0 to 255 and a saturation range of 0 to 100. The plants in this study were variable in color but generally were green and had hue values within the range of 30 to 120, and saturation values within the range of 10 to 100. Similar to the methods used by Purcell (2000), occasionally these values had to be adjusted slightly (±5%) to correct for seasonal foliage color change.

Once the range of colors was determined, an overlay was applied to indicate the green pixels to be counted for plant cover. Then the measurement objects function, which quantifies area under the overlay, was selected and the output displayed in a worksheet. The output, based on the calibration, was given in cm^2.

One of the five species, *D. cooperi*, had inflorescences that were outside the 30-120 hue and 10-100 saturation range. The remaining species either had inflorescences within that range or did not bloom during the trial period. In order to account for the red *D. cooperi* inflorescence as a contribution to DIA plant cover, an additional red pixel range of hue 200-255 and saturation 10-100 were included during seasonal bloom of each year (Figure 2.1).

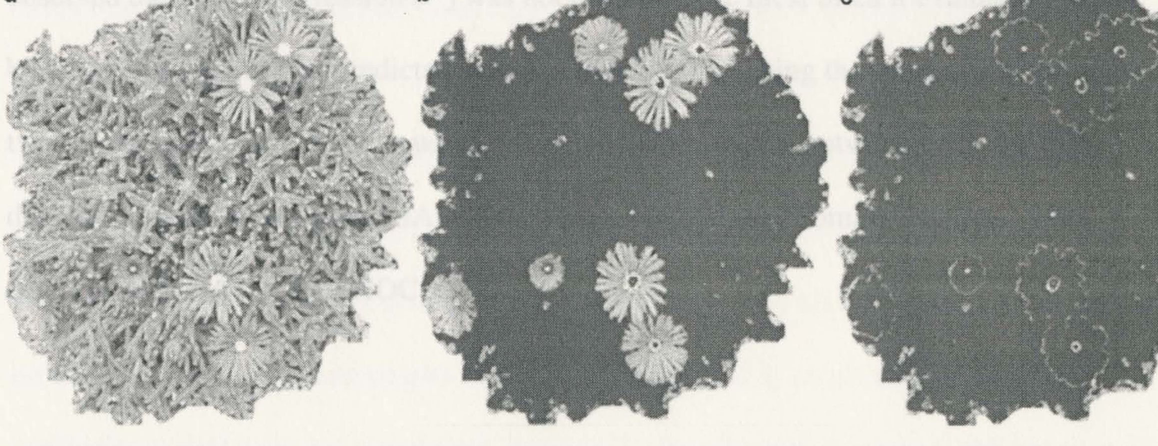

Figure 2.1. Example of *D. cooperi* plant during analysis in SigmaScan Pro 5.0 image analysis program: a) digital image prior to analysis b) with overlay for green pixel range and c) with overlay of green and red pixel range to include inflorescence.

Both the C2D and DIA data were collected on eight dates over two years and were analyzed to determine plant cover. Four dates in 2008 at six week intervals (14-May, 25-June, 06-August and 16-September) and four dates at six week intervals in 2009 (13-May, 24-June, 05-August and 15-September) were evaluated.

Additionally, all above ground plant biomass was harvested on 15-October-09 or 22-October-09. Individual plant biomass was quantified after a minimum of 72 hours of drying in a 70°C oven, when plant parts reached a constant weight (Emilsson, 2008).

2.2.3. Statistical analysis. A repeated measures analysis of variance STAT/GLIMMIX (general linear model for mixture distributions) procedure in SAS® version 9.02 (SAS Institute Inc., Cary, NC) was performed using t-tests ($\alpha = 0.05$) for multiple comparisons of means to show differences in plant cover between species for both the DIA and C2D data sets. Data for analysis were transformed to the square root scale to equalize and normalize the residuals. Results have GLIMMIX significant differences ($p \leq 0.05$) unless otherwise noted.

Correlation coefficients (r) were used to evaluate the relationship between the two observed data sets. Regression (r^2) was not used because most often it evaluates the fit between observed versus predicted values instead of evaluating the relationship between two observed data sets, such as with correlation. Correlations between C2D and DIA data sets, as well as between DIA and biomass and C2D and biomass data sets, were determined in SAS using PROC COR.

2.3. Results and Discussion

Every individual plant of each of the six species survived the 2008 growing season. Overwintering during the 2008-2009 season was 100% successful for four of the six species. *Antennaria parvifolia*, which had a 65% overwintering survival rate, was included in the data analysis. However, *E. umbellatum aureum* 'Psdowns', which had only a 12.5% overwintering rate, was not included in the data analysis. Plant cover is reported in terms of days from trial initiation; with Day 1 being the day the modules were placed on the green roof (26-March-08), and Day 49 being the first date of comparison (14-May-08).

2.3.1. Species evaluations. Plant cover by DIA over the eight consecutive evaluation dates is shown in Figure 2.2. Plant cover was significantly different on each date for most species comparisons. For example, on the first date of comparison, Day 49, all species were significantly different from each other ($p \leq 0.05$) except *B. gracilis* and *O. fragilis* (these two species had the least cover on this day). On Day 91, all species were significantly different from each other except *B. gracilis* and *S. lanceolatum*. For the remaining two dates of the first year, Day 133 and Day 174 all species were significantly different from each other.

Similar to what was observed during 2008, most plant cover comparisons in 2009 between species on each date were significant. However, on Day 413 the comparison between *A. parvifolia* and *B. gracilis* was not significant. By Day 455, plant cover values for many of the species congregate on the graph (Figure 2.2) resulting in two sets of comparisons that were not significant: between *B. gracilis* and *D. cooperi* and between *D. cooperi* and *S. lanceolatum*. As the species rebounded in plant cover from overwintering stress, all comparisons were significant again except for between *O. fragilis* and *S. lanceolatum* on Day 497 and between *B. gracilis* and *D. cooperi* on Day 538.

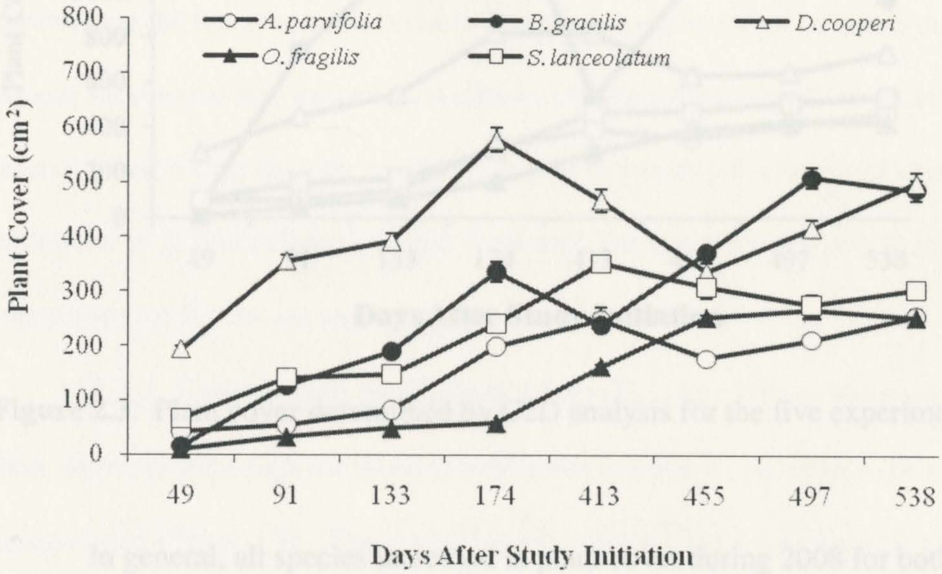

Figure 2.2. Plant cover determined by DIA analysis for the five experimental species.

The C2D data for plant cover is represented in Figure 2.3. Nearly every species comparison on each date yielded significant differences in plant cover. During 2008 the comparisons between *A. parvifolia* and *S. lanceolatum* on Day 49 and on Day 174 were not significantly different; all remaining species comparisons were significantly different that year. During 2009, all comparisons were significant except for the comparisons between *A. parvifolia* and *O. fragilis* on Day 413 and again on Day 538.

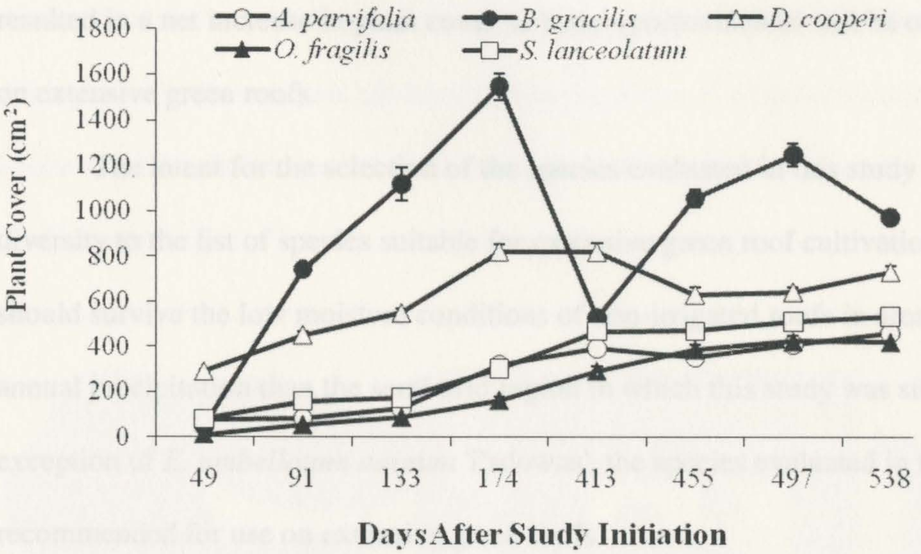

Figure 2.3. Plant cover determined by C2D analysis for the five experimental species.

In general, all species increased in plant cover during 2008 for both DIA and C2D data sets. However, during 2009, four of the five species showed temporary declines in plant cover, the exception being *O. fragilis*. This reduction in plant cover is likely a result of overwintering stress. A similar phenomenon can be observed in the growth index graphs for species evaluated in a Michigan study, specifically, *Agastache foeniculum*, *Aster laevis*, *Coreopsis lanceolata* and several other species (Monterusso et al., 2005).

On Day 538, the final date of plant cover comparisons, the two species with the highest plant cover were *B. gracilis* and *D. cooperi*, with the remaining three species closely grouped in plant cover: *A. parvifolia*, *O. fragilis* and *S. lanceolatum*. Therefore, based on evaluations over two consecutive growing seasons on an extensive green roof, *B. gracilis* and *D. cooperi* were more successful than *A. parvifolia*, *O. fragilis* and *S. lanceolatum*. However, *A. parvifolia*, *O. fragilis* and *S. lanceolatum* survived and resulted in a net increase in plant cover so these species should still be considered for use on extensive green roofs.

The intent for the selection of the species evaluated in this study was to add diversity to the list of species suitable for extensive green roof cultivation. These species should survive the low moisture conditions of non-irrigated roofs in areas with higher annual precipitation than the semi-arid region in which this study was situated. With the exception of *E. umbellatum aureum* 'Psdowns', the species evaluated in this study can be recommended for use on extensive green roofs.

2.3.2. Correlation coefficient analysis. Correlations between the C2D and DIA data sets were high for three groundcover species: *A. parvifolia*, *D. copperi* and *S. lanceolatum* (Table 2.3). The remaining two species had lower but still good correlations between the two data sets: *B. gracilis* with an upright growth habit and *O. fragilis* with a decumbent growth habit.

Table 2.3. Correlation coefficients (r) between C2D and DIA data sets for eight dates and their mean for five species (n = 40 except *A. parvifolia* where n = 26 in 2009 only).

Correlations (r)	**2008 Growing Season**				**2009 Growing Season**				**Mean**
Species	5/14	6/25	8/06	9/16	5/13	6/24	8/05	9/15	
A. parvifolia	0.84	0.91	0.92	0.95	0.97	0.78	0.88	0.84	0.89
B. gracilis	0.84	0.78	0.59	0.63	0.76	0.64	0.70	0.65	0.70
D. cooperi	0.84	0.86	0.96	0.90	0.83	0.78	0.70	0.86	0.84
O. fragilis	0.71	0.42	0.70	0.71	0.61	0.58	0.70	0.76	0.65
S. lanceolatum	0.92	0.95	0.95	0.97	0.89	0.49	0.36	0.47	0.75

Of the species evaluated in this study, the groundcover *A. parvifolia* had the highest mean correlation coefficient (r = 0.89) between the two data sets. The lowest correlation occurred on Day 455 (r = 0.78) after the plants had come out of winter dormancy with irregular regrowth patterns (Figure 2.4a). Since C2D data measures plant diameters at the widest points of the plant axises, areas of dieback within those diameters are included in the analysis, giving an overestimation of actual plant cover. *Delosperma cooperi*, with a similar growth habit to *A. parvifolia*, resulted in parallel correlation coefficients.

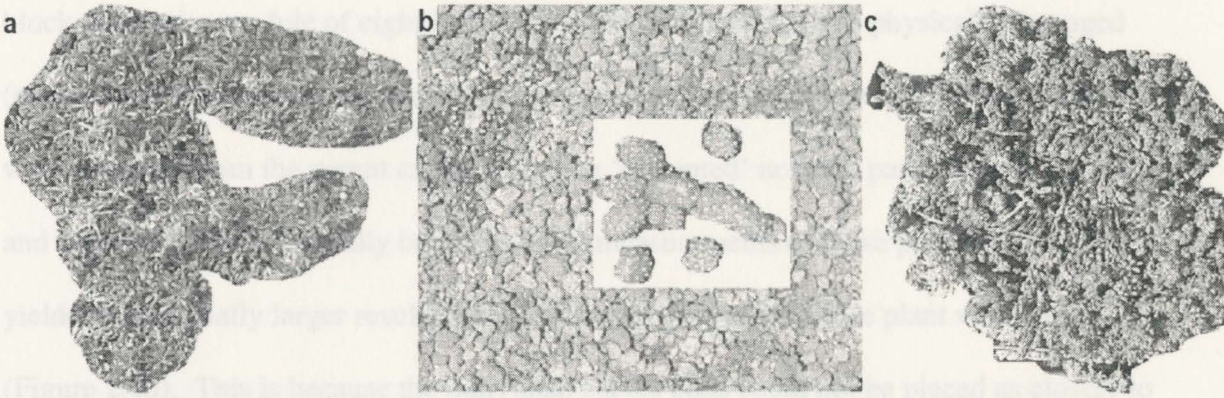

Figure 2.4. Examples of a) *A. parvifolia* (on Day 455) irregular growth habit after overwintering, b) *O. fragilis* (on Day 91) after physical damage and c) *S. lanceolatum* (on Day 455) post- inflorescence center die-back.

The lower correlation value between the two data sets for *B. gracilis* can be explained by a much more upright, open and sparse growth habit compared to the groundcover species. Therefore, measurements of plant size by hand (C2D) will show larger results relative to the DIA results, which quantify the amount of green plant tissue in a given area. The DIA data quantifies only plant cover visible from above while C2D data assumes that all of the area within the measured diameters is plant cover. This phenomenon is apparent by a visual comparison of the plant cover curves in Figures 2.2 and 2.3 for this species. The correlation coefficient ($r = 0.84$) was the highest for *B. gracilis* on Day 49 when it had the shortest, densest growth habit.

The highest correlations for *O. fragilis* occurred in September of each year (r = 0.71 and r = 0.79, respectively) when the pads of the cacti were filled out. This agrees with results from a green roof study in Michigan where *O. humifosa*, a native cactus, attained the largest size in September (Monterusso et al., 2005).

On Day 91, *O. fragilis* had a low correlation (r = 0.42) because in two of the five blocks the entire module of eight individual cacti had recently been physically damaged (pads removed) by extension cords that were dragged over the plants. All of the pads that were removed from the parent cactus had to be 'replanted' near the parent plant. Rooting and regrowth occurred rapidly but the manual measurements of those plants on Day 91 yielded superficially larger results than they would have if the entire plant were intact (Figure 2.4b). This is because the individual cactus pads could not be placed as closely to the parent plant at replanting as they were while on the plant. Therefore, a wider set of diameters were recorded after replanting. If the two damaged blocks are removed from the correlation analysis on that date, the value improves for the remaining three blocks (r = 0.67).

Correlations in 2008 were very strong for *S. lanceolatum* (mean r = 0.95). However, the two year mean correlation coefficient was affected by the lower correlation values during 2009. In 2009, bloom occurred early in the season in three of the five blocks and after the inflorescence senesced (prior to Day 455), the center of each plant died out leaving an irregular circular area of green around the perimeter of the plant (Figure 2.4c). Therefore the C2D measurements showed the plant to be much larger than what the DIA quantified, hence the reduced correlation values for 2009.

Time invested for each method of quantifying plant cover was approximately 1 minute per plant per measurement date for the C2D method and approximately 2 minutes per plant per date for the DIA method, which is similar to Richardson et al. (2001). Although the DIA method took longer than the C2D method in this study, several factors could be altered in future studies to reduce the time required for DIA. For example, if the color contrast between the growing media and the foliage were greater, the step in Microsoft® Paint could be avoided, which was approximately 20 seconds per plant per date. Additionally, if the camera tripod was located in a fixed location and the modules were the mobile portion, images would not have to be calibrated individually but instead could be batch calibrated, as described in Karcher and Richardson (2005).

While the time commitment may have been higher using DIA in this study, correlations indicate that accuracy was improved. In four of the five species discussed, (the exception being *D. cooperi*), date or growth period discrepancies between the DIA and C2D data sets could be attributed to overestimation of plant cover by the C2D measurements.

2.3.3. Biomass. Biomass accumulation from harvested plants was correlated with the last date of DIA and C2D to evaluate how well plant cover corresponded with individual plant biomass accumulation (Table 2.4). In general, correlations between the last date of DIA and biomass data were high (mean $r = 0.83$) for the three groundcover plants: *A. parvifolia*, *D. cooperi* and *S. lanceolatum*. *Bouteloua gracilis,* with a more upright growth habit had a lower correlation ($r = 0.64$) likely because images taken from directly above would not account for biomass as if taken from the vertical as in Tackenberg (2007). Correlations for *O. fragilis* were the lowest among the species in this study ($r = 0.41$); this low correlation was attributed to the decumbent growth habit of this species and pads aligned both vertically and horizontally. Thus, similar to *B. gracilis*, vertical biomass was not accounted for when an image was taken directly above the plant (Figure 2.4b).

Table 2.4. Correlations between DIA and biomass, and C2D and biomass, on final date of DIA and C2D data collection (15-September-09) for the five species ($n = 40$ except *A. parvifolia* where $n = 26$).

Species	DIA Correlations (r)	C2D Correlations (r)
A. parvifolia	0.79	0.54
B. gracilis	0.64	0.19
D. cooperi	0.87	0.79
O. fragilis	0.41	0.18
S. lanceolatum	0.84	0.40

While plant diameters, not height, were used in the current study, biomass was only highly correlated to C2D for one of the five species, *D. cooperi*; the remaining four species had low correlation values. It appears the low correlations of those species are parallel to the low correlations between DIA and C2D: the C2D data did not account for the irregular growth patterns whereas DIA did take those growth patterns into account.

2.4. Conclusion

All six species increased in plant cover during the first growing season but the trend did not continue for the second growing season. Survival over the winter season was successful for five of the six speces; *E. umbellatum aureum* 'Psdowns' experienced low winter survival and was removed from the study in 2009. In 2009, there was a temporary reduction in plant cover as a result of overwintering stress for four of the five remaining species; the exception being *O. fragilis*.

At the end of the study, *B. gracilis* and *D. cooperi* had outperformed *A. parvifolia*, *O. fragilis* and *S. lanceolatum*, indicating that *B. gracilis* and *D. cooperi* are more suitable for green roof culture in semi-arid regions. However, because all five of these species survived over the two years of this study, all five species should be considered for use on extensive green roofs.

Owing to the high correlation coefficient values between DIA and C2D for the groundcover species (*A. parvifolia*, *D. cooperi* and *S. lanceolatum*), these two methods are useful for quantifying plant cover. Digital image analysis appears to be a reliable substitution for the less accurate C2D method. Additionally, DIA can be used to estimate biomass accumulation (especially for groundcover species), but C2D data did not correlate well with biomass data in this study.

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Chapter 3. Moisture Content of Extensive Green Roof Growing Media and Growth Response of Fifteen Plant Species During Dry Down

Jennifer M. Bousselot[4], James E. Klett[5] and Ronda D. Koski[6]

3.0.1. Abstract. Success of an extensive green roof is primarily dependent on plant species ability to survive the low moisture content of the growing media. Due to the well-drained nature of the growing media, plants adaptable to dry, porous soils are primarily used in extensive green roof applications. Although *Sedum* species have dominated the plant palette for extensive green roofs, there is growing interest in expanding the plant list for extensive green roof systems. In order to effectively select suitable plants, species need to be evaluated in terms of their response to gradual and prolonged dry down of the growing media. A study to determine the relative rates of dry down for fifteen species was conducted in greenhouse and outdoor trials. During dry downs that extended over five months, succulent and herbaceous species dried down at

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different rates. Although, not all succulent or herbaceous plants had consistent moisture contents during the initial 18 days of dry down. Despite differences in dry down, the succulent species, as a group, maintained viable foliage for over five times longer than the herbaceous species. The revival rates of the succulent species were nearly double those of the herbaceous species. Therefore, not only are succulent species more likely to be longer-lived during periods of drought, but these species are more likely to resume growth soon after water is made available. Based on these results, irrigation frequency is recommended for succulent species at a maximum of 28 day intervals and herbaceous species at a maximum of 14 day intervals.

3.1. Introduction

Green roofs provide many benefits to urban communities, and can be used to help alleviate the negative effects of urbanization (Getter and Rowe, 2006). The growing media used for extensive green roofs is extremely porous, very well drained, and prone to extreme fluctuations in moisture content. Due to the characteristics of the growing media, plant species utilized in extensive green roof systems must be able to adapt to periods of low moisture availability in their root zones.

Succulents, especially species of *Sedum*, have been the most studied and utilized plants for green roofs (Berghage et al., 2007; Dunnett and Nolan, 2004; Durhman et al., 2006; Durhman et al., 2007; Emilsson, 2003; Kircher, 2004; Latocha and Batorska, 2007; Monterusso et al., 2005; Nagase and Thuring, 2006; Sendo et al., 2007; Snodgrass and Snodgrass, 2006; VanWoert et al., 2005). One of the main reasons *Sedums* are so ideally suited to green roof cultivation is the fact that many possess Crassulacean acid metabolism (CAM). In general, CAM plants keep their stomata closed during the day when transpiration rates are normally high, and open them at night when transpiration rates are significantly lower. This is in contrast to C3 and C4 plants, which do not keep their stomata closed during the day and therefore have higher water use rates than CAM plants.

In order to avoid issues associated with *Sedum* monocultures and to enhance plant species biodiversity attractive to regionally native arthropod and avian species, additional plant species will need to be incorporated in to the extensive green roof plant palette (Durhman et al., 2006; Getter and Rowe, 2006; Monterusso et al., 2005; Rowe et al., 2005; Wolf and Lundholm, 2008). *Sedum* monocultures result in a monotone effect (Dunnett and Nolan, 2004) and have a higher probability of pest problems than a system that has diversity because most pests are host specific and if there is a surplus of their preferred host plant available, pest populations can exceed the threshold limit of the host. Additionally, a diversified plant palette on an extensive green roof may be able to adapt to variable moisture conditions and maximize the evaporative cooling benefit, thus extending the benefits of extensive green roofs (Compton and Whitlow, 2006).

Incorporating local or regional native plants into extensive green roof systems has been investigated by others (Dunnett and Nolan, 2004; Durhman et al., 2007; Kircher, 2004; Latocha and Batorska, 2007; Monterusso et al., 2005), however the research in this area suggests that very few plant species can match the growth and survival performance of the non-native *Sedum* species (Dunnett and Nolan, 2004; Durhman et al., 2007; Kircher, 2004; Latocha and Batorska, 2007; Monterusso et al., 2005). This could be because the properties of the soils in which the native plants evolved are significantly different from those of the well-drained, soilless green roof growing media.

Evaluating plants that are native to areas characterized by growing conditions similar to well-drained extensive green roofs may yield more favorable results. Habitats that develop on shallow, rocky and well-drained soils mimic the conditions typical of an extensive green roof and may be sources of additional plant species suitable for extensive green roof culture. For example, plant species native to rocky and well-drained areas in Michigan have been incorporated into the plant palette for extensive green roofs in the Great Lakes region (Durhman et al., 2007).

Additional examples of habitats that mimic conditions typical of an extensive green roof can be found in Colorado (Getter and Rowe, 2006), particularly in the semi-arid areas of the state. These semi-arid areas possess shallow, rocky and well-drained soils, and receive low annual precipitation (often with extended periods of below normal precipitation). Thus plant species native to these areas possess mechanisms that allow them to tolerant drought conditions.

Regardless of plant species origin, the survival and the success of plants in an extensive green roof located in a semi-arid region require irrigation, and predictions have been made that success of extensive green roofs in areas with infrequent precipitation events is improbable unless supplemental irrigation is provided (Miller, 2003).

Due to the porous and well-drained nature of the growing media used in extensive green roof systems, plants species considered for use in such systems need to be evaluated for their response to gradual and long-term drying of the growing media. Thus, relative rate of dry down for plant species considered for use in such systems is an important characteristic to assess. In semi-arid regions, such knowledge will help to determine the need for irrigation and the frequency of irrigation events for these species. The goal of this study was to determine the impact of gradual drying of extensive green roof growing media on the growth of fifteen plant species, and to determine the relative water use for each of the fifteen species.

3.2. Materials and Methods

In northern Colorado, fifteen plant species were utilized in three dry down trials (two greenhouse trials, and one outdoor trial). The greenhouse trials were performed one year apart to minimize seasonal variations in solar radiation. Based on the results of the initial greenhouse trial, a subset of species was selected for use in the outdoor trial. Environmental conditions for both greenhouse trials and the outdoor trial are summarized in Table 3.1.

For all three trials, 24 propagules from 128-cell plug trays were used. The growing media resembled a commercially available extensive green roof growing media, and was composed of five parts expanded shale (≤ 1 cm diameter granular size), two parts sphagnum peat moss, two parts perlite and one part vermiculite, by volume. The composition of the growing media was consistent across all trials (Table 3.2).

Table 3.1. Means of environmental conditions for the greenhouse trials and outdoor trial (standard errors in parenthesis).

Trial	Temperature	Relative Humidity	Solar Radiation
Greenhouse 2008[1]	21.85°C (0.05)	57.73% (0.13)	162.36 $W \cdot m^{-2}$ (1.87)
Greenhouse 2009[2]	21.66°C (0.04)	56.82% (0.16)	163.13 $W \cdot m^{-2}$ (1.91)
Outdoor 2009[3]	16.74°C (0.13)	58.75% (0.28)	311.84 $W \cdot m^{-2}$ (4.36)

[1]From 9-03-2008 to 9-30-2008 [2]From 9-03-2009 to 9-30-2009
[3]From 8-20-2009 to 9-30-2009

Table 3.2. Physical characteristics of the growing media used in all three trials.

Growing Media Characteristic		**Value**
Bulk Density		0.77 g/cc
Particle Density		2.20 g/cc
Saturated Hydraulic Conductivity		0.0087 cm/s
At Maximum Water Capacity	Air Content	13.8 %
	Water Content	51.1 %

3.2.1. Greenhouse trials. Propagules of each species were planted in individual containers and established for 10 weeks in a greenhouse. The species evaluated were: *Allium cernuum* Roth. (nodding onion), *Antennaria parvifolia* Nutt. (small-leaf pussytoes), *Artemisia frigida* Willd. (fringed sage), *Bouteloua gracilis* (Kunth) Lag. ex Griffiths (blue grama), *Buchloe dactyloides* (Nutt.) Engelm. (buffalograss), *Carex flacca* Schreb. (sedge), *Delosperma cooperi* (Hook. f.) L. Bol. (hardy ice plant), *Delosperma nubigenum* (Schltr.) L. Bol. (yellow ice plant), *Penstemon pinifolius* Greene (pineleaf penstemon), *Sedum acre* L. (goldmoss stonecrop), *Sedum album* L. (white stonecrop), *Sedum lanceolatum* Torr. (lanceleaf stonecrop), *Sedum spurium* Marsch-Bieb. 'John Creech' (two-lined stonecrop), *Sempervivum* 'Royal Ruby' (hens and chicks) and *Thymus pseudolanuginosus* Ronn. (woolly thyme). The containers used were circular green plastic 15.2-cm diameter by 10.8-cm deep pots. Each container was filled with growing media to a depth of 10 cm, to equal the depth of the modules used in the outdoor trial. Each trial had a randomized complete block design.

After planting in containers, plants were irrigated to saturation every 48 hours; this irrigation regimen was continued during the establishment period until ten days prior to initiation of dry down period. Then, irrigation was tapered to every 72 hours between irrigation events for two irrigations, and finally to 96 hours before the final irrigation just prior to dry down initiation. At the final irrigation, all plants were irrigated with ≥450 ml and free drainage was allowed for at least 12 hours prior to taking the first growing media moisture measurement. Fertilizer (Scotts Osmocote Pro 19-5-8) was applied at 5 g per propagule, 4 weeks prior to dry down initiation. Pots containing growing media with no vegetation served as the non-vegetated controls and were used to evaluate evaporation.

3.2.2. Outdoor trial. The species evaluated in the outdoor trial were planted as monocultures in 0.61m x 1.22m x 10cm black plastic modules. The species evaluated were: *A. parvifolia*, *A. frigida*, *B. dactyloides*, *D. cooperi*, *P. pinifolius*, *S. album*, *S. lanceolatum*, *S. spurium* 'John Creech', and *S.* 'Royal Ruby'. Three replications (modules) per species were planted with eight propagules per module to equal 24 individuals of each species in the trial. This trial had a randomized complete block design. Plants were established for 15 weeks, 5 weeks longer than the greenhouse trials. Due to cool, wet spring weather conditions, accompanied by multiple hail storms that stunted plant growth, outdoor establishment was slower and plants took longer to reach a size similar to plants in the initial greenhouse trial. After planting, plants were irrigated and fertilized as described for the greenhouse trials. Non-vegetated trays (growing media with no vegetation) served as the non-vegetated controls and were used to evaluate evaporation.

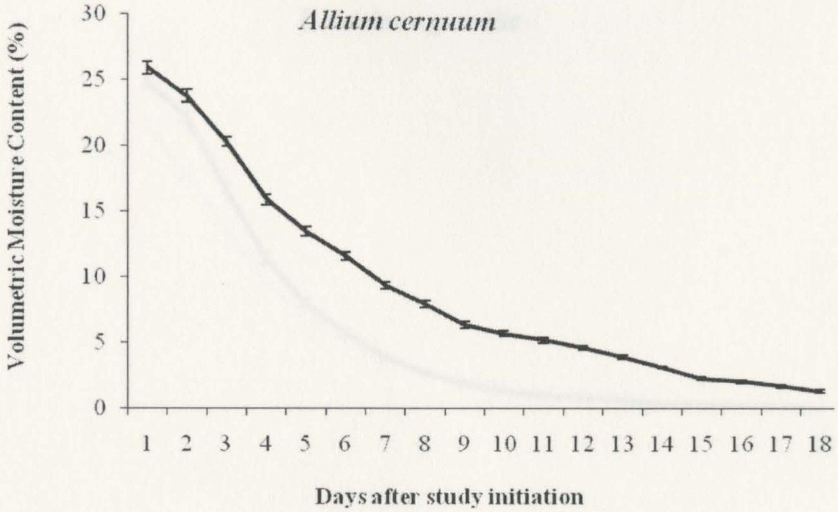
3.2.3. Data collection and statistical analysis. For all three trials, growing media volumetric moisture content (VMC) was recorded daily for each plant using a ThetaProbe ML2x (Delta-T Devices, Ltd., Cambridge, UK). Values were collected daily until they remained constant, which occurred about 18 days after initiation of dry down period. Water use for each species was estimated from VMC data by subtracting the growing media VMC of the non-vegetated control for each day.

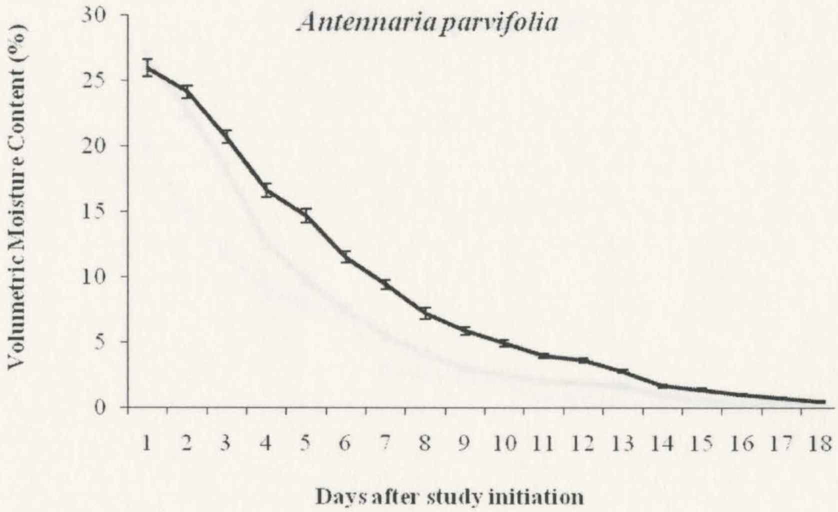
The number of days to top growth dieback for each plant was determined. The date when no viable green tissue remained above the growing media surface was recorded and used to determine the number of days to top growth dieback. On the day when no viable green tissue remained above the growing media surface, plants were re-watered to determine if they had gone dormant or actually died, in other words, their revival ability.

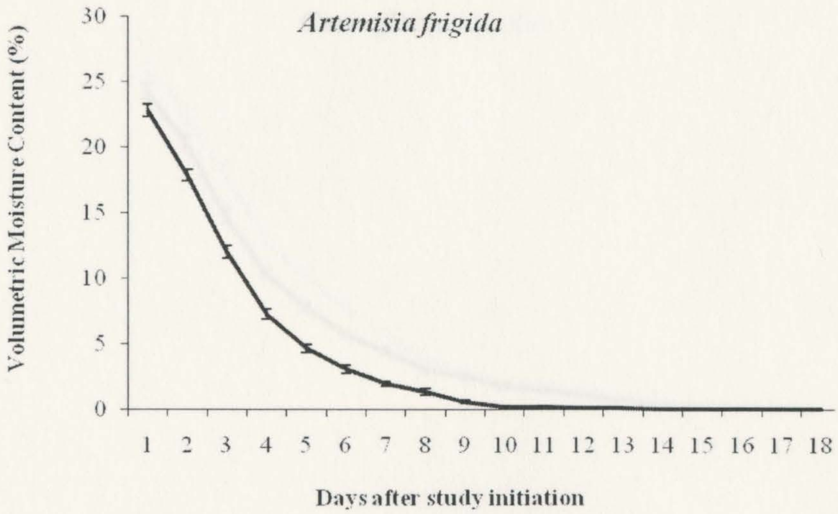
Water use and days to top growth dieback data were analyzed using the GLIMMIX procedure in SAS® version 9.02 (SAS Institute Inc., Cary, NC). Data for analysis were transformed to the square root scale to equalize and normalize the residuals. All significant differences are at the $p \leq 0.05$ level.

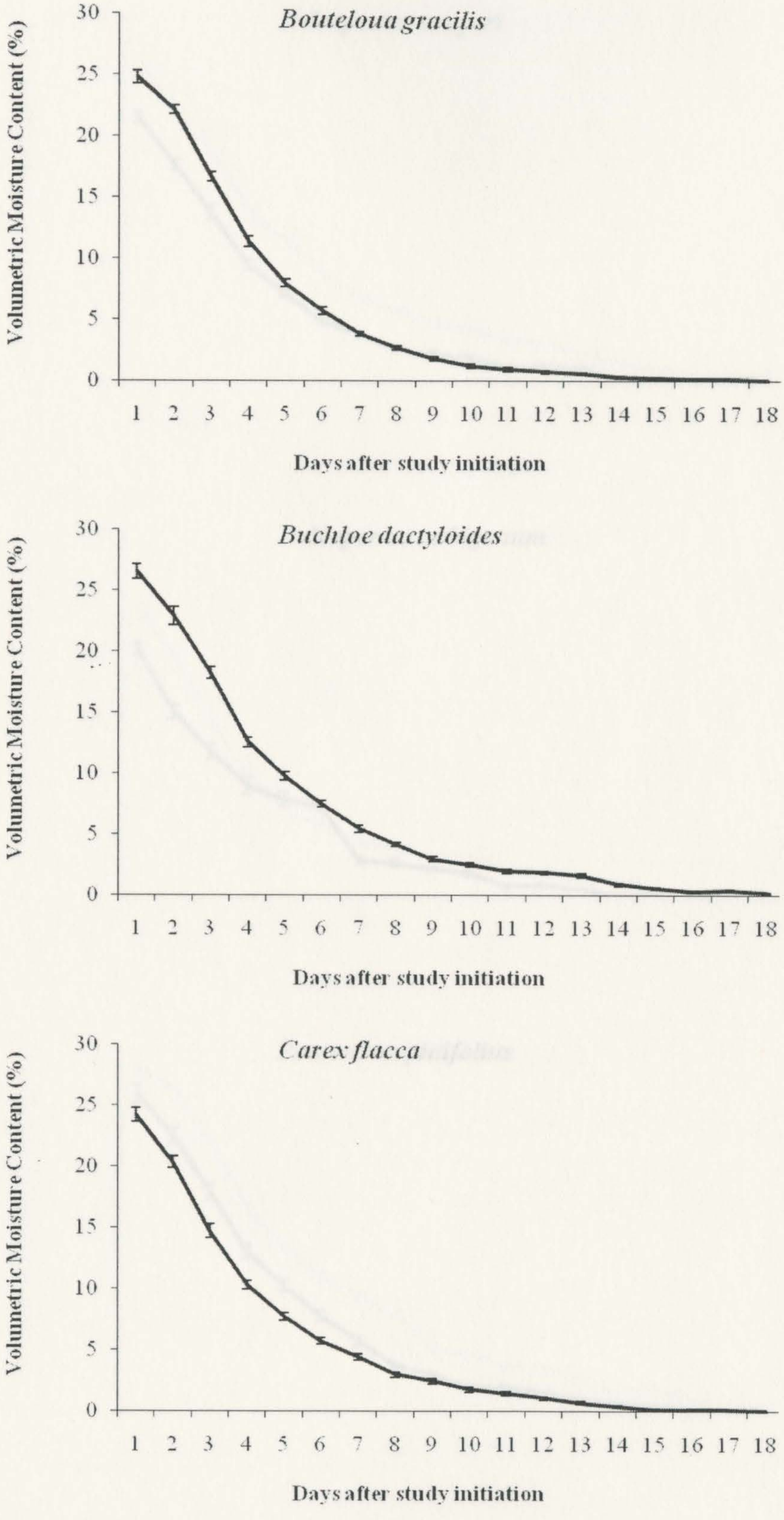
3.3. Results and Discussion

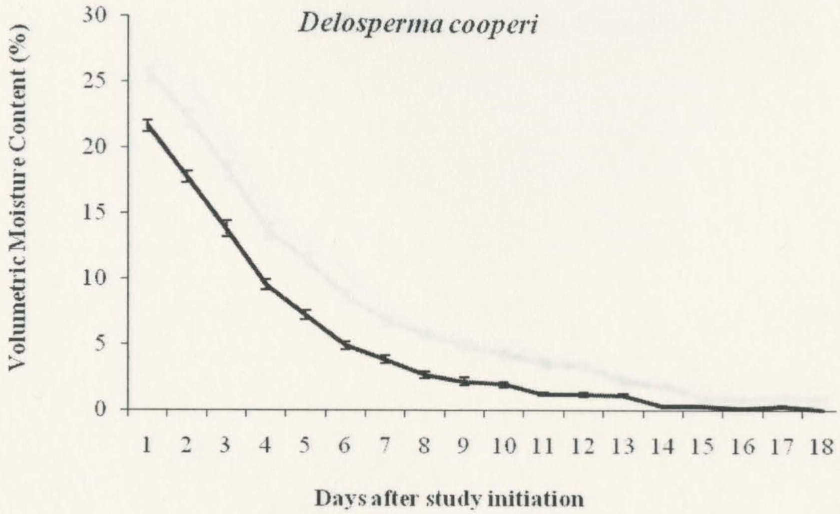
3.3.1. Greenhouse trials. Results for the greenhouse trials show change of VMC for up to 18 days after initiation of dry down period, depending on the species (Figure 3.1). This is a much longer period of time when compared with a study conducted in a Michigan greenhouse trial, which found that VMC of a mixture of *Sedums* ceased changing after only seven days, with some species reaching 0% VMC in as little as one day (VanWoert et al., 2005). The dissimilarity between studies is most likely due to differences among species, differences in developmental stages of plants, differences in growing media depth, solar radiation intensity and possibly growing media moisture holding capacities.

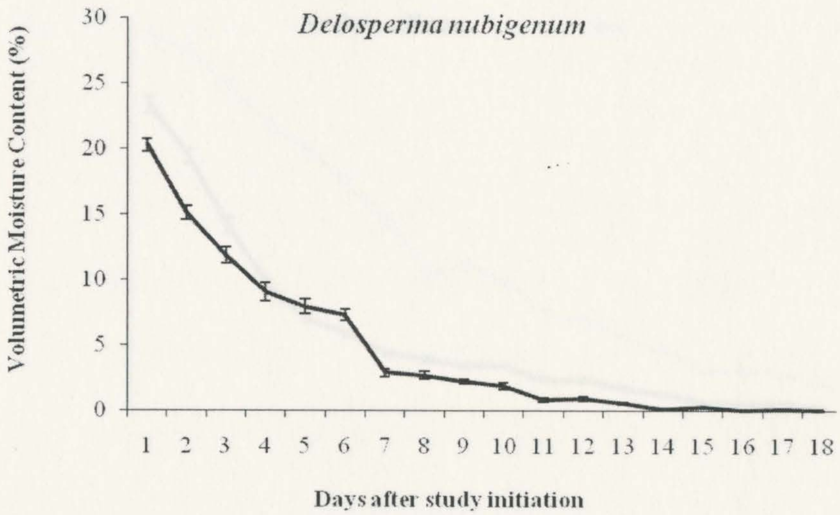

Allium cernuum
Volumetric Moisture Content (%)
30
25
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Days after study initiation

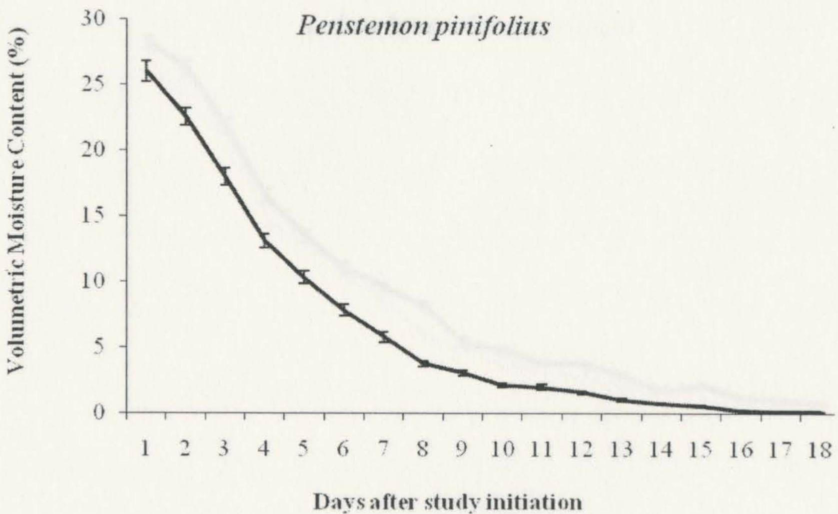

Antennaria parvifolia
Volumetric Moisture Content (%)
30
25
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Days after study initiation

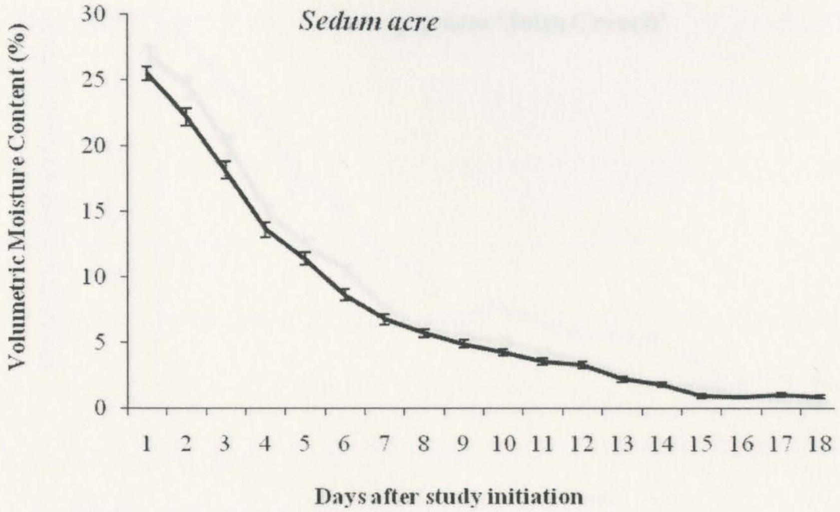

Artemisia frigida
Volumetric Moisture Content (%)
30
25
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Days after study initiation

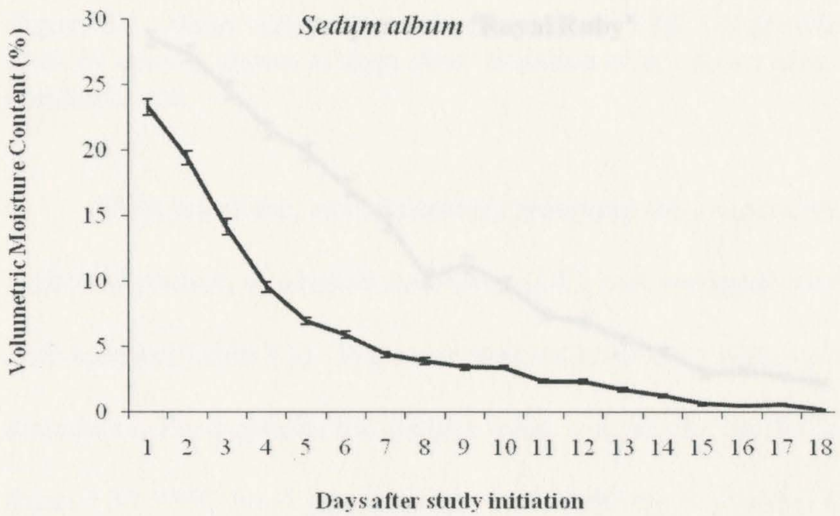

Bouteloua gracilis
Volumetric Moisture Content (%)
Days after study initiation
Buchloe dactyloides
Volumetric Moisture Content (%)
Days after study initiation
Carex flacca
Volumetric Moisture Content (%)
Days after study initiation

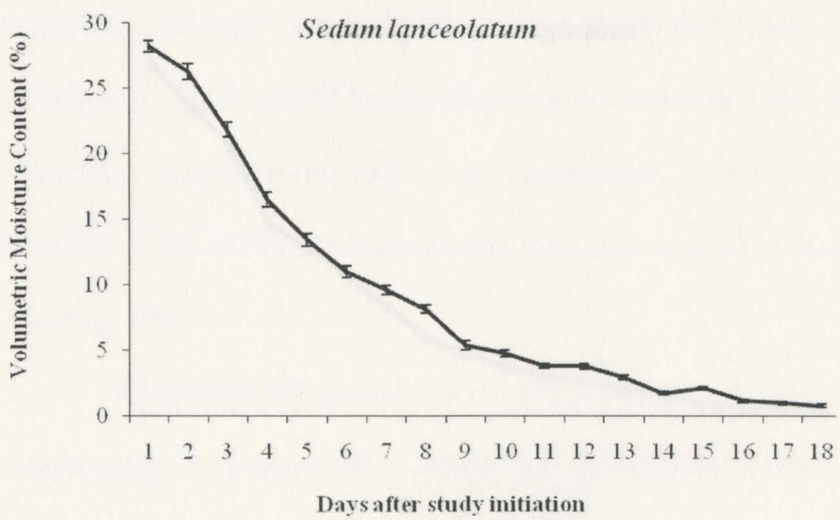

Delosperma cooperi
Volumetric Moisture Content (%)
0
5
10
15
20
25
30
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Days after study initiation

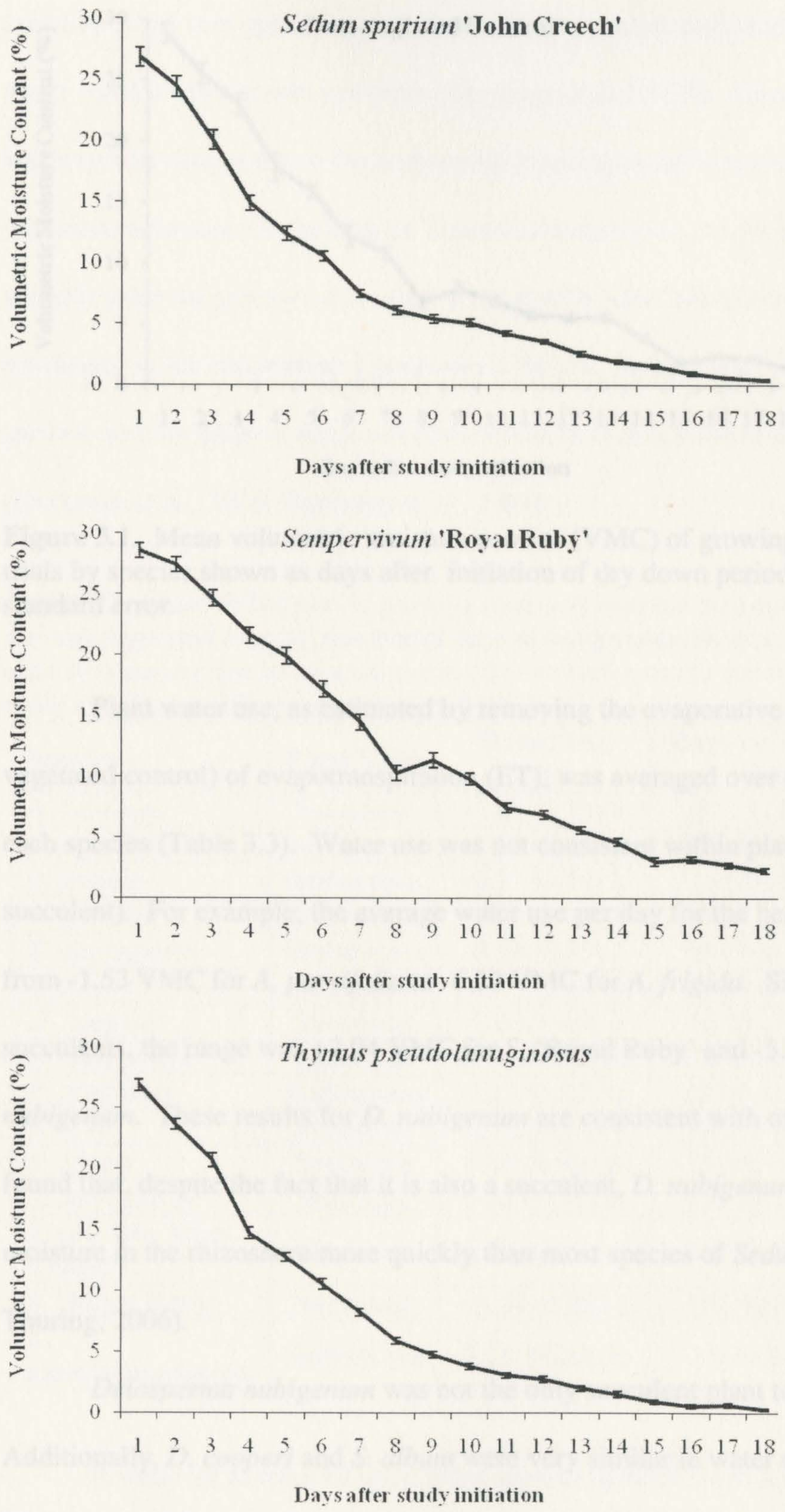

Delosperma nubigenum
Volumetric Moisture Content (%)
0
5
10
15
20
25
30
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Days after study initiation


Penstemon pinifolius
Volumetric Moisture Content (%)
0
5
10
15
20
25
30
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Days after study initiation


Sedum acre
Volumetric Moisture Content (%)
30
25
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Days after study initiation


Sedum album
Volumetric Moisture Content (%)
30
25
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Days after study initiation


Sedum lanceolatum
Volumetric Moisture Content (%)
30
25
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Days after study initiation


Sedum spurium 'John Creech'
Volumetric Moisture Content (%)
0 5 10 15 20 25 30
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Days after study initiation
Sempervivum 'Royal Ruby'
Volumetric Moisture Content (%)
0 5 10 15 20 25 30
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Days after study initiation
Thymus pseudolanuginosus
Volumetric Moisture Content (%)
0 5 10 15 20 25 30
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Days after study initiation

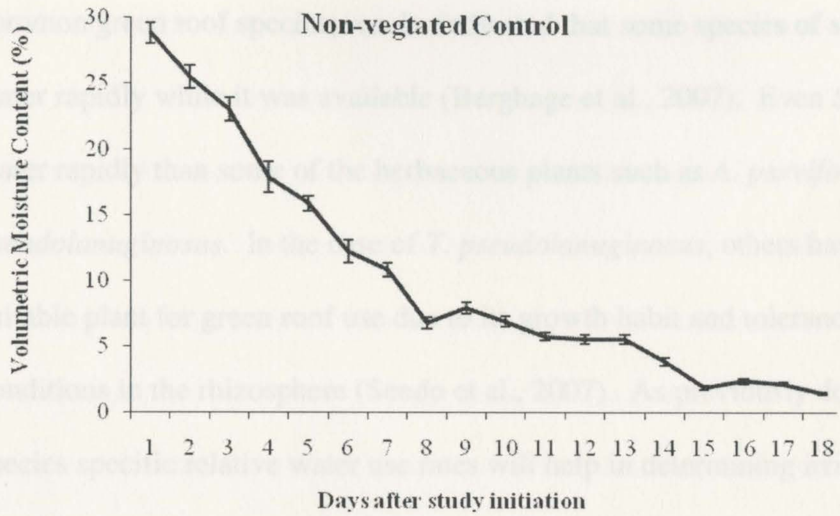


Figure 3.1. Mean volumetric moisture content (VMC) of growing media for greenhouse trials by species shown as days after initiation of dry down period. Error bars represent standard error.

Plant water use, as estimated by removing the evaporative portion (i.e. non-vegetated control) of evapotranspiration (ET), was averaged over the 18 day period for each species (Table 3.3). Water use was not consistent within plant type (i.e. herbaceous, succulent). For example, the average water use per day for the herbaceous species ranged from -1.53 VMC for *A. parvifolia* to -6.23 VMC for *A. frigida*. Similarly for the succulents, the range was +2.04 VMC for *S.* 'Royal Ruby' and -5.56 VMC for *D. nubigenum*. These results for *D. nubigenum* are consistent with other research, which found that, despite the fact that it is also a succulent, *D. nubigenum* depletes available moisture in the rhizoshere more quickly than most species of *Sedum* (Nagase and Thuring, 2006).

Delosperma nubigenum was not the only succulent plant to have high water use. Additionally, *D. cooperi* and *S. album* were very similar in water use to *D. nubigenum*. This agrees with research in another greenhouse study that evaluated dry down rates of common green roof species; results indicated that some species of succulent plants used water rapidly while it was available (Berghage et al., 2007). Even *S. acre* used more water rapidly than some of the herbaceous plants such as *A. parvifolia* and *T. pseudolanuginosus*. In the case of *T. pseudolanuginosus*, others have also found it to be a suitable plant for green roof use due to its growth habit and tolerance to low moisture conditions in the rhizosphere (Sendo et al., 2007). As previously documented, knowing species specific relative water use rates will help in determining irrigation frequency (Durhman et al., 2006; Durhman et al., 2004).

Table 3.3. Mean difference in growing media volumetric moisture content (VMC) from the non-vegetated control, number of days to top growth dieback, and percent revival after re-watering, for all species averaged over both greenhouse trials. Lower case letters show significant differences at the $p \leq 0.05$ level.

Species	Plant Type	Water Use (SE)	Days to Dieback (SE)	Revival
A. cernuum	Succulent	-1.13 (0.25) b	59.25 (1.77) f	91.67%
A. parvifolia	Herbaceous	-1.53 (0.19) c	22.79 (0.65) d	31.25%
A. frigida	Herbaceous	-6.23 (0.74) k	16.08 (0.32) a	8.33%
B. gracilis	Herbaceous	-4.63 (0.46) hi	18.23 (0.71) ab	22.92%
B. dactyloides	Herbaceous	-3.56 (0.35) f	20.19 (0.90) bc	37.50%
C. flacca	Herbaceous	-4.77 (0.50) hij	20.13 (0.90) bc	27.08%
D. cooperi	Succulent	-5.24 (0.60) ij	52.25 (1.44) e	0.00%
D. nubigenum	Succulent	-5.56 (0.69) ijk	107.06 (3.46) g	2.08%
P. pinifolius	Herbaceous	-3.63 (0.32) fg	20.09 (0.67) bc	0.00%
S. acre	Succulent	-2.72 (0.31) e	107.67 (6.46) g	2.08%
S. album	Succulent	-4.48 (0.60) gh	151.00 (0.00) j	58.33%
S. lanceolatum	Succulent	-1.22 (0.27) bc	138.71 (2.53) i	54.17%
S. spurium 'John Creech'	Succulent	-2.00 (0.22) cd	127.81 (3.72) h	56.25%
S. 'Royal Ruby'	Succulent	+2.04 (0.36) a	151.00 (0.00) j	69.44%
T. pseudolanuginosus	Herbaceous	-2.26 (0.20) de	20.75 (0.87) c	31.25%

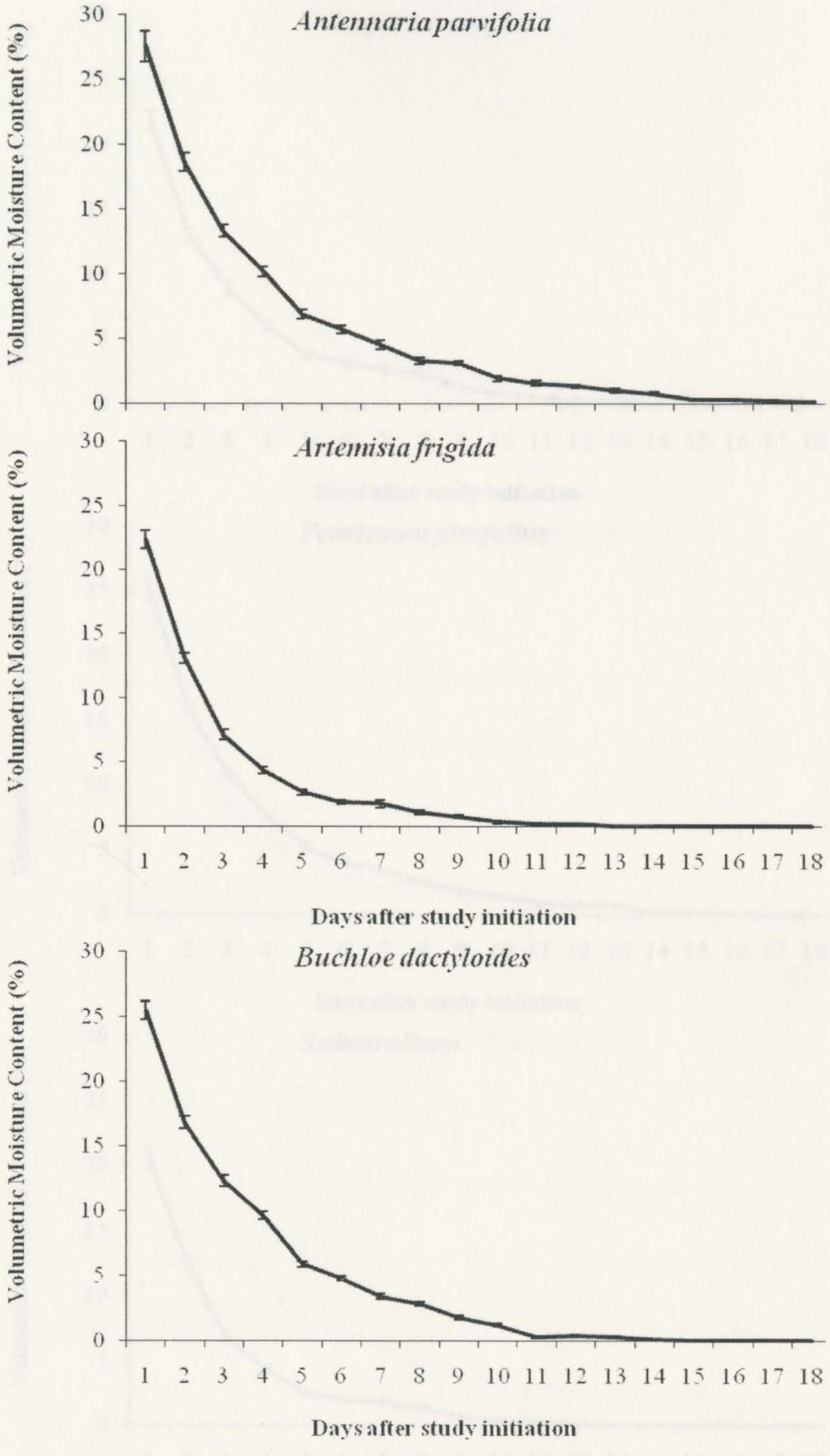
Results for number of days to top growth dieback show a clear division between the herbaceous and succulent species (Table 3.3). The herbaceous plants had a mean of

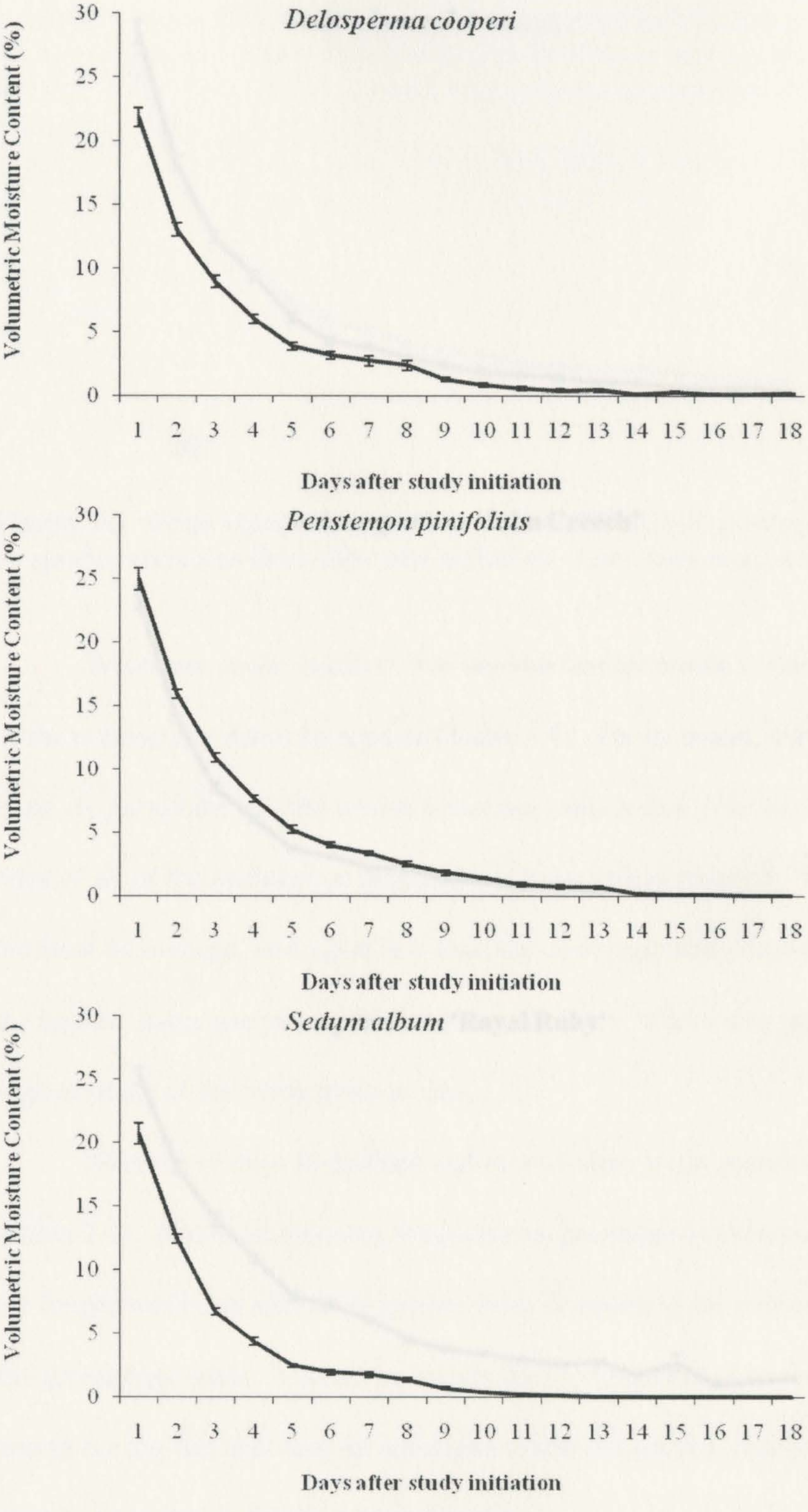
19.75 days to die back while the succulent species had an average of 111.75 days to die back. Two of the succulent species (*S. album* and *S.* 'Royal Ruby') did not have any replications that died back during any of the 151-day trials (Table 3.3). These are similar results to a study in Michigan where the succulent species of *Sedums* remained viable for the entire four month period (Durhman et al., 2004). Additionally, *Sedum rubrotinctum* R. T. Clausen has been shown to remain alive for up to 2 years in a greenhouse without irrigation (Teeri et al., 1986). However, *S. rubrotinctum* cannot survive where winter temperatures fall below 6.6 °C (20 °F), thus this species is not suitable for use on perennial extensive green roofs in Colorado.

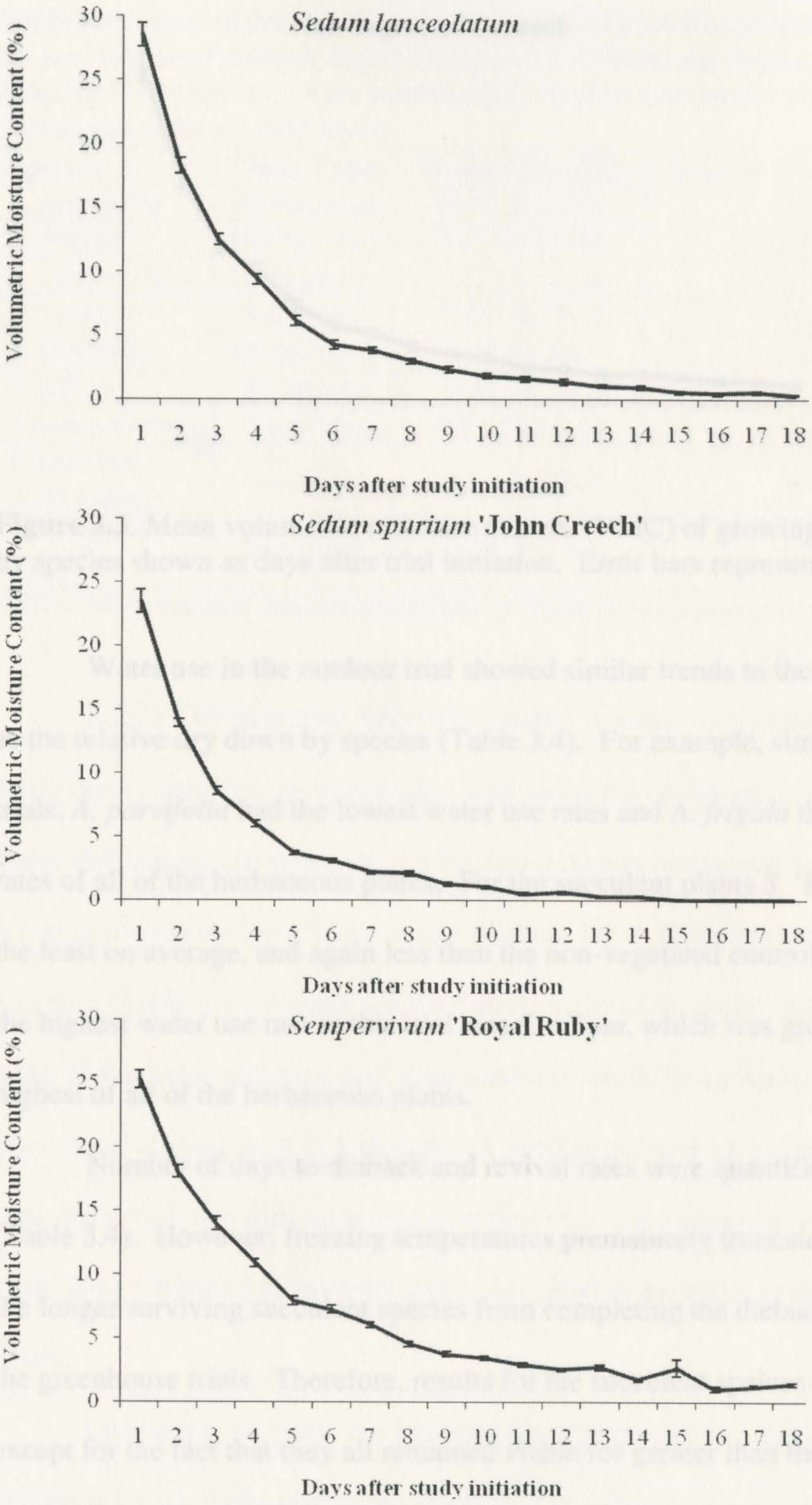
Once the top growth of an individual plant had died back, the plant was re-watered to determine if the plant had entered into dormancy or died. If plants had not died during the 151 day study, water was applied at the end of the study to evaluate if they could recover from an extended period of drought (Table 3.3). The herbaceous plants had a mean of 22.62% revival while the succulent species had an average of 41.75% revival (Table 3.3). Figure 3.2 shows the difference in plant appearance from the beginning of the study compared to twelve days later.

Figure 3.2. Example block showing the change in plant appearance a) the day after the trial began and b) day 12.

3.3.2. Outdoor trial. The results of the outdoor trial had similar trends to the greenhouse trials concerning rate of dry down of the herbaceous and succulents (Figure 3.3). In general, the succulent plants dried down more slowly than the herbaceous plants, although exceptions did occur. For example, *A. parvifolia* retained more moisture for longer than most of the succulent species, except *S.* 'Royal Ruby', which is similar to what occurred in the greenhouse trials (Figure 3.1).


Antennaria parvifolia
Artemisia frigida
Buchloe dactyloides
Volumetric Moisture Content (%)
Days after study initiation
0
5
10
15
20
25
30
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18


Delosperma cooperi
Volumetric Moisture Content (%)
30
25
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Days after study initiation
Penstemon pinifolius
Volumetric Moisture Content (%)
30
25
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Days after study initiation
Sedum album
Volumetric Moisture Content (%)
30
25
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Days after study initiation



Sedum lanceolatum
Sedum spurium 'John Creech'
Sempervivum 'Royal Ruby'
Volumetric Moisture Content (%)
Days after study initiation
0
5
10
15
20
25
30
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

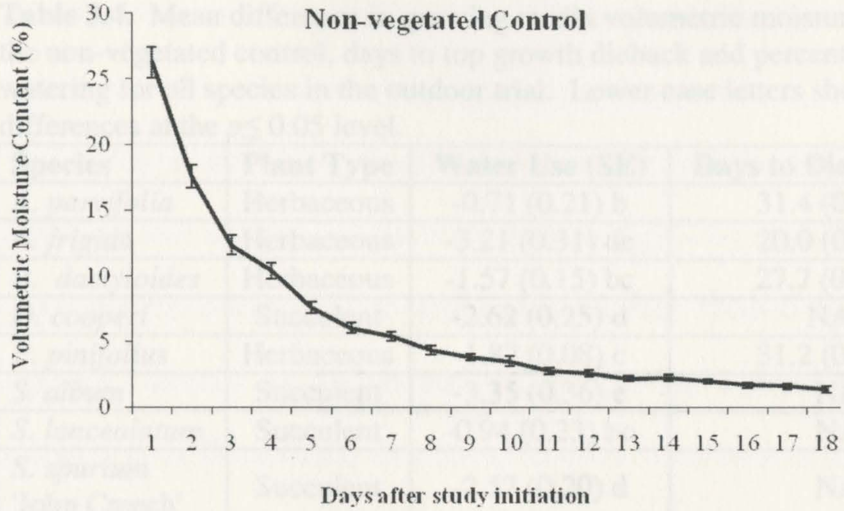


Figure 3.3. Mean volumetric moisture content (VMC) of growing media for outdoor trial by species shown as days after trial initiation. Error bars represent standard error.

Water use in the outdoor trial showed similar trends to the greenhouse trials as far as the relative dry down by species (Table 3.4). For example, similar to the greenhouse trials, *A. parvifolia* had the lowest water use rates and *A. frigida* the highest water use rates of all of the herbaceous plants. For the succulent plants *S.* 'Royal Ruby' transpired the least on average, and again less than the non-vegetated control. The succulent with the highest water use rate in this trial was *S. album*, which was greater than even the highest of all of the herbaceous plants.

Number of days to dieback and revival rates were quantified for the outdoor trial (Table 3.4). However, freezing temperatures prematurely truncated the study preventing the longer surviving succulent species from completing the dieback process as noted in the greenhouse trials. Therefore, results for the succulent speices are not applicable except for the fact that they all remained viable for greater than the 43 days of the trial prior to exposure to freezing temperatures.

Table 3.4. Mean difference in growing media volumetric moisture content (VMC) from the non-vegetated control, days to top growth dieback and percent revival after re-watering for all species in the outdoor trial. Lower case letters show significant differences at the $p \leq 0.05$ level.

Species	Plant Type	Water Use (SE)	Days to Dieback (SE)	Revival
A. parvifolia	Herbaceous	-0.71 (0.21) b	31.4 (0.24) c	54.17%
A. frigida	Herbaceous	-3.21 (0.31) de	20.0 (0.31) a	50.00%
B. dactyloides	Herbaceous	-1.57 (0.15) bc	27.7 (0.25) b	41.67%
D. cooperi	Succulent	-2.62 (0.25) d	NA†	NA
P. pinifolius	Herbaceous	-1.82 (0.08) c	31.2 (0.42) c	20.83%
S. album	Succulent	-3.35 (0.36) e	NA	NA
S. lanceolatum	Succulent	-0.94 (0.23) bc	NA	NA
S. spurium 'John Creech'	Succulent	-2.57 (0.20) d	NA	NA
S. 'Royal Ruby'	Succulent	+0.23 (0.15) a	NA	NA

†NA = Not available (due to truncation of study from freezing temperatures.)

3.3.3. Comparison between trials. A visual comparison of the two sets of dry down curves between the greenhouse and outdoor trials shows qualitative differences. These differences can be explained by divergent environmental conditions. Greenhouse growing conditions have lower solar radiation due to filtration through the greenhouse covering (Table 3.1). Lower solar radiation in the greenhouse would favor lower ET rates; higher solar radiation and wind outdoors would favor higher ET rates, especially in a semi-arid climate such as Colorado. A rooftop environment could potentially have an even higher ET rate than either the greenhouse or the outdoor trial conditions in this study due to higher temperatures and lower relative humidity in urban areas (Schmidt, 2006).

Differences in water use between the greenhouse and outdoor trials can be explained by the difference in the amount of growing media not covered by plant canopy. As mentioned above, the VMC curves (Figures 3.1 and 3.3) show a faster dry down outside. However, when looking at the differences in water use values (Tables 3.3 and 3.4), the plants in the outdoor trial appear to use less water.

The number of days to dieback took longer outdoors than in the greenhouse. The difference here also has to do with the amount of growing media in the module and it is likely that the cooler nighttime temperatures outdoors (than in the greenhouse) would reduce ET demand. As the modules used outdoors had a greater rooting volume to draw moisture from, theoretically they mined moisture from those areas of the module without vegetation between the plants. In general, revival rates were also greater outdoors than indoors, due to the same phenomenon: increased root zone from which to mine resources.

3.3.4. Irrigation recommendations. Due to the differences in water use and number of days to dieback between succulents and herbaceous species, irrigation frequency recommendations are different. For succulent species, it has been recommended that irrigation be provided at 28 day intervals for growing media at a depth of 6cm (VanWoert et al., 2005). The current study would concur with that recommendation as all succulents remained viable for at least 28 days. Additionally, while it is difficult to establish permanent wilting points for many succulent species because they retain moisture in their foliage (Berghage et al., 2007), irrigating at least 10 days after VMC ceases to change (Day 18 in this study) appears to be an appropriate and resourceful management tactic for extensive green roofs.

For the herbaceous plants in this study, the irrigation frequency recommendation will be increased. If number of days to dieback are an indication of tolerance of low VMC, then irrigation should be provided more often than every 16 days, which was the mean days to dieback for the earliest species to dieback, *A. frigida*. In a greenhouse moisture deficit study for pot culture, selected herbaceous species were treated to a series of 10 day dry down cycles and resulted in the plants remaining viable at VMC contents near 0% (Starman and Lombardini, 2006). Even if VMC drops below wilting point, the species in the current study should be able to remain viable until moisture is again supplied. Therefore, irrigation frequency recommendations for the herbaceous species in this study are at least every 14 days.

3.4. Conclusion

There was no clear division between succulent and herbaceous species in dry down curves because there are differences within plant types. Additionally, water use during the 18 day dry down was inconsistent within plant type. However, the general trend was that succulent species retained more moisture for longer than herbaceous species.

Dieback and revival rates differed by plant type as well. The succulent plants had viable foliage for over five times longer than the herbaceous plants in the greenhouse. After dieback, the revival rates of the succulent plants were nearly double the herbaceous. Therefore, not only are the succulents longer-lived during drought but they have a better chance of surviving a period of drought once water is again made available.

Irrigation frequency recommendations varied by plant type. Succulent species should be irrigated at least every 28 days in extensive green roof culture while herbaceous species should be irrigated at 14 day intervals or more frequently, depending on individual species requirements. It is important to note that irrigation frequency would need to be increased if irrigation events supply suboptimal moisture.

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Chapter 4. Evaluating a Natural Zeolite as an Amendment for Extensive Green Roof Growing Media

Jennifer M. Bousselot[7], James E. Klett[8] and Ronda D. Koski[9]

4.0.1. Abstract. This research examined soilless green roof growing media blends on an existing modular extensive green roof in Denver, Colorado. Growing media blends evaluated include a typical extensive green roof growing media, Green Grid® and Green Grid® plus varying percentages of ZeoPro™ H-Plus. Plant taxa used included *Sedum acre* L., *Sedum album* L., *Sedum spurium* Marsch-Bieb. 'Dragons Blood' and *S. spurium* 'John Creech', all which were already in use on the green roof. Growing media blends were evaluated based on plant taxa growth performance. Data collected included digital images to measure plant area covered using digital image analysis (DIA) and growing media volumetric moisture content (VMC). DIA data were analyzed using the GLIMMIX procedure in SAS as multiple comparisons of growing media blends for each taxa from eight dates over two growing seasons. The VMC data were analysed using the GLIMMIX procedure from seven dates over two years. The addition of zeolite to the

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typical extensive green roof growing media improved establishment year plant cover for *S. acre* and *S. album* but hindered overwintering. Conversely, the two cultivars of *S. spurium* did not show a benefit of plant cover from the addition of zeolite in the first year but did the second year. As the percentage of zeolite in the growing media increased, VMC also increased, despite the fact that laboratory results showed decreasing water holding capacity as zeolite percentage increased.

4.1. Introduction

Green roofs are an increasingly utilized solution to many urban environmental problems (Getter and Rowe, 2006). They have effectively been used, worldwide, as a mitigation tactic for urban stormwater management and urban heat island (UHI) effect, and for increasing the amount of green space available in cities.

Most extensive green roof growing media are predominantly made up of lightweight aggregate such as expanded clay, expanded shale, heat-expanded slate, and pumice (volcanic rock) (Friedrich, 2005). These materials allow for rapid drainage but have low nutrient holding capacity (Friedrich, 2005; Panayiotis et al., 2003; Rowe et al., 2006). While lightweight aggregates are beneficial for green roof growing media drainage and for satisfying building structural requirements, on their own these lightweight aggregates do not make ideal growing media for most plants. In a recent study, various percentages of heat-expanded slate were evaluated as green roof growing media. However, as the percentage of heat-expanded slate in the growing media increased, performance of the *Sedum* species, in general, decreased (Rowe et al., 2006).

Organic matter is well known to be beneficial for root growth, however, extensive green roof growing media with high organic matter content (typically $\geq 20\%$ by volume) has resulted in shrinkage over time (Beattie and Berghage, 2004; FLL, 2008; Friedrich, 2005; Miller, 2003). This shrinkage is due to the gradual break down of the organic matter. Even coarse organic materials, such as coir and peat moss, will eventually breakdown over the life of the green roof. Thus, use of green roof growing media with high organic matter content would require replenishment of the organic matter component, which is not time- or cost-effective for most green roof systems (Rowe et al., 2006). Therefore most extensive green roof growing media are composed primarily of mineral-based materials (Beattie and Berghage, 2004; Miller, 2003).

One material that has been used in shallow, well-drained golf greens to improve nutrient holding and water holding capacities is an expanded potassium-calcium clinoptilolite product, commonly referred to as zeolite (Miller, 2000; Murphy et al., 2005). ZeoPro™ is one type of zeolite that is mined from volcanic deposits, has a lattice structure suitable for plant extractable nutrient and moisture retention, and a granular diameter range of 0.4-2.4 mm.

Incorporating zeolite into a typical mineral-based green roof growing media may improve nutrient holding and water holding capacities. The objectives of this study were to evaluate plant response to a series of extensive green roof growing media blends containing various percentages of zeolite.

4.2. Materials and Methods

Rooftop experiments were conducted on the roof of the 8th floor of the building that houses the EPA Region 8 Headquarters (1595 Wynkoop, Denver, CO). A 10-cm deep extensive modular (tray) GreenGrid® (Weston Solutions, Inc., Vernon Hills, IL) system was installed in the fall of 2006. Research modules were placed among the existing modules in the spring of 2008.

The species used to evaluate the zeolite amendment were the *Sedum* taxa already in use on the green roof: *Sedum acre* (goldmoss stonecrop), *Sedum album* (white stonecrop), *Sedum spurium* (two-lined stonecrop) 'Dragon's Blood' and *S. spurium* 'John Creech'. The *Sedums* were planted as a mixed stand (one plant per taxa per module) in 61 cm x 61 cm x 10 cm modules on 30.5 cm centers from 128-cell plug trays.

Modules were filled with one of four growing media blends: 3:0 GreenGrid® growing media to zeolite (0% ZeoPro™ H-Plus, from ZeoponiX, Inc. Boulder, CO), 2:1 GreenGrid® to zeolite (33% zeolite), 1:2 Green Grid® to zeolite (66% zeolite) and 0:3 Green Grid® to zeolite (100% zeolite). The GreenGrid® growing media is a proprietary blend that is lightweight, well-drained and designed for use in this modular system. It contains various percentages of expanded clay, peat, perlite and vermiculite. Chemical and physical characteristics of the growing media blends can be found in Table 4.1.

Planted modules were hand watered every 48 hr to saturation and maintained at 23.9°C daytime and 18.3°C nighttime temperatures. Modules were moved outdoors to acclimate on 20-Mar-08 and fertilizer (Scott's Osmocote Pro 19-5-8) was applied at the rate of 41.5 g per tray. On 26-Mar-08 the trays were installed on the EPA Region 8 green roof in Denver, CO.

Table 4.1. Chemical and physical characteristics of the four growing media.

Growing Media Characteristic		***0% zeolite***	***33% zeolite***	***66% zeolite***	***100% zeolite***
Organic Matter Content		4.9%	1.8%	0.6%	0.3%
NO_3-Nitrogen (N)		105 ppm	197 ppm	158 ppm	21 ppm
Phosphorus (P)		19 ppm	21 ppm	26 ppm	14 ppm
Potassium (K)		251 ppm	1215 ppm	1456 ppm	1597 ppm
Bulk Density		0.66 g/cc	0.75 g/cc	0.90 g/cc	0.97 g/cc
Particle Density		1.96 g/cc	2.01 g/cc	2.26 g/cc	2.35 g/cc
Saturated Hydraulic Conductivity		0.0102 cm/s	0.0108 cm/s	0.0101 cm/s	0.0154 cm/s
At Max Water Capacity	*Air Content*	17.7%	13.6%	14.9%	26.8%
	Water Content	48.6%	48.9%	45.1%	32.0%
At pF = 1.8 (FLL, 2008)	*Air Content*	35.7%	32.8%	32.3%	39.4%
	Water Content	30.6%	29.7%	27.7%	19.5%

During the 2008 growing season, irrigation was supplied by 3.5 lph drip emitters spaced every 30.5 cm. At initiation of study, irrigation was provided at 18.7 mm/week and then reduced to 8.0 mm/week on 15-August. In order to provide more uniform coverage of water, the irrigation system was changed to an overhead rotator system during the 2009 growing season. Irrigation was provided at 6.4 mm/week starting 09-July-09. Irrigation initiation in 2009 was delayed due to an unusually moist spring, with precipitation 81.3%, 14.2%, and 64.4% above normal for April, May and June, respectively. Weather for the 2008 and 2009 growing seasons are summarized in Table 4.2 with graphs in Appendix 1.

4.2.1. Data Collection. Plant area covered (plant cover) was determined by taking digital images, similar to a concurrent study evaluating plant species on the green roof (Bousselot et al., 2009). A FujiFilm FinePix S3000 (6x optical zoom 3.2 mega pixels lens) camera was mounted to a 190xprob tripod (Bogen Manfrotto, Ramsey, NJ) with an extendable horizontal arm. Digital image analysis (DIA) was performed using

SigmaScan Pro 5.0 (SPAA Science, Chicago, IL) image analysis software. The DIA data were analyzed to evaluate the progression of plant cover over time.

Table 4.2. Mean monthly weather data for the 2008 and 2009 growing seasons.

Weather	May		June		July		August		September	
	2008[1]	2009[2]	2008[1]	2009[2]	2008[1]	2009[2]	2008[2]	2009[2]	2008[2]	2009[2]
Min. temp. (°C)	6.7	10.7	11.9	13.5	16.8	16.3	16.7	15.9	11.3	11.8
Max. temp. (°C)	22.6	24.7	29.4	28.3	34.4	31.8	31.7	32.0	26.5	27.6
Precip (mm)	64.3	56.4	16.8	41.3	3.8	63.5	8.4	21.8	16.0	17.5

[1]National Weather Service station (ID: 052223) at Denver Water (1600 W. 12th Avenue, Denver, CO) collected 2.6 km away from green roof.

[2]Campbell Scientific (Logan, UT) weather station located on the EPA Region 8 green roof (1595 Wynkoop Street, Denver, CO).

DIA data were collected on eight dates over two years and were analyzed to determine plant cover. Four dates in 2008 at six week intervals (14-May [Day 49], 25-June [Day 91], 06-August [Day 133] and 16-September [Day 174]) and four dates at six week intervals in 2009 (13-May [Day 413], 24-June [Day 455], 05-August [Day 497] and 15-September [Day 538]) were evaluated.

Additionally, volumetric moisture content (VMC) of the growing media was quantified using a ThetaProbe ML2X (Delta-T Devices, Cambridge, UK). The ThetaProbe was inserted into the growing media up to the depth of the probe (5 cm). Three readings per module per date were recorded. For the VMC data, four dates in 2008 (14-May [Day 49], 25-June [Day 91], 06-August [Day 133] and 16-September [Day 174]) and three dates in 2009 (27-May [Day 426], 19-August [Day 510] and 15-September [Day 538]) were evaluated. *Note*: the 2009 dates for VMC data are different than the dates for DIA data due to technical difficulties with the ThetaProbe.

4.2.2. Experimental Design and Data Analysis. The experiment was laid out as a randomized complete block design. There were ten blocks with each of the four treatments per block (Figure 4.1).

Both data sets were analyzed using a repeated measures analysis of variance procedure (GLIMMIX) in SAS® version 9.02 (SAS Institute Inc., Cary, NC). The GLIMMIX procedure was performed using t-tests for multiple comparisons of means to show differences in plant cover and VMC. The DIA data were transformed for analysis to the log scale to equalize and normalize the residuals; no transformation was performed on the VMC data. All significant differences are at the $p \leq 0.05$ level.

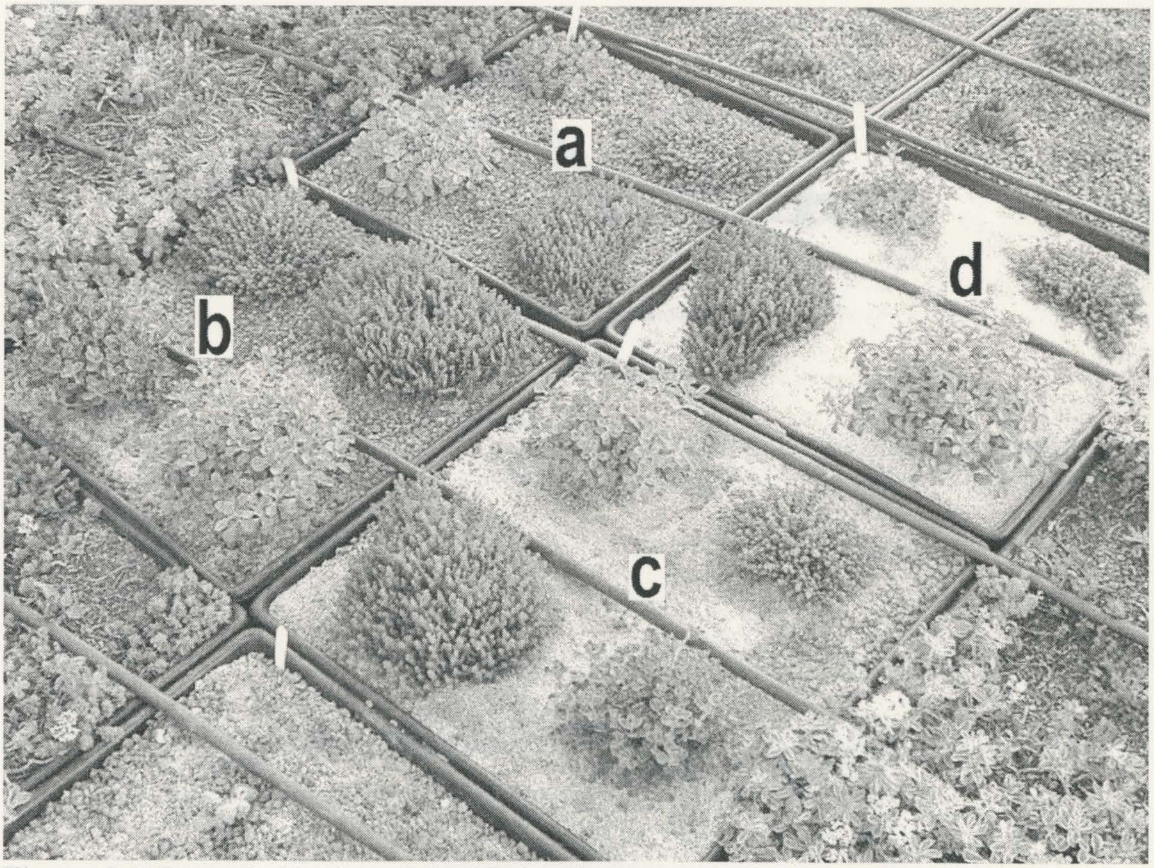
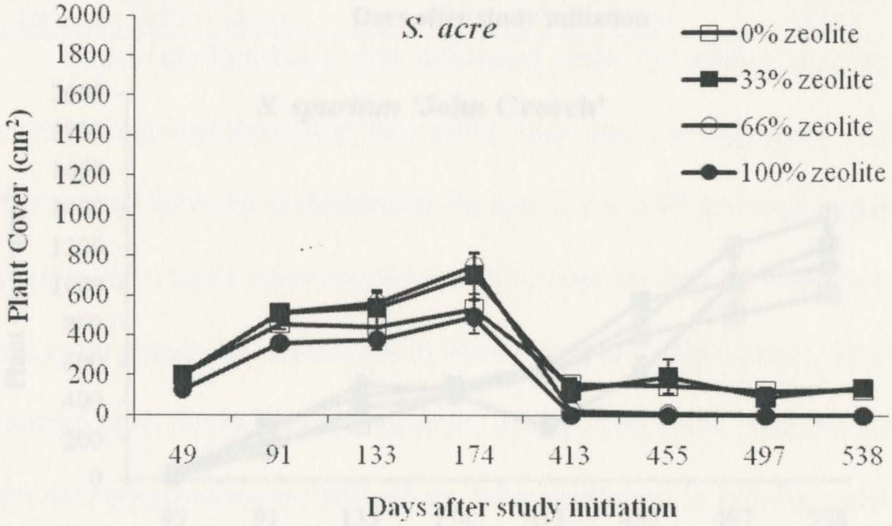
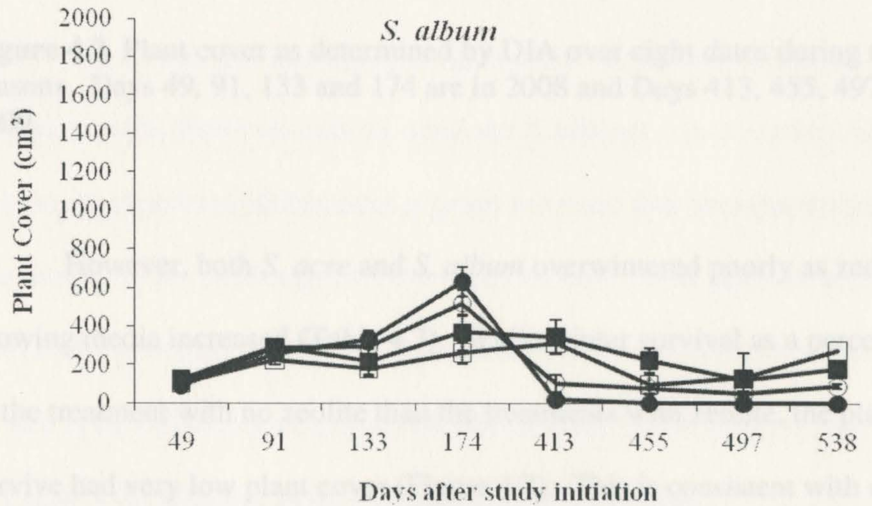


Figure 4.1. Example block on 7-01-08 showing treatments a) 0% zeolite, (counter-clockwise) b) 33% zeolite, c) 66% zeolite and d) 100% zeolite.

4.3. Results and Discussion

All four *Sedum* taxa responded to the addition of zeolite, however, not all in the same growing season or at the same percentage of zeolite (Figure 4.2). For example, by the end of 2008, *S. acre* had the highest plant cover in the mixed blends (33% and 66% zeolite) and the lowest in the uniform blends (0% and 100% zeolite). While *S. album* increased in plant cover with increasing zeolite content of the growing media.





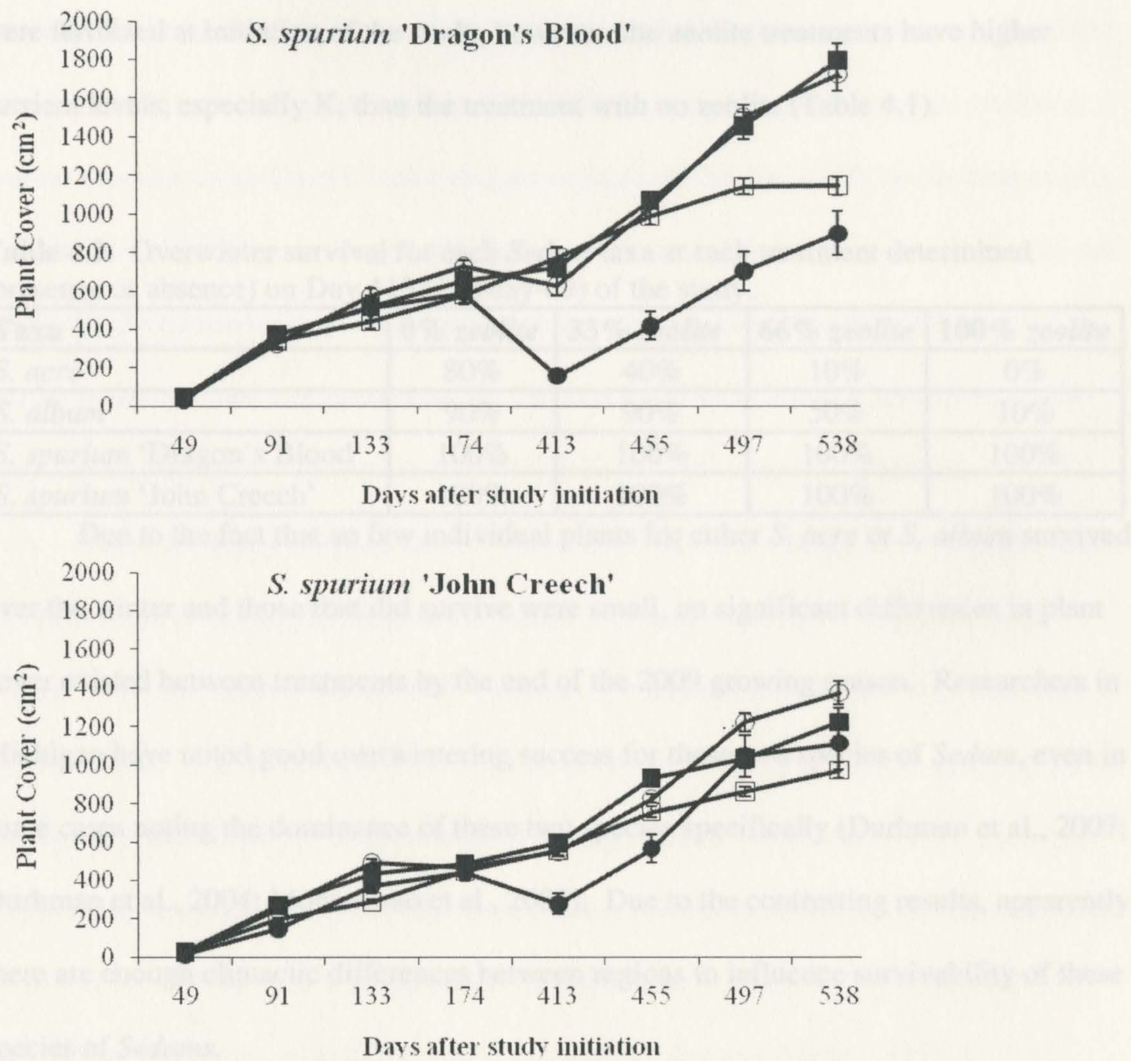


Figure 4.2. Plant cover as determined by DIA over eight dates during two growing seasons. Days 49, 91, 133 and 174 are in 2008 and Days 413, 455, 497 and 538 are in 2009.

However, both *S. acre* and *S. album* overwintered poorly as zeolite content of the growing media increased (Table 4.3). While winter survival as a percentage was higher in the treatment with no zeolite than the treatments with zeolite, the plants that did survive had very low plant cover (Figure 4.2). This is consistent with research that showed plants that were not fertilized were smaller in size but survived over the winter compared to those that were fertilized (Rowe et al., 2006). In the current study, all plants were fertilized at initiation of the study, however, the zeolite treatments have higher nutrient levels, especially K, than the treatment with no zeolite (Table 4.1).

Table 4.3. Overwinter survival for each *Sedum* taxa at each treatment determined (presence or absence) on Day 413 (13-May-09) of the study.

Taxa	***0% zeolite***	***33% zeolite***	***66% zeolite***	***100% zeolite***
S. acre	80%	40%	10%	0%
S. album	90%	90%	50%	10%
S. spurium 'Dragon's Blood'	100%	100%	100%	100%
S. spurium 'John Creech'	100%	100%	100%	100%

Due to the fact that so few individual plants for either *S. acre* or *S. album* survived over the winter and those that did survive were small, no significant differences in plant cover existed between treatments by the end of the 2009 growing season. Researchers in Michigan have noted good overwintering success for these two species of *Sedum*, even in some cases noting the dominance of these two species specifically (Durhman et al., 2007; Durhman et al., 2004; Monterusso et al., 2005). Due to the contrasting results, apparently there are enough climactic differences between regions to influence survivability of these species of *Sedums*.

The two *S. spurium* taxa ('Dragon's Blood and 'John Creech') showed different results than the other two taxa (*S. acre* and *S. album*). At the end of the 2008 growing season, no significant differences in plant cover existed between treatments for either *S. spurium* cultivar. Although overwintering showed 100% survival across treatments for both *S. spurium* cultivars (Table 4.3), plants in the 100% zeolite treatment were reduced in size at the beginning of the second season (note the decrease in plant cover on Day 413 in Figure 4.2), which is clearly an effect of overwintering.

Due in part to this phenomenon, the 2009 results for the *S. spurium* cultivars show significant differences by treatment. For *S. spurium* 'Dragon's Blood', the 100% zeolite treatment had significantly lower plant cover from all other treatments through the 2009 growing season except on the last day (Day 538) compared to the 0% zeolite treatment. *Sedum spurium* 'John Creech' showed a similar pattern but the 100% zeolite treatment recovered in plant cover more quickly than the 'Dragon's Blood' cultivar. Therefore the 100% zeolite treatment was significantly lower in plant cover from the 33% and 66% zeolite treatments early in the season, on Days 413 and 455. The 0% zeolite treatment was only significantly different on Day 413 from the 100% zeolite treatment.

There are many possible factors which affected survivability of these green roof plants in these different growing media blends, especially during the winter season. Winter VMC and diurnal temperature fluctuation related to media color may influence plant survival. The mean daily minimum temperature of the GreenGrid® growing media during the winter months (December 2008 through March 2009) was -3.0°C. However, minimum temperature alone may not be the only problem as *Sedum spectabile* has been shown to not survive -3.0°C temperatures in September but, depending on the cultivar, can survive conditions at less than -20°C in January (Iles and Agnew, 1995). Additionally, the root hardiness of these species is unknown in this type of shallow, well-drained system. Finally, while it has not been formally documented, root size in relation to top growth for some of these species (i.e. *S. acre* and *S. album*) has been found to be noticeably less in luxury nutrient and moisture content situations compared to drier and lower fertility growing media.

4.3.1. Growing media VMC. Results of the VMC data indicate that moisture holding capacities of treatments varied by their relative proportion of zeolite (Table 4.4). During the first three evaluation dates of 2008, the trend is that the least amount of moisture was present in the 0% zeolite treatment and the highest was in the 100% zeolite treatment. These results are consistent with research in turf grass, which shows higher moisture contents in substrates that contain clinoptilolite than in sand alone (Miller, 2000; Murphy et al., 2005).

Table 4.4. Growing media volumetric moisture content (VMC) on seven dates over two growing seasons (standard error in parenthesis). Days 49, 91, 133 and 174 are in 2008 and Days 426, 510 and 538 are in 2009. Lower case letters indicate significant differences at the $p \leq 0.05$ level.

VMC	*Day 49*	*Day 91*	*Day 133*	*Day 174*	*Day 426*[3]	*Day 510*	*Day 538*[4]
0% zeolite	14.02% (0.77) b	5.16% (1.11) d	8.05% (1.62) b	12.78% (1.13) a	13.58% (1.08) a	7.49% (0.84) ab	9.85% (1.06) a
33% zeolite	15.62% (0.51) ab	7.30% (1.55) cd	10.12% (1.04) b	12.83% (0.72) a	14.00% (1.26) a	6.42% (0.45) b	7.32% (0.59) a
66% zeolite	14.43% (0.49) b	9.28% (0.95) bc	9.46% (1.37) b	12.65% (0.70) a	14.53% (0.75) a	6.86% (0.46) b	7.96% (0.55) a
100% zeolite	17.69% (0.32) a	12.02% (1.57) a	10.81% (1.90) a	12.53% (0.61) a	15.65% (0.60) a	9.44% (0.63) a	9.21% (0.44) a

[3]Precipitation equaling 31.24 mm was recorded within 24 hours prior to VMC sampling.

[4]Precipitation equaling 13.46 mm was recorded within 24 hours prior to VMC sampling.

Additionally, a qualitative comparison between irrigation application methods can be made as there were two different systems used in the two years of the study. As noted above, a drip irrigation system was used in 2008 and an overhead rotator system was used in 2009. This means that the overhead rotator system is equally, if not more appropriately, suited to this type of extensive green roof system because it effectively supplies parallel VMC for the plants while only using one third of the water as the drip irrigation system. This observation is in agreement with observations discussed in other regions of North America (Beattie and Berghage, 2004; Friedrich, 2005).

4.4. Conclusions

The addition of zeolite to the growing media on an extensive green roof improved establishment year growth for *S. acre* and *S. album* but hindered their overwintering success. Conversely, the two cultivars of *S. spurium* did not show benefit from the addition of zeolite in the first year (2008) but did the second year (2009). Therefore, the addition of zeolite to extensive green roof growing media is beneficial for certain species of *Sedum*.

In general, VMC increased with increasing zeolite content of the growing media. Despite the fact that laboratory results showed decreasing water holding capacity as zeolite percentage increased. Additionally, the overhead rotator irrigation system was apparently more efficient than the drip irrigation at supplying similar VMC to plants.

4.5. Literature Cited

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Appendix 1. Environmental Conditions on the Green Roof

A Campbell Scientific weather station was installed on the green roof during the spring 2008 to monitor the environmental conditions for a concurrent study on green roof mitigation of the urban heat island effect (Table A.1). Final equipment calibrations allowed for accurate data to be reported starting 01-August-08 and continuing through the remainder of the study. Data is presented in Figures A.1-A.6.

Table A.1. Weather monitoring equipment used on the green roof.

Campbell Scientific Equipment (Model #)	**Description**	**Range of Tolerance**
Temperature and Relative Humidity Probe (HMP45C)	Measures temperature and RH at 12 inch height	-40º to +60ºC
Type-T Thermocouple (105T)	Membrane and growing media temperature	-78° to +50°C
Young Wind Sentry set (03001-L)	Wind speed and direction	0 to 50 m/s
Tipping Bucket (TE525WS-L)	Precipitation gage	0° to +50°C
Snowfall conversion adaptor (CS705)	Converts snowfall into rain equivalent	to -20°C
Datalogger (CR1000)	Data storage device	

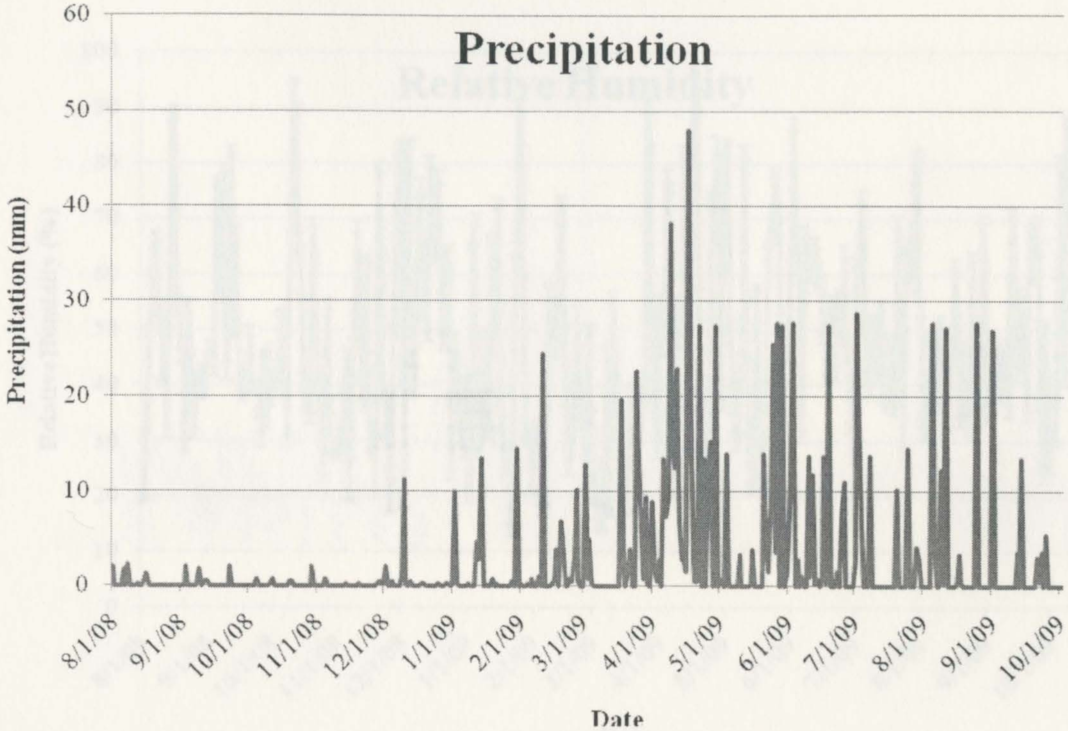

Figure A.1. Daily precipitation totals on the green roof during the study.

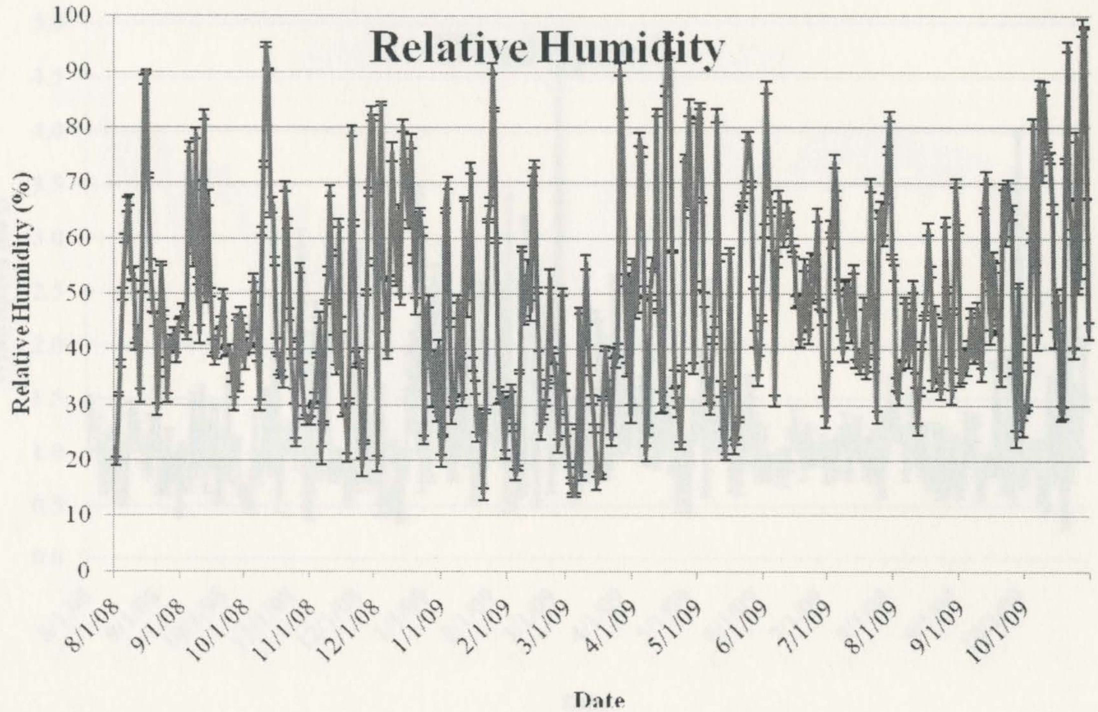

Figure A.2. Daily mean and standard error for relative humidity.

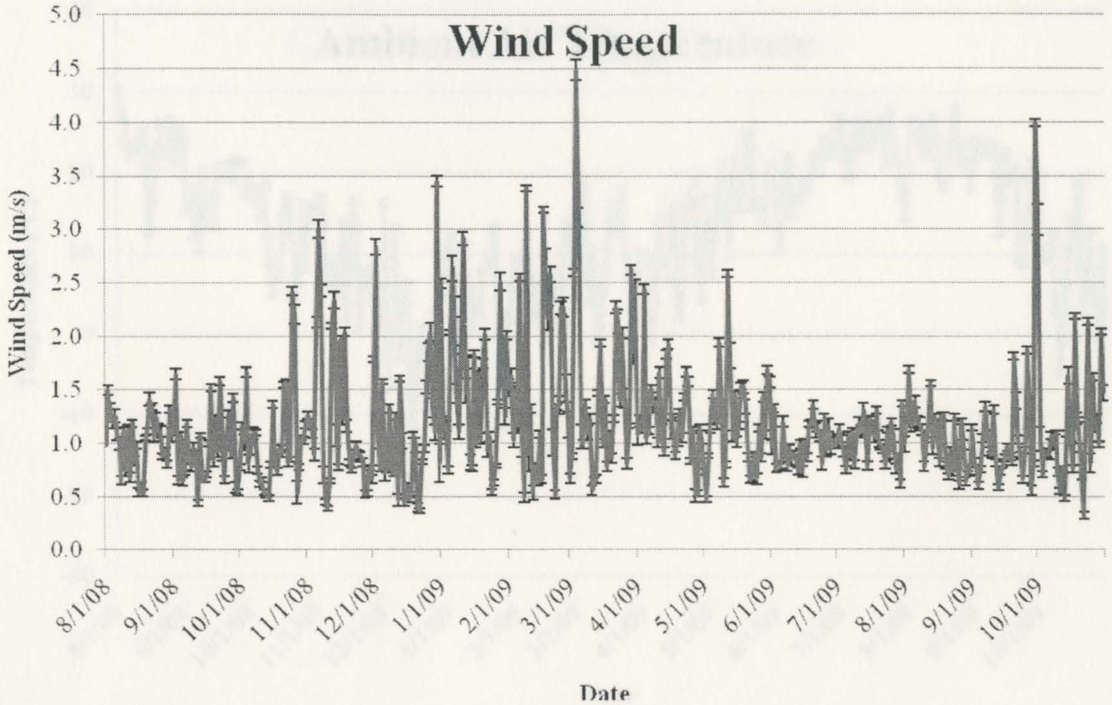

Figure A.3. Daily mean and standard error for wind speed in meters/second.

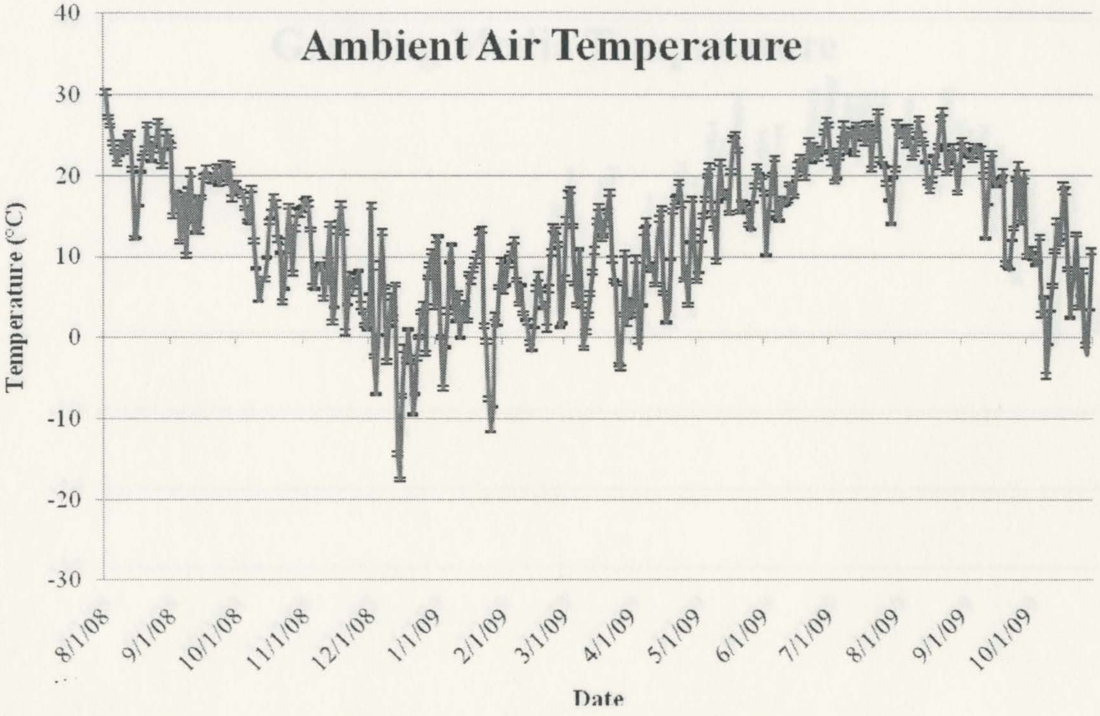

Figure A.4. Daily mean and standard error for ambient air temperature.

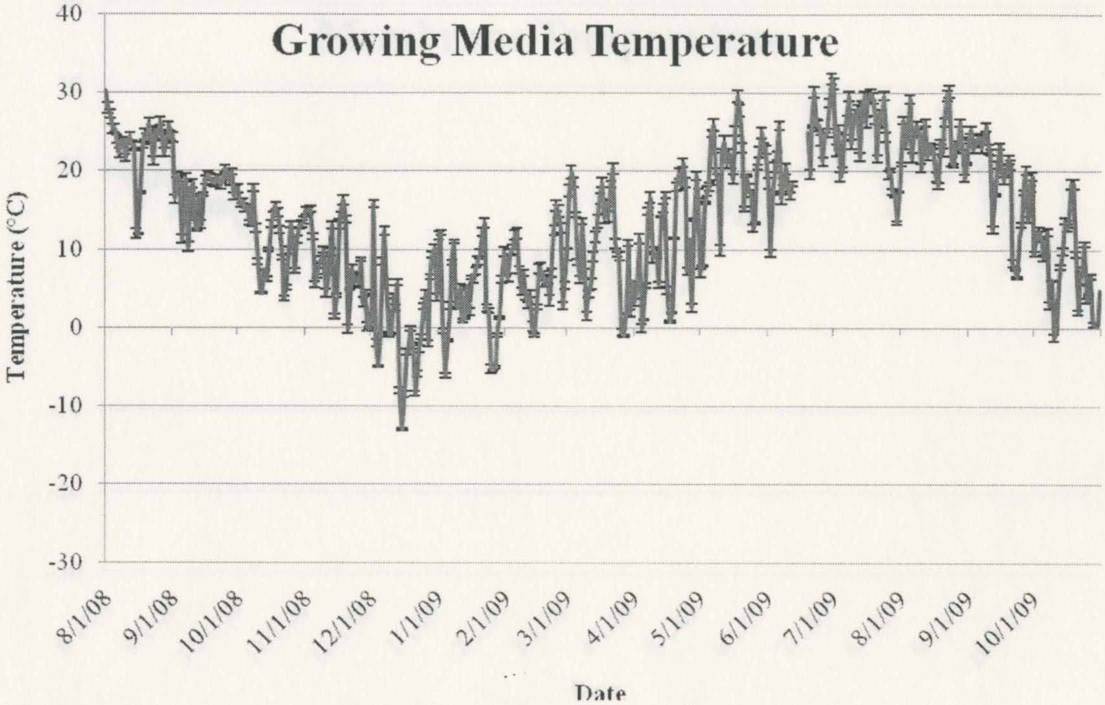

Figure A.5. Daily mean and standard error for growing media temperature.

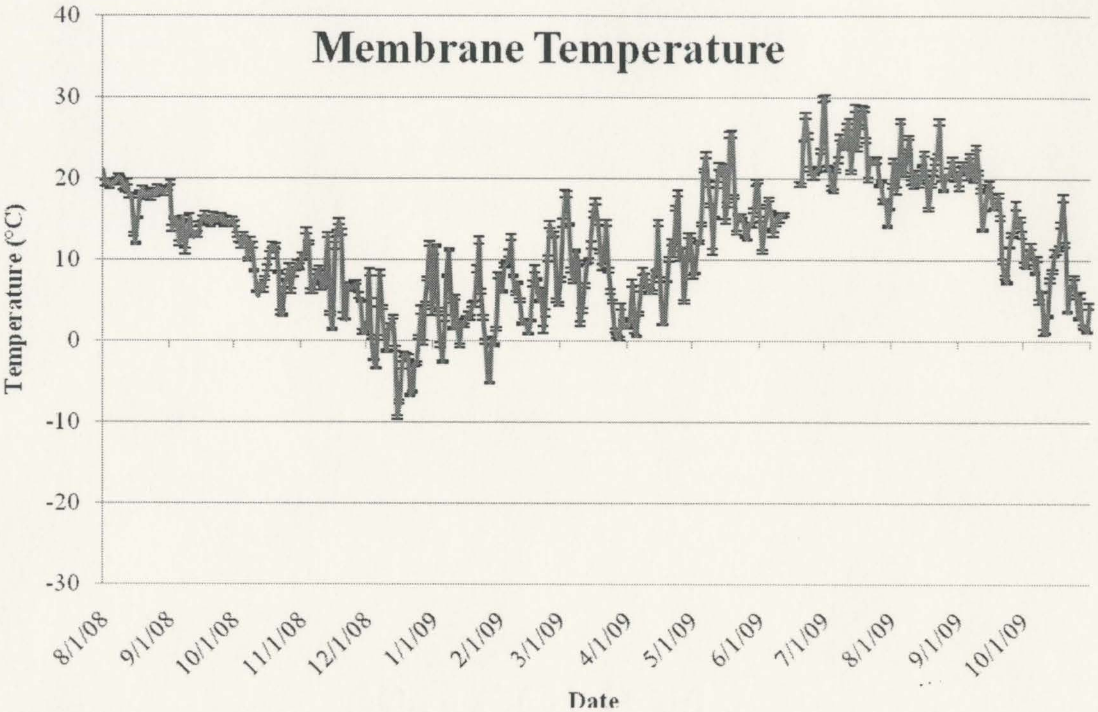

Figure A.6. Daily mean and standard error for roof membrane temperature.