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Evaluation of Green Roof Plants and Materials for Semi-Arid Climates

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Notice

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Abstract

While green roof systems have proven to be highly effective in the evaporative cooling of buildings, reduction of roof top temperatures, protection of roof membranes from solar radiation degradation, reducing stormwater runoff, as well as beautification of the urban roof top landscapes throughout Europe and in several regions in North America, green roof systems have not been evaluated in the high elevation, semi-arid regions in the United States. Because of the risk of plant failure from incorrectly selected species, the paucity of information on green roofs in this region, and the large potential for environmental benefits, studies were conducted on various performance parameters on the green roof of the building that houses the EPA Region 8 Headquarters in Denver, Colorado.

Green roofs are vegetated roof tops. Green roofs provide several benefits to urban environments, including reduction of stormwater run-off volumes and intensity, filtration of stormwater discharge, reduction of the urban heat island effect, temperature moderation within the building underlying the green roof, and beautification of urban roof top landscapes. In order to provide these benefits, the green roofs must receive sufficient amounts of water and nutrients to keep the plants alive. In the semi-arid, high elevation environment of the Front Range of Colorado, green roof plants have not been scientifically tested for long term survivability and adaptability. The low annual precipitation, short periods of snow cover, low average relative humidity, high solar radiation (due to high elevation above sea level, approximately 1.6 km), high wind velocities, and predominantly sunny days all add up to challenging growing conditions for many species of plants.

Due to the porous and well-drained nature of the typical growing media used in extensive (shallow) green roof systems, plant species considered for use in such systems need to be evaluated for their response water requirements and survivability and growth habits over multiple years. Thus, relative rate of dry down of the moisture content of the media 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.

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Acronyms and Abbreviations

ASTM	American Society for Testing and Materials
CEC	cation exchange capacity
CAM	crassulacean acid metabolism
CSU	Colorado State University
C2D	converted two-dimensional
DIA	digital image analysis
EPA	Environmental Protection Agency
ET	evapotranspiration
ET_0	evapotranspiration reference rate
ET_C	crop evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FLL	Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau
K_C	crop coefficient
NA	not applicable
RARE	Regional Applied Research Effort
SE	standard error
UHI	urban heat island
VMC	volumetric moisture content

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Executive Summary

This report is the result of a three part Environmental Protection Agency (EPA) Regional Applied Research Effort (RARE) project that involved evaluating green roof stormwater management, mitigation of the Urban Heat Island (UHI) effect and biological evaluation in a high elevation semi-arid area of the United States. The overall research strategy was to facilitate the development of green roof systems within the urban communities encompassed within the boundaries of EPA's Region 8.

Green roofs (roofs covered with vegetation) have been proven to provide several benefits to urban environments, including reduction of volume and intensity of stormwater run-off, filtration of stormwater discharge, reduction of the UHI Effect, temperature moderation within the building underlying the green roof, and beautification of urban roof top landscapes. Green roofs are based on a design that uses mineral aggregates such as expanded clays, expanded shales, expanded slates or pumice in the growing medium. These materials provide good drainage and stability but they tend to have low nutrient- and water-holding capacities.

There are two main types of green roofs: extensive and intensive. Extensive green roofs are characterized by shallow growing medium, usually less than 15 cm (6.0 in.) deep, while intensive green roofs are characterized by deep growing medium, from 15 cm (6.0 in.) up to 1 m (3 ft), but can even be deeper. The shallower extensive green roofs are typically the only option for existing structure but are also utilized more often on newer buildings due to increased cost for structural support and growing media for intensive roofs. However, the shallow depth and comparatively quick drainage of the media in extensive roofs traditionally has not supported a large diversity of plant species due to root zone limitations. 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. Many environmental factors affect the moisture content of the growing medium such as surface temperature, ambient air temperature, intensity and duration of solar radiation, plants, relative humidity, and rate of air movement (wind), as well as growing medium depth and composition.

Due to the porous and well-drained nature of the typical growing medium used in extensive green roof systems, the success or failure of an extensive green roof is primarily dependent on a plant species' ability to grow in the media. These challenges are intensified for extensive green roofs on roof tops of buildings in areas characterized by high elevation and semi-arid climate. Success of an extensive green roof is primarily dependent on plant species ability to survive the low moisture content of the growing medium. 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.

This report is the culmination of a series of three studies conducted in 2008 and 2009 to determine some performance characteristics of several plants species grown in extensive green roof growing media. Most of the studies were conducted on an extensive green roof located on the roof of the building housing the offices of the EPA's Region 8 Headquarter in Denver, Colorado with a portion at the Fort Colllins Colorado State University (CSU) campus. Plant taxa monitored included *Allium cernuum* (nodding onion), *Antennaria parvifolia* (small-leaf pussytoes), *Artemisia frigida* (fringed sage), *Bouteloua gracilis* (blue grama), *Buchloe dactyloides* (buffalograss), *Carex flacca* (heath sedge), *Delosperma cooperi* (hardy ice plant, trailing ice plant or pink carpet), *Delosperma nubigenum* (yellow ice plant), *Eriogonum umbellatum aureum* (Kannah Creek® buckwheat) 'Psdowns', *Penstemon pinifolius* (pineleaf penstemon), *Opuntia fragilis* (brittle prickly pear), *Sedum acre* (goldmoss stonecrop), *Sedum album* (white stonecrop), *Sedum lanceolatum* (lanceleaf stonecrop), *Sedum spurium* (two-lined or tworow stonecrop) 'Dragons Blood', *Sedum spurium* (two-lined stonecrop) 'John Creech', *Sempervivum* (hens and chicks) 'Royal Ruby' and *Thymus pseudolanuginosus* (woolly thyme). All plants in the study are considered perennials (USDA, 2012). Table 1 is a summary of the plants responses to environmental conditions, differing media and irrigation regimes across the three studies performed on the Region 8 green roof. Some plants are listed multiple times.

Table 1 Plant Responses to Media Amendments, Type of Irrigation and Environmental Conditions on Region 8 Green Roof

Criteria	Succulents	Herbaceous
Plants benefiting from overhead rotary irrigation	*Delosperma cooperi* *Opuntia fragilis*	*Antennaria parvifolia* *Bouteloua gracilis*
Plants <u>not</u> benefiting from overhead rotary irrigation	*Sedum acre*[1] *Sedum album*	
Plants benefiting from 50% zeolite amendment	*Opuntia fragilis* *Sedum lanceolatum* *Sempervivum* 'Royal Ruby'	*Allium cernuum* *Bouteloua gracilis*
Plants <u>not</u> benefiting from 50% zeolite amendment	*Delosperma cooperi*	*Antennaria parvifolia* *Eriogonum umbellatum aureum*
Plants benefiting from 33% or 66% zeolite amendment	*Sedum spurium* 'Dragons Blood' and 'John Creech'	Not Applicable
Plants <u>not</u> benefiting from 33% or 66% zeolite amendment	*Sedum acre* *Sedum album*	Not Applicable
Plants subject to over wintering stress	*Sedum acre* *Sedum album*	*Antennaria parvifolia* *Buchloe dactyloides* *Eriogonum umbellatum aureum*

[1] Potential overwintering stress on these species due to desiccation may confound this result as plants may leaf out in spring and die later.

In the Single Species Study, plant area covered (plant cover) was determined using two methods: digital image analysis data (DIA) and two-dimensional data (C2D). The first is based on pixel analysis of digital images of the plants, and the latter is based on manually collected measurements of the plants; comparisons were then made between the two methods. For each of six plant species 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 were made between DIA data and final biomass, and C2D and final biomass. Eight individual plants were planted, each with a 93 cm^2 (1.0 ft^2) square of growing space and 10 cm depth. Plant cover increased for all six species during the 2008 growing season. Due to the low overwintering rate (12.5%) of *E. umbellatum aureum*, this species 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 the cactus *O. fragilis* though this increase may have resulted in part from damaged pads being replanted early on in the study. In terms of plant cover, both quantification methods (C2D and DIA) revealed that *B. gracilis* and *D. cooperi* outperformed *A. parvifolia*, *O. fragilis*, and *S. lanceolatum*. Thus, five of the six species evaluated in this study appear to be appropriate for use in extensive green roof applications in high-elevation semi-arid areas with little snow cover, if irrigated in the growing season.

In the Mixed Species Study, five modules were filled with the existing green roof growing medium used for EPA Region 8 green roof and the other five were planted with a 50% by volume zeolite amendment with the existing growing medium. These ten modules were planted with one plant of each of the following eight species (*A. cernuum, A. parvifolia, B. gracilis, D. cooperi, E. umbellatum aureum*, *O. fragilis, S. lanceolatum,* and *Sempervivum* 'Royal Ruby'). One module of each growing medium type was placed in each of the five blocks. Similar plant cover data as in the first study were collected. At the end of the study, the two species that had the highest plant cover were *B. gracilis* and *D. cooperi*; plant cover for all other species was much lower. Similar to the Single Species Study, *E. umbellatum aureum* and *A. parvifolia* had the lowest overwintering rates, though *E. umbellatum aureum* had greater plant cover than *A. parvifolia* and increased in plant cover through 2009, thereby benefiting from the mixed stand planting, while *A. parvifolia* declined, especially in the 50% zeolite amendment. As in the Single Species Study, *O. fragilis* increased in plant cover over; this increase was not as dramatic, though it confirms increase was not due to extra plantings.

In the Zeolite Amendment Study, blends of a typical green roof growing medium (GreenGrid®) and a zeolite product (ZeoPro™ H-Plus) were examined on the EPA green roof. The four growing media evaluated included a GreenGrid® control with no ZeoPro™ H-Plus, 67% GreenGrid® with 33% ZeoPro™ H-Plus, 34% GreenGrid® with 66% ZeoPro™ H-Plus, and no GreenGrid® with 100% ZeoPro™ H-Plus. Plants used in this study included *S. acre*, *S. album*, and *S. spurium* cultivars 'Dragons Blood' and 'John Creech', all of which were already in use on the EPA green roof. The four growing media mixes were evaluated based on plant taxa growth performance. During the initial year, the additions of zeolite to the typical extensive green roof growing medium improved plant cover for all four plants. However, *S. acre* and *S. album* had poor overwintering success and died out late in the spring of 2009. Conversely, the two cultivars of *S. spurium*, which were native to the area, exhibited an increase in plant cover during the second year. *S. spurium* cultivars 'Dragons Blood' and 'John Creech' had the highest plant cover in the with 33% and 66% ZeoPro™ H-Plus mixtures. The 100% ZeoPro™ H-Plus negatively impacted plant cover for all these species, but serves as a proof of concept of potential alternative green roof media.

Volumetric moisture content (VMC) data were collected from the modules described in the above studies over variety of dates. The overhead rotary irrigation system installed in June, 2009 delivered a more consistent amount of water throughout the green roof as measured by instantaneous VMC measurements. Less irrigation was applied in 2009 with the spray irrigation, than in 2008 with the drip irrigation system. Overall, the overhead rotary irrigation increased biomass and plant cover. Many individual plants benefitted from the switch from drip irrigation to overhead rotary irrigation, however, several *Sedum* species, i.e., *S. acre*, *S. album*, *S. lanceolatum* actually declined. *S. acre* and *S. album* had low overwintering success to begin with, while *S. lanceolatum* had lower plant cover at the end of the Mixed Plant Study in the control medium (without zeolite amendment) but significantly increased in plant cover with the 50% zeolite amendment. 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. The effects of shading, i.e., increased VMC in one section of the roof, were statistically observed in the Single Species Study but not in the Mixed Species Study due to different plant uptake rates of water under varying conditions.

In the fourth study, Moisture Deficit Study (or dry down study), eight succulent species and seven herbaceous species were dried down at different rates over a period of five months. The Moisture Deficit Study was conducted on Fort Collins campus of Colorado State University; this was a two part study with one part taking place inside a greenhouse, and the second part taking place out of doors. In this study, fifteen plant taxa were evaluated for response to gradual and long-term drying of the porous extensive green roof growing medium. Taxa evaluated were *A. cernuum*, *A. parvifolia*, *A. frigida*, *B. gracilis*, *B. dactyloides*, *C. flacca* (heath sedge), *D. cooperi*, *D. nubigenum*, *P. pinifolius*, *S. acre*, *S. album*, *S. lanceolatum*, *S. spurium* 'John Creech', *Sempervivum* 'Royal Ruby', and *T. pseudolanuginosus*. 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. These results indicate that succulent species are more likely to be longer-lived during periods of drought and 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 in the semi-arid, high elevation environment of the Front Range of Colorado during non freezing conditions; however, this minimal irrigation recommendation assumes the media be brought to field capacity at the beginning and end of intervals, either through rainfall, irrigation or combination thereof.

Due to diverse effects observed in this study due to changes in irrigation regime, varying results for species between the monoculture and mixed stand plantings, and interaction effects with zeolite amendments, future studies should look at root growth in addition to top growth of plants, especially for herbaceous species. The low overwintering success or eventual die-off of several species in the study, i.e., *S. acre*, *S. album*, *A. parvifolia*, *B. dactyloides* and *E. umbellatum aureum* and over all winter dieback of most of the observed species may be an indication desiccation of roots due to limited snow cover and winter precipitation. Plants that did survive the winter may be competitively better at obtaining water resources. An additional limited irrigation regime to prevent plant desiccation during winter months may improve some plants survival in extensive green roofs in arid regions.

Chapter 1 Introduction

Green roofs are planted for many reasons, including stormwater management, reducing the urban heat island (UHI) effect, and beautification of urban roof top landscapes. In order to maximize these benefits, the plants of the green roofs have to remain alive. In the semi-arid, high elevation environment of the Front Range of Colorado, green roofs have not been scientifically tested for long term survivability and adaptability. The low annual precipitation, short periods of snow cover, low average relative humidity, high solar radiation (due to elevation above sea level, approximately 1.6 km), high wind velocities, and predominantly sunny days all add up to challenging growing conditions for many species of plants. Therefore, plants from other environments characterized by more ideal growing conditions, i.e. high moisture, high humidity and more cloud cover, may not survive when planted in an extensive green roof.

The success of plants on an extensive green roof is primarily dependent on the particular species' ability to survive the often low moisture content of the growing media. Due to the well-drained nature of the soil-less growing media, plants capable of surviving dry, porous soils are primarily used in extensive green roof applications. Cuttings of *Sedums* are often used on extensive green roofs because of their relative tolerance to moisture deficit conditions and the fact that many are evergreen groundcovers. Although *Sedums* have dominated the plant palette for extensive green roofs, there is increased interest in expanding the plant list for extensive green roof systems. Researching additional plant species not already in use on extensive green roofs will expand the plant palette. Diversifying the plant palette of green roofs, especially with native species, will potentially open additional habitat choices for macroinvertebrates and bird species in urban areas.

The modern extensive green roof is based on a design that uses mineral aggregates such as expanded clays, shales, and slates, or pumice in the growing media. These materials provide good drainage and stability but tend to have low nutrient- and water-holding capacities. Amendments with compost can increase water holding capacity and nutrients, but can also leach nutrients. To date, region-specific research on extensive green roof growing media mixes has been limited. For example, zeolite was tested as a 10% blend to pumice and compost by weight to develop local green roof materials for New Zealand, reducing cost for transport (Fassman and Simcock, 2008). Therefore additional research on growing media mixes appropriate for use on green roofs is necessary. Similar to the need for diversifying plant species on a green roof, additional growing media amendments and mixes will benefit green roof systems as well, especially as the plant palette increases.

Colorado has several native plant species that grow in shallow, rocky, well-drained soils which may be good candidates for extensive green roof plants (Getter and Rowe, 2006). Several plant species native to Colorado along with one species of plant native to an area of South Africa with growing conditions similar to those that occur in

Colorado, *Delosperma cooperi* (hardy ice plant, trailing ice plant or pink carpet), were tested alongside other *Sedums* already on the EPA Region 8 green roof. In order to effectively select suitable plants, species need to be evaluated in terms of response to the climatic conditions and ability to adapt to the extensive green roof growing media.

Most commercially available extensive green roof growing media is predominantly made up of expanded slate, shale or clay. These lightweight, well-drained materials (but not so light that they blow away) do not break down like organic materials. However, these materials typically drain quickly (due to macro-pore space) and do not hold nutrients very well due to low cation exchange capacity (CEC). Compost has been commonly added to increase nutrient and water retention content but this is an organic amendment. The German Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) guidelines limit organic content within green roof media to reduce potential for shrinkage of the vegetation support and to limit impact to long term success of the roof (Philippi, 2011). The FLL recommends 8% (dry weight) or less organic content based on the loss on ignition method; however, recommendations for higher organic matter content have topped 15% in drier climates (Miller, 2011). As an extensive green roof matures though, organic content will drop to about 4% due to oxidation and biodegradation (Miller, 2011). The FLL (2008) guidelines also recommend a distribution of aggregate sizes for vegetation substrates.

Inorganic materials that have all of the benefits of expanded slates, shales or clays, plus have more micro-pore space and higher CEC would be ideal amendments to existing extensive green roof growing media. A potential amendment or alternative medium would be a zeolite. Zeolites are hydrated aluminosilicates of alkaline and alkaline-earth metals (Virta, 2001). There are about 40 naturally occurring zeolites and hundreds of synthetic zeolites; both naturally occurring and synthetic zeolites have widespread commercial applications because of the unique sorption, ion-exchange, molecular sieve and catalytic properties zeolites offer (Virta, 2001). Usage of naturally occurring zeolites has been increasing in horticulture, typically as a soil conditioners or growth media, though this is not currently one of the top four domestic usages of these minerals (Virta, 2009). Research with turfgrass demonstrates higher moisture contents in substrates that contain clinoptilolite (a natural zeolite) than in sand alone (Miller, 2000; Murphy et al., 2005).

Data collected through this project were used to complete the following four studies:

1. The Single Species Study determined suitability of six plant species for extensive green roof use in the semi-arid, high elevation Front Range of Colorado.
2. The Zeolite Amendment Study determined suitability of zeolite as growing media amendment for supporting plant growth in an extensive green roof system.
3. The Mixed Species Study evaluated mixed stands of trial plant species when grown in extensive green roof growing media and media with 50% zeolite amendment.
4. The Moisture Deficit Study determined the impact of moisture deficit on 15 plant species through controlled dry downs, i.e. periods without irrigation.

The research for studies 1, 2 and 3 took place on the EPA Region 8 Headquarters green roof in downtown Denver, CO. The research for Study 4 was performed on the Colorado State University (CSU) campus in Fort Collins and included eight succulent and seven herbaceous species. The plant studies 1 and 3 are presented in Chapter 4 and 5, respectively, followed by studies 2 and 4 in Chapter 6 and Chapter 8, respectively. Chapter 7 discusses the measurements of volumetric moisture content (VMC) for studies 1, 2 and 3.

Overwintering success in these experiments is of vital importance as Front Range Colorado winters are typically characterized by warm sunny days (frequently up to 15ºC [60ºF] or above) and freezing nights with high winds occurring often and unpredictable precipitation and snow cover duration. These environmental conditions are difficult for plants due to moisture limitations. Plants still require moisture during the winter to prevent winter desiccation and maintain adequate root metabolism. Drought resistance in the shallow, well-drained media of extensive green roofs is a significant factor of plant survivability. In addition, different plants use water at different rates; therefore plant water use determines the appropriateness of plants in green roof applications.

Error bars have been used in the figures. However, standard error was used in figures for plant cover analysis rather than standard of deviation. This is because error bars with standard of deviation would obscure data and general trends. Standard error was calculated by dividing the standard deviation by the square root of the number of test performed. Standard error still shows relative variance of the individual species to the various trials without obscuring data points or general trends. Standard deviation was used in the figures for VMC analysis.

Chapter 2 Conclusions and Recommendations

Conclusions

The following conclusions are based on evaluations over two consecutive growing seasons on an extensive green roof in a semi-arid, high elevation location with irrigation.

Single Species Study

In general, all six species studied increased in plant cover during 2008 for both digital image analysis data (DIA) and two-dimensional data (C2D) data sets. However, four of the five species showed temporary declines in plant cover after winter dormancy with the initiation of the second year of monitoring in May, 2009, the exception being *Opuntia fragilis* (brittle prickly pear). This reduction in plant cover is likely due to dieback due to overwintering stress; the sixth species, *Eriogonum umbellatum aureum* (Kannah Creek® buckwheat) 'Psdowns', had severe die-off and was not monitored in 2009. A similar phenomenon can be observed in the growth index graphs for species evaluated in a Michigan study, specifically, *Agastache foeniculum*, *Aster laevis*, and *Coreopsis lanceolata* (Monterusso et al., 2005). Analysis by DIA and C2D were comparable though the early bloom of *S. lanceolatum* and subsequent senescing in 2009 led to higher readings by C2D than with DIA.

On the final date of plant cover comparisons (Day 538 [9/15/2009]), the two species with the highest plant cover were *Bouteloua gracilis* (blue grama) and *D. cooperi*, with the remaining three species closely grouped in plant cover (*Antennaria parvifolia* (small-leaf pussytoes), *O. fragilis* and *Sedum lanceolatum* (lanceleaf stonecrop)). While *B. gracilis* and *D. cooperi* were more successful than *A. parvifolia*, *O. fragilis* and *S. lanceolatum* these latter species survived and resulted in a net increase in plant cover so these species should still be considered for use on extensive green roofs.

Mixed Species Study

Similar to the Single Species Study, the two species that had the highest plant cover were *D. cooperi* (3950 cm^2) and *B. gracilis* (1220 cm^2) while plant cover for all other species was much lower (> 1000 cm^2). The results for both these species were also higher in the 50% zeolite amendment, approximately 5 and 25%, respectively. Unlike the Single Species Study, *B. gracilis* showed poor overwintering in both regular media (65% loss) and 50% zeolite amendment (75% loss), possibly due to competition from the mixed stand of species. However, *E. umbellatum aureum* was much more successful than in the single species study, indicating that this species benefitted from the mixed stand planting. The 50% zeolite amendment also appeared to detrimentally affect *A. parvifolia*, which had 60% overwintering loss and 63% reduction in plant cover, and *Allium cernuum* (nodding onion), which had 25% overwintering loss and 43% reduction in plant cover. Both of these species also had less than 100 cm^2 cover. At end of the 2009 growing season, surviving plants in the zeolite had greater peak plant cover with increases of 26% for the herbaceous plants and over 36% for the succulents, with the exception of *A. cernuum*, which actually declined.

Zeolite Amendment Study

The addition of zeolite to the growing media used in an extensive green roof system potentially improved establishment year growth for *Sedum acre* (goldmoss stonecrop) at 33 and 66% mixtures and *Sedum album* (white stonecrop) at all zeolite mixtures, but hindered overwintering success, particularly at 66% and 100% zeolite for both species. The ultimate die-off of almost all *Sedums* at all levels of zeolite mixture and in the controls was most likely an indication of desiccation of the roots during winter.

Of the two cultivars of *S. spurium*, both 'John Creech' and 'Dragons Blood' had minor benefits at the 33% and 66% addition of zeolite in the first year (2008) but had greater benefits in the second year (2009). This coincided with a switch in form drip irrigation to overhead rotary irrigation. For 'John Creech' this was at all levels of zeolite, while 'Dragoons Blood' was limited to improvements in the 33% and 66% mixtures.

The addition of zeolite to extensive green roof growing media may be beneficial for some but not all species. The 100% zeolite negatively impacted over winter success of all species studied; however, this is a proof of concept that other media may be pursued for green roof applications. Competition through variation in water use by the plants in this study may have impacted the survivability of *S. acre* and *S. album.*

Volumetric Moisture Content Analysis

VMC data suggest that the overhead rotary irrigation system was more efficient than the drip irrigation at supplying uniform distribution of water. This is due to the quick, vertical draining properties of the media which does not allow for lateral water movement (except along drainage layer which may be beyond root system) and could nullify the benefits of drip irrigation if plants are not directly under the emitter.

The potential effects of shading a portion of the green roof by the upper floors of Region 8 headquarters building were observed in the Single Species Study, as volumetric moisture content (VMC) of the east side of the roof was statistically higher than other sections of the roof during the study. This effect was not observed during the Mixed Species Study. In the Single Species Study, plants would be expected to use water at the same rate, while there was greater variation in plant water uptake rates in the Mixed Species Study, due in part to varying conditions across the roof and interactions between plants.

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. Statistical analysis indicated that lower observed VMC in 33% and 66% ZeoPro™ H-Plus mixtures correlated with increased plant cover in 2009 when the overhead rotary irrigation system was in use.

Less irrigation was applied in 2009 with the overhead rotary irrigation, than in 2008 with the drip irrigation system. Year to year for the months July through September, there was 10% more rainfall in 2009, i.e., 97 mm compared to 88.1mm, but there was 32% less irrigation required, i.e., 200 mm compared to 270 mm.

O. fragilis , a cactus, consistently had higher VMC than other species and plant cover consistently increased after two seasons. It would appear that irrigation and rainfall rates were more than this species required.

Moisture Deficit Study

While there was no clear division between succulent and herbaceous species in dry down curves, there were differences among species within plant types. Additionally, relative water use during the 18 day dry down was inconsistent within plant type. However, the general trend was that the growing medium planted with succulent species retained more moisture for a longer period of time than did the growing medium planted with the herbaceous species.

Dieback and revival rates differed by plant type as well. The succulent plant species 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 more resistant to drought stress at the onset of extended periods of insufficient moisture in planting medium, but they have a better chance of recovering after a drought once water is again made available.

Irrigation frequency recommendations for extensive green roof culture in the high elevation environment of the Front Range of Colorado varies by plant type; succulent species should be irrigated at least every 28 days while herbaceous species should be irrigated at least every 14 day intervals (more frequently for species with high water use requirements). Irrigation frequency will need to increase if the duration of an irrigation event supplies an insufficient amount of water to satisfy a species water use requirements, i.e., irrigation, rainfall event or combination thereof is below field capacity of the media.

Implications

After the initial year of this study, it became obvious that the drip irrigation system was not suitable for supplying the water needs of the *Sedum* plants growing in an extensive green roof in a semi-arid, high elevation environment due to the well-drained nature of the growing medium. *Sedums* are shallow rooted plants that can be started on roofs by planting individual plugs or by spreading cuttings out over the roof. Only a small cone of moisture developed around the emitters of the drip irrigation system which were spaced approximately 30 cm (1 ft) apart. The overhead rotary irrigation system provided more uniform coverage of water over the area than did the drip irrigation. The implication is that overhead rotary irrigation overall increased plant cover, partly by allowing *Sedums* to spread across roof because more uniform moisture was available.

For the Zeolite Amendment Study, complications from overwintering i.e., cold temperatures, lack of rainfall and absence of irrigation, affected the species *S. acre* and *S. album*, and to a lesser extent the *S. spurium* cultivars. While many factors could influence overwintering in the amended green roof growing media, it is clear that having a portion of zeolite in the growing media improved plant cover for some of the species but did not improve plant cover in for all species monitored. Winter irrigation may be required for some plants if there is lack or rainfall or snow cover to prevent desiccation of roots.

For the Moisture Deficit Study (dry down study), rates of growing media dry down over the initial 18 day period were variable by species for both the herbaceous and succulent groups. However, the days to dieback and revival after rewatering show clear differences in the two groups of plants with succulents taking over five times longer to dieback and almost twice as successful at recovering compared to the herbaceous species.

Recommendations for Further Study

Each of these studies could have follow-up research. For example, dozens of species could be evaluated similar to the Single Species Study. Additional growing media blends incorporating zeolite at finer scales, i.e. at 5% increments to approximately 65%, or different amendments could be investigated to determine if these blends improve the moisture-holding and nutrient-holding capacity of green roof growing media. Irrigation frequencies for additional species grown in an extensive green roof system could also be evaluated. As zeolite amendments appear to benefit some plant species while not improving or even hindering others, further studies of species specific reactions to zeolite amendment are required, particularly as it pertains to overwintering success or loss. Also, studies of zeolite amendments as it applies to a mixture of plantings, which is the typical practice in green roof applications, are necessary.

For the Single Species Study, 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 survived the low moisture conditions of semi-arid region with annual average precipitation less than 400 mm. Other conditions of the Front Range including high solar radiance, high wind velocities and high number of sunny days contribute to high evapotranspiration rates and a need to irrigate the plants in this environment. The calculated evapotranspiration reference rate (ET_0) was approximately 960 mm for the period between March and October, 2009, while total rainfall and irrigation for this period was 660 mm. The species evaluated in this study can be recommended for more widespread use on extensive green roofs in regions with less overall harsh conditions, and correspondingly lower ET_0. The succulent species should be tested for non-irrigated roofs in areas with annual growing season precipitation exceeding 500 mm which corresponds to approximately half the observed ET_0 during months for which ET_0 could be calculated in this study.

The low overwintering success or eventual die-off of several species in the study, i.e., *S. acre*, *S. album*, *A. parvifolia*, *B. dactyloides* and *E. umbellatum aureum* may be an indication desiccation of roots due to limited snow cover and rainfall during the winter. Measurement of moisture content and development of a limited irrigation regime to prevent desiccation during winter months may improve plant survival in green roofs in arid regions or areas of limited snow cover.

Due to the observations that plant success in the Single Species Study and Mixed Species Study varied by species, with either adverse and beneficial interactions most likely due to differing water usage rates by the species observed, additional studies of both individual plants and mixed plantings is warranted. A similar recommendation was made recently by Cook-Patton and Bauerle (2012). Tracking mixed plant species studies may identify species that mutually benefit survivability and plant growth and may yield other benefits like increased runoff uptake or cooler roofs. The potential for increased stormwater control due a mixed stand planting was observed by Lundholm et al. (2010) as well cooler temperatures in the substrate.

Additional analysis of plant biomass may be warranted. *Sedums* have shallow rooted systems which would seem more well suited for overhead rotary irrigation while some herbaceous species have tap roots which might benefit from drip irrigation if the emitter is placed next to plant. Assessing root mass in addition to top growth may provide further insight into choosing the right irrigation system for the individual type of plants, especially herbaceous plants which have more extensive root systems than succulents.

Chapter 3 Materials and Methods

Environmental Conditions of Study Sites

Environmental conditions were monitored at five minute intervals on the EPA Region 8 green roof in Denver, Colorado (studies 1-3) by use of Campbell Scientific weather monitoring equipment (Table 3-1). The dry down characteristics of extensive green roof growing media and the impact of dry down on plant species (study 4) were evaluated in greenhouse and outdoor trials at the CSU campus in Fort Collins, CO. Environmental conditions were monitored in Fort Collins by HOBO weather monitoring equipment at 15 minute intervals (Table 3-2).

Table 3-1: Weather Monitoring Equipment on the EPA Region 8 Green Roof

Campbell Scientific Equipment (Model #)	Description	Range of Tolerance
Infrared Radiometer (IRR-P)	Surface temperature of vegetation	-55º to +80ºC
Temperature and Relative Humidity Probe (HMP45C)	Measures temperature and relative humidity at 0.3 m (1 ft) height	-40º to +60ºC
Young Wind Sentry set (03001-L)	Wind speed and direction at 1 m (3 ft) height	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
Silicon Pyranometer (LI200X)	Solar radiation sensor	-40° to +65°C
Datalogger (CR1000)	Data storage device	

Table 3-2: Weather Monitoring Equipment at the Fort Collins, CO Research Location.

Onset/Apogee (Model #)	Description	Range of Tolerance
HOBO® Temperature and Relative Humidity Probe (U12)	Measures temperature and RH	-20º to +70ºC
Apogee Precision Pyranometer (SP-110)	Solar radiation sensor	-40º to +55ºC
HOBO® Datalogger (U12-013)	Data storage device	

For studies 1, 2 and 3, after determining which plants survived, plant area data (plant cover) measurements were taken over time to determine success. Digital images were taken throughout the growing season to determine growth rate by measuring change in plant cover over time. Whenever digital images were taken, two plant widths and plant height were also recorded in cm. Growing media VMC data were collected to determine relative water use of plants for all three studies. At the end of the experiments, study 1 plants were harvested so that top growth or above ground biomass could be determined for each plant.

Figure 3-1 shows the layout of individual plants for studies 1-3. A label was pasted on one end of each module and all modules were oriented the same direction. Figure 3-2 shows the layout of modules in blocks for studies 1-3.

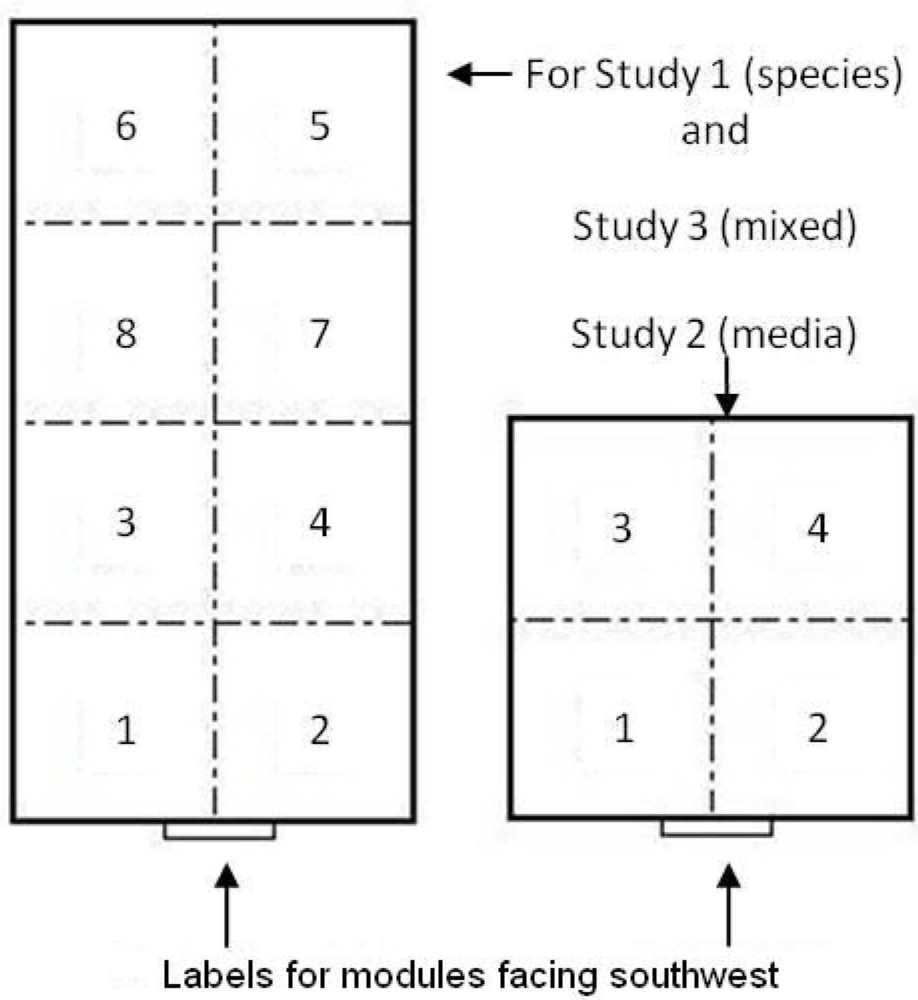


Figure 3-1 Layout of plants in individual modules for studies 1, 2 and 3.

Plant Cover by Digital Images

As a measure of plant growth rate and success, plant cover (cm^2) digital images were taken every two weeks. The data was analyzed by DIA and presented for four dates (at 6-week intervals) in the growing season of 2008 and 2009 as results were most demonstrative at these intervals (the same intervals were used for studies 2 and 3 and C2D). A Fuji Film S3000 3.2 mega pixel camera with a six times optical zoom lens was mounted to a Bogen Manfrotto 190xprob tripod (Ramsey, NJ) with an extendable horizontal arm. A plum bob was used to ensure that all photos are taken from a preset distance, and a bubble level on the back of the camera ensured the photo orientation was consistent for every picture. The same camera and image settings were used to keep constant any differences these factors could make in image quality.

The digital images were analyzed using SigmaScan Pro 5.0 image analysis software (SPAA Science, Chicago, IL). This image analysis was used to draw outlines for each plant in each digital image. Durham et al. (2007) successfully used this method in their trials to measure growth rates of green roof species.

Figure 3-2 Initial layout of blocks for studies 1, 2 and 3.

Plant Cover by Converted Two-dimensionsal

Concurrent to the DIA, individual plant widths were measured four times in the growing season in of 2008 and 2009 for each of the three studies. Two widths, one parallel to the short end of the module (0.61 m [2 ft]) and the other was perpendicular to it, were measured using a ruler down to 1 mm to achieve C2D.

Biomass

All above growing media portions of each plant in study 1 were harvested at the end of the experiment. Root weights were not measured because neighboring plant roots grew together and would be difficult to separate. Plants were cut at growing media level, rinsed in water to remove growing media debris, patted dry with a paper towel and fresh weight mass was recorded. Samples were inserted into a pre-labeled 13 x 8 x 27 cm (5 x 3 x 10 in.)

brown paper bag (Rite Aid, Harrisburg, PA) to allow air and water movement through the paper. The samples were dried in an oven at 70ºC for 72 hr and weighed for biomass.

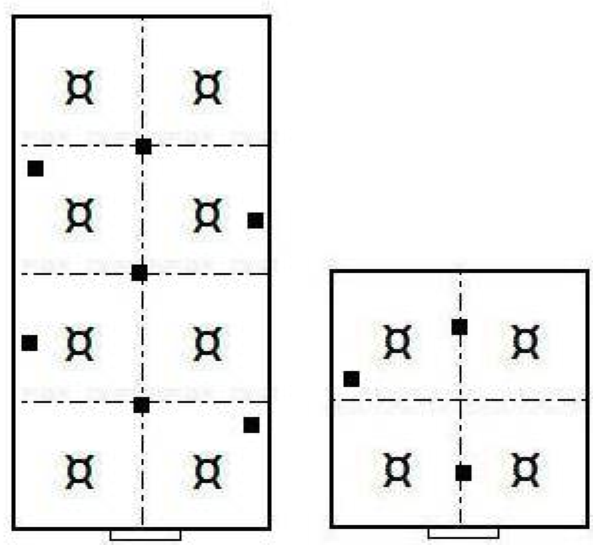
Growing Media Volumetric Moisture Content

The commercially available extensive green roof growing media is a proprietary blend created for use in the GreenGrid® product line. The mix is 80% inorganic and 20% organic materials by volume. Growing media physical properties were analyzed by Hummel & Co, Inc. Laboratory in Trumansburg, NY, USA. All physical properties were tested per American Society for Testing and Materials (ASTM) E2399. Analytical methods included organic matter (ASTM F1647, method 1, loss on ignition), dry density, particle density (ASTM D5550), saturated hydraulic conductivity (permeability), total porosity, and air and water filled porosity at maximum water capacity and field capacity.

A Delta-T ThetaProbe ML2X (Delta-T Devices, Cambridge, UK) was used to take instantaneous readings of growing medium VMC. ThetaProbe devices were previously used successfully in extensive green roof research (Monterusso et al., 2005; VanWoert et al., 2005; Durhman et al., 2006). Accuracy of the ThetaProbe is ±0.01 m^3/m^3 in 0 - 40ºC. The sensor is factory calibrated after manufacturing and prior to the sensor being sealed. Accuracy was tested at least once per month by dipping the probe in a cup of water and getting a reading of 100% VMC. The probe was inserted into the growing medium to a depth equal to the length of the probe (5 cm) and at least 1 cm from the edge of the container; VMC readings appeared instantly on the analogue output screen of the attached handheld meter and readings were written down on a data sheet. While there are standard gravimetric procedures for determining VMC, there is no standard published method for calibrating the sensor beyond factory. A correction curve for a particular media could be derived by developing ThetaProbe response to gravimetrically tested VMC; however, this does not account for individual species plant roots. The advantage of using the probe is the non-destructive means of testing. As such however, the VMC data presented here are to be considered relative and not absolute VMC.

For studies 1 (determination of suitability of plant species for extensive green roof use in the semi-arid, high elevation Front Range of Colorado), 3 (evaluation of trial plant species when grown in mixed stands modified extensive green roof growing media), and 2 (determination of suitability of zeolite amendments for supporting plant growth when grown in an extensive green roof system), growing media measurements of VMC were analyzed at the beginning, middle and end of September in 2008 and 2009. Additionally, VMC was analyzed for concurrent plant cover measurements for the Zeolite Amendment Study.

Figure 3-3 shows an example of media moisture measurement locations for the two different module sizes. Each plant studied was centered on a 93 cm^2 (1.0 ft^2) square represented the module edges and the dotted lines. Seven total measurements (represented by the black squares) per measurement date were taken in the 61 x 122 cm (2 x 4 ft) modules for studies 1 and 3 and three total measurements (again, represented by the black squares) were taken in each of the 61 x 61 cm (2 x 2 ft) modules for study 2. For the larger modules, three measurements were taken down the center of the module and two on each side of the module to get an even distribution of growing media moisture within the module. Similarly, two measurements were taken down the center and one on the side of the smaller modules.



Black squares represent sampling locations

Circular symbols represent single plantings

Figure 3-3 Examples of planting and volumetric moisture content sampling locations.

For Study 4 (determination of dry down characteristics of extensive green roof growing media and the impact of dry down on plant species), growing media VMC was recorded daily for each plant using the ThetaProbe. Values were collected daily until they remained constant. Relative water use for each species was estimated from VMC data by subtracting the growing media VMC of the non-vegetated control for each day. For the outdoor study, a rainproof cover was used during threats of rain.

Analytical Methods

The digital image data was analyzed using Sigma Scan Pro 5.0 image analysis software (SPAA Science, Chicago, IL). This program measures growth rates by analyzing predetermined ranges of pixel colors on digital images.

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. Means, standard deviations, standard errors and correlations between C2D and DIA data sets, as well as between DIA and biomass and C2D and biomass data sets, were determined in Excel (Microsoft Office Excel, 2007).

Statisca (StatSoft, Inc. 2003, version 6) was used for statistical analysis and graph development in Chapter 7. Factorial multivariate and univariate analysis of variance (MANOVA, StatSoft, Inc. 2003, version 6) were used to test for effects of independent variables VMC and total irrigation (rainfall and irrigation) versus categorical variables. Follow up univariate factorial ANOVAs were used to further probe any significant multivariate effects. Statistical significance was fixed at $p < 0.05$.

Chapter 4 Single Species Study

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 succeed on extensive green roofs has revealed that succulents, predominantly *Sedum* taxa, out-perform most non-succulents (Monterusso et al., 2005; Rowe et al., 2006; Durhman et al., 2007). 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 suited for use in extensive green roof systems (Getter and Rowe, 2006). With the exception of *D. cooperi*, five of the six species used in this study are native to the western United States in general and Colorado in particular (Table 4-1).

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. Manually measured plant growth indices are frequently used as a measure of plant performance. Typically, measurements of plant diameters are used to estimate plant cover. The current research converts two plant diameters into the area of a circle to estimate plant cover (C2D). DIA is another method used for quantification of plant area which requires periodic photographing of plants and then digitally analyzing the images to quantify plant cover. DIA can also be used to estimate or validate biomass accumulation in plants.

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 six species in the study (Table 4-1), approximate plant cover was obtained by manually measuring diameters of each plant and then converting those diameters into approximate plant cover (C2D). In addition, digital images of these same plants were taken periodically throughout the growing season; these images were then digitally analyzed to quantify plant cover (DIA). The DIA data were compared to the C2D data.

The specific objectives of the research for the Single Species Study 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
4. determine the correlation between C2D and plant biomass.

In this study, a treatment was one of six species (Table 4-1). A series of modules, each containing one of the six species per module, were placed into one of five blocks. Thus a total of six species, each replicated in five blocks resulted in 30 modules. In each module, eight individual plants were planted, each with 93 cm^2 (1.0 ft^2) of growing space. See Chapter 3 for greater details on the materials and methods and layout of the modules (Figure 3-2).

Table 4-1: Plant Species Evaluated in the Single Species Study

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

Results

Every individual plant of each of the six species (n=240) survived the 2008 growing season. During the 2008-2009 season four of the six species had 100% survival rate. *A. parvifolia*, which had a 65% survival rate for the first measurement on May 13, 2009, was included in the data analysis. However, *E. umbellatum aureum* 'Psdowns', which had only a 12.5% survival 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 (March 26, 2008), and Day 49 being the first date of comparison (May 14, 2008). Table 4-2 contains the days of data collection during the study and their corresponding calendar dates. Table 4-3 contains weather data during the period of study.

Table 4-2 Days of Study and Corresponding Calendar Dates

Day of study	Calendar date
49	May 14, 2008
91	June 25, 2008
133	August 6, 2008
174	September 16, 2008
413	May 13, 2009
455	June 24, 2009
497	August 5, 2009
538	September 15, 2009

Table 4-3 indicates that there was only 550.6 mm (21.68 in.) of rainfall from July, 2008 through October, 2009. Average monthly rainfall was 34.5 mm (1.36 in). From November, 2008 through January, 2009, there was less than 10 mm (0.4 in) per month this sustained period amounted to 25.7 mm (1.0 in). Limited precipitation and cold temperatures may have led to overwintering stress of the plants, especially the herbaceous plants, i.e., *A. parvifolia* and *E. umbellatum aureum*. On January 5, 2009, ambient temperatures dropped below -10 C° and temperatures at the green roof membrane dropped to -5 C°, implying frozen temperatures existed throughout the root zone. During growing season, roughly mid-April through mid October, only May through September had non-freezing temperatures. The green roof plants were supplemented with irrigation; this irrigation system is turned off during winter to prevent breakage due to freezing. Parts of the irrigation system were damaged in the 2008/2009 winter leading to replacement of the irrigation system in June, 2009. Rainfall in March, 2009 was half that of ET_0, while

April, 2009 exceeded ET_0 (see Table 7-1). Though rainfall rates may not have been sufficient through May, which was less than ½ ET_0, overwintering stress appears to be the main cause for loss of the herbaceous species. As the first measurement for 2009 was May 13, 2009, an earlier assessment of plant survivability may have more clearly demonstrated that it was due to over winter stress and not due to lack of rainfall at the start of the growing season or problems with the irrigation system.

Table 4-3 Weather Data from Region 8 Green Roof

Year	Month	Temperature (C°)			Relative humidity (%)		Mean daily solar radiation (MJ/m^2-d)	Mean wind speed (m/s)	Total rainfall (mm)
		Mean maximum daily	Mean minimum daily	Mean daily	Mean maximum daily	Mean minimum daily			
2008	June	30.5	14.2	22.3	59.6	16.2	25.82	1.58	16.4[1]
	July	35.7	19.2	27.4	55.2	14.6	24.14	1.44	4.3
	August	31.6	16.7	24.2	71.7	24.8	19.90	1.21	55.6
	September	26.5	11.3	18.9	73.5	26.0	16.94	1.12	28.2
	October	21.3	5.8	13.5	72.3	24.6	12.58	1.20	17.5
	November	16.8	1.9	9.3	69.6	23.0	8.70	1.39	6.9
	December	9.4	-5.9	1.8	78.3	28.2	7.71	1.35	8.89
2009	January	12.7	-2.1	5.3	63.5	23.2	7.90	1.78	9.91
	February	14.4	-0.8	6.8	67.6	17.5	8.16	1.78	15.7
	March	17.2	0.9	9.0	59.5	15.7	9.21	1.80	44.2
	April	17.1	3.0	10.0	79.7	31.4	16.6	1.46	108.2
	May	24.7	10.7	17.7	73.3	26.4	20.67	1.40	53.6
	June	28.3	13.5	20.9	80.7	26.9	21.77	1.16	55.4
	July	31.8	16.3	24.1	82.4	25.8	22.18	1.21	60.2
	August	32.0	15.9	23.9	73.9	20.4	20.8	1.23	20.8
	September	27.6	11.8	19.7	76.7	22.5	16.58	1.27	16.0
	October	15.2	1.8	8.5	84.4	36.6	10.95	1.36	45.2

[1] National Weather Service station (ID: 052223) at Denver Water (1600 W. 12th Avenue, Denver, CO) collected 2.6 km away from Region 8 green roof.

All species increased in plant cover during the 2008 growing season with *D. cooperi* and *B. gracilis* being the largest in size at the end of both the first and second seasons. *O. fragilis* had the lowest plant cover at the end of 2008 but steadily increased through most of 2009. The remaining four species all exhibited temporary declines in plant cover during the first measurement of the 2009 growing season. This appeared to be due to overwintering stress, which is illustrated by *D. cooperi* in Figure 4-1. Plant cover by DIA and C2D over the period of study is shown in Figure 4-2 and Figure 4-3, respectively. The mean and error bars were calculated based on the surviving plants (error bars represent standard error).

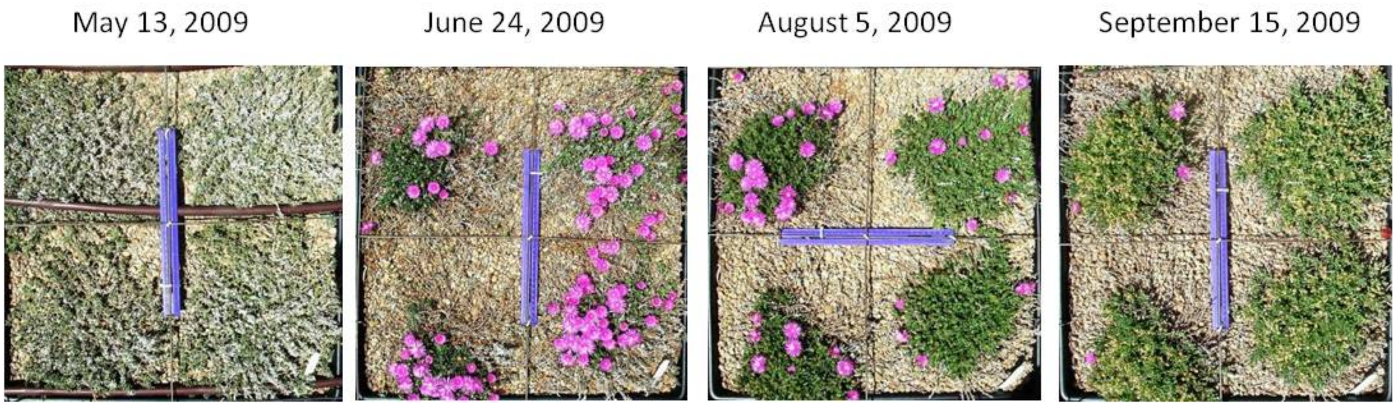


Figure 4-1: Example of 2009 recovery as series of the same four *D. cooperi* plants on Days 413, 455, 497 and 538.

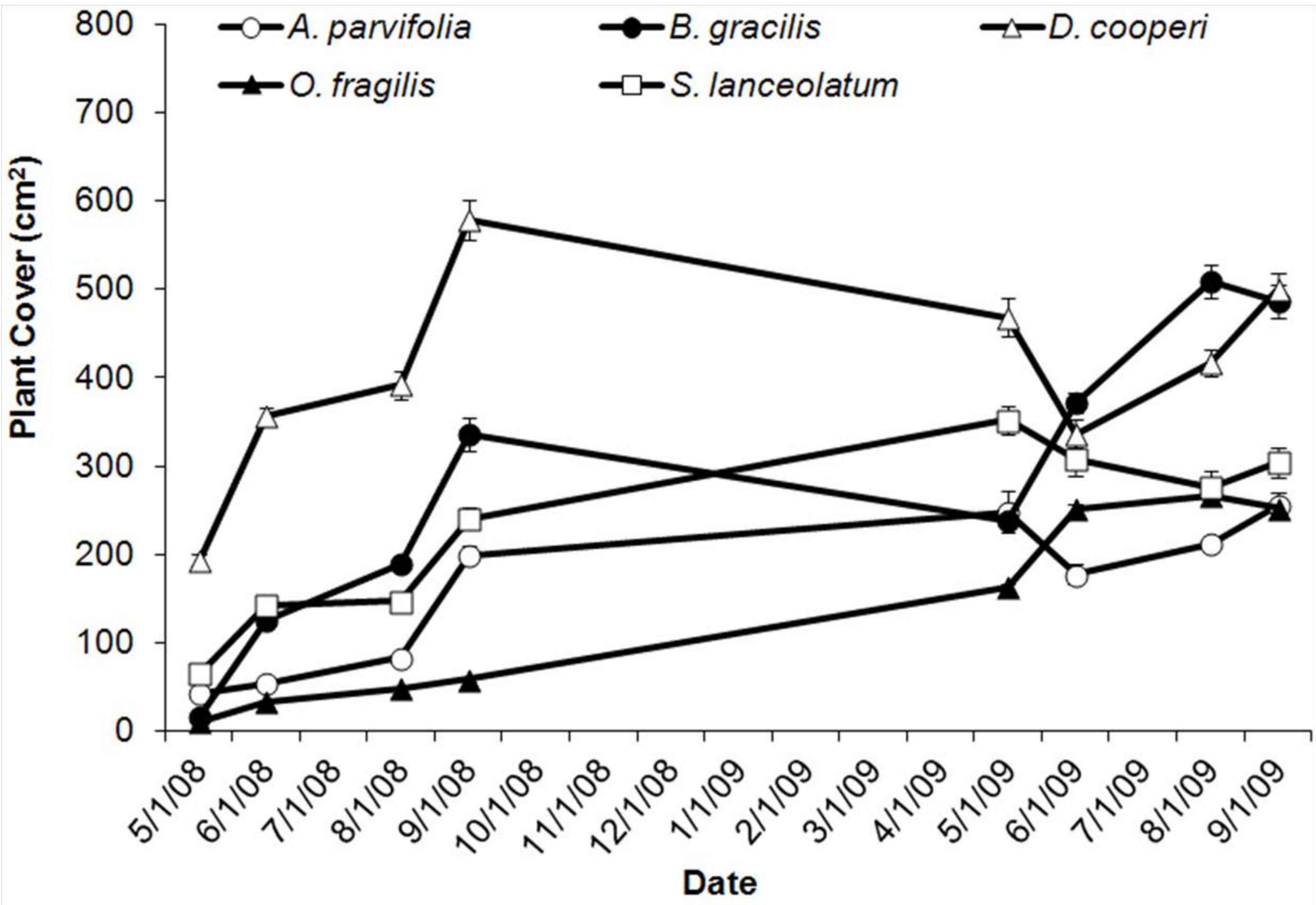


Figure 4-2 Plant cover determined by DIA analysis for the five experimental species over period of study.

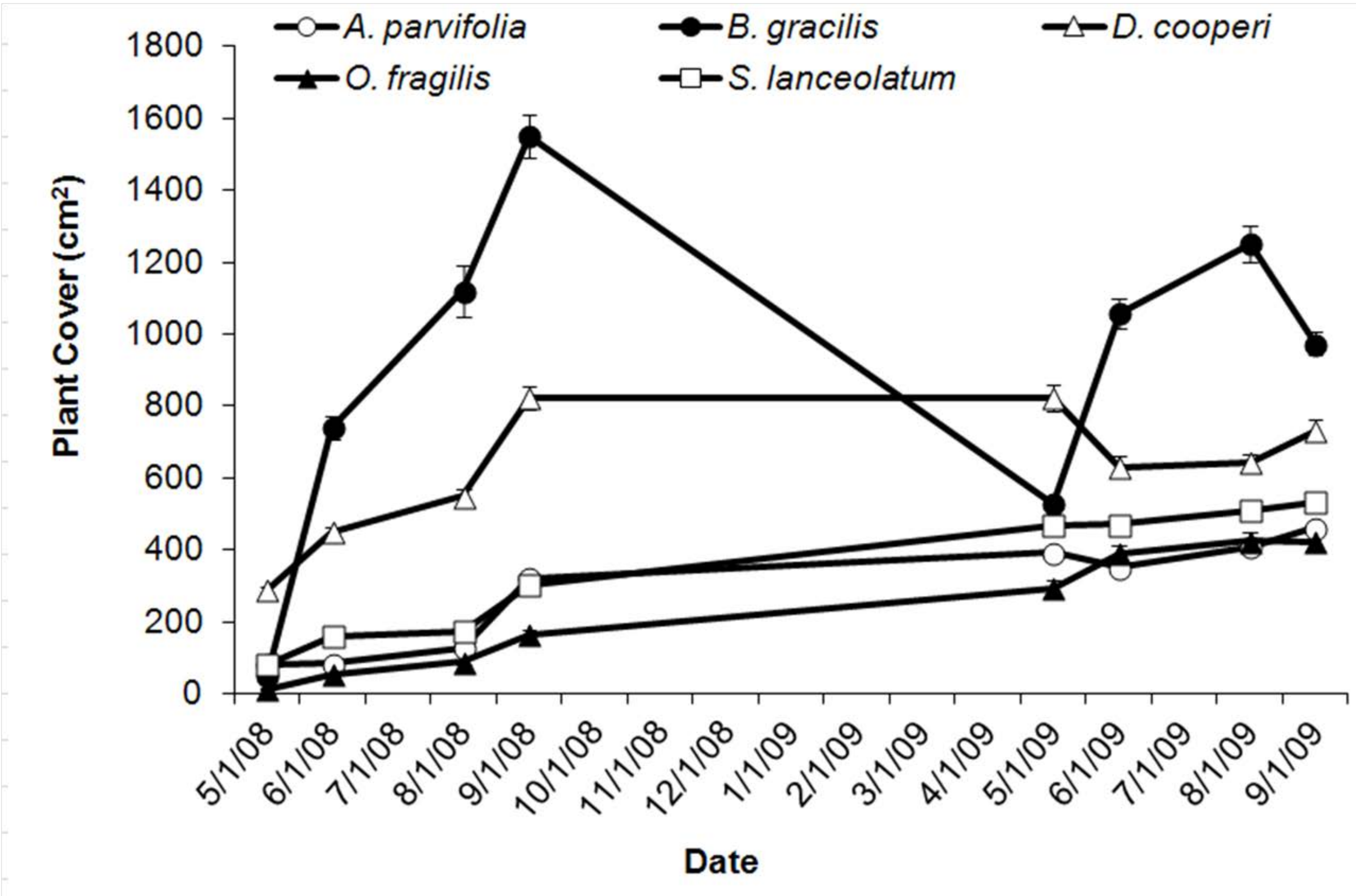


Figure 4-3 Plant cover determined by C2D analysis for the five experimental species over period of study.

For comparative purposes of the two plant cover methods used, DIA data over the eight consecutive evaluation dates are shown in Figure 4-4 and the C2D data are represented in Figure 4-5 (error bars represent standard error and vertical bar indicates separation in years). While the data shown in both figures show similar trends in plant cover, there are a few key differences. For example, with *B. gracilis*, there are large differences in scale between Figure 4-4 and Figure 4-5. This difference 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 quantify only plant cover (green pixels) visible from above while C2D data assume that all of the area within the measured diameters is plant cover.

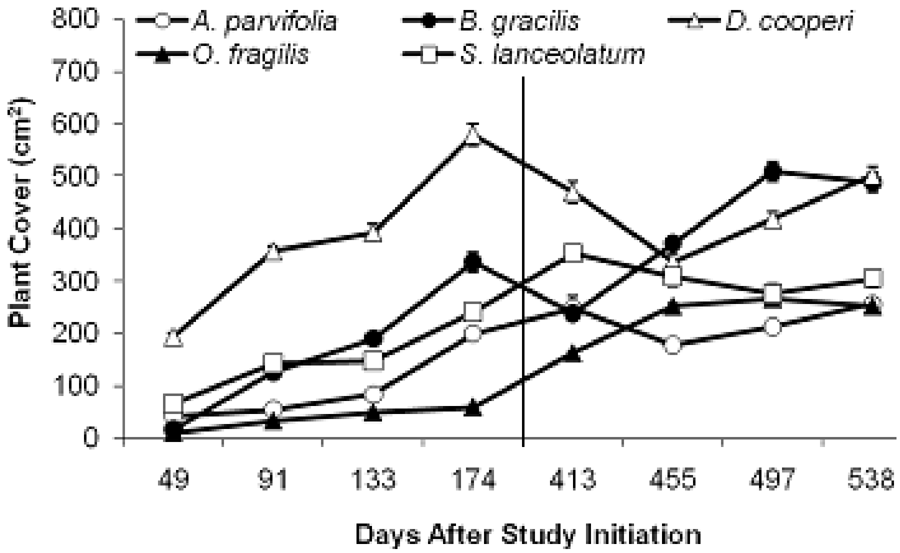


Figure 4-4 Plant cover determined by DIA analysis for the five experimental species for eight measurements.

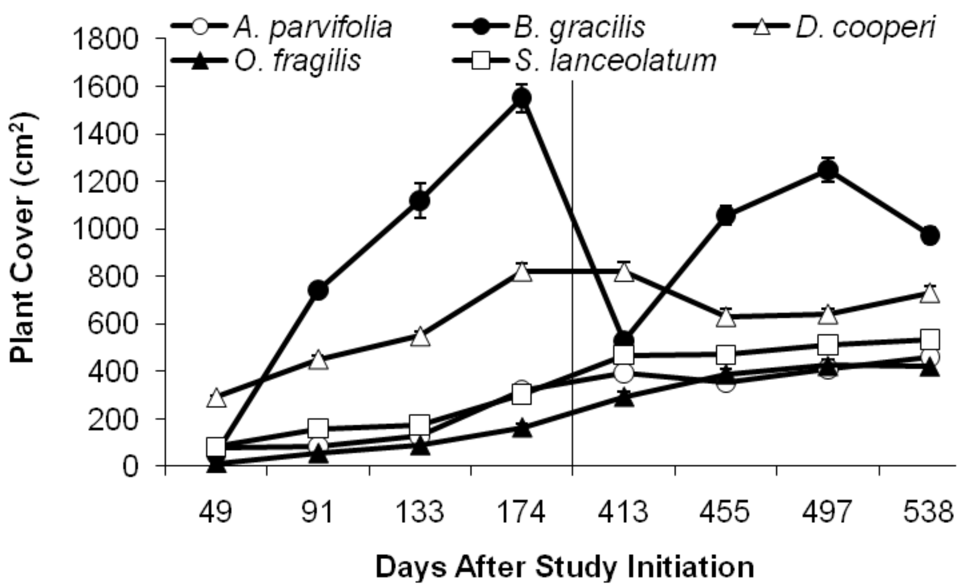


Figure 4-5: Plant cover determined by C2D analysis for the five experimental species eight measurements.

Comparison between Trials

Recovery of many of the species after winter dormancy yielded irregular regrowth patterns (Figure 4-1 and Figure 4-6). Since C2D data measure plant diameters at the widest points of the plant axes, areas of dieback within those diameters are included in the analysis, giving an overestimation of actual plant cover. Therefore, most discrepancies between the DIA and C2D data sets could be attributed to overestimation of plant cover by the C2D measurements. Figure 4-6 shows the following examples of irregular growth patterns: 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-bloom center dieback. Figure 4-7 shows results of correlation analysis between DIA and C2D.

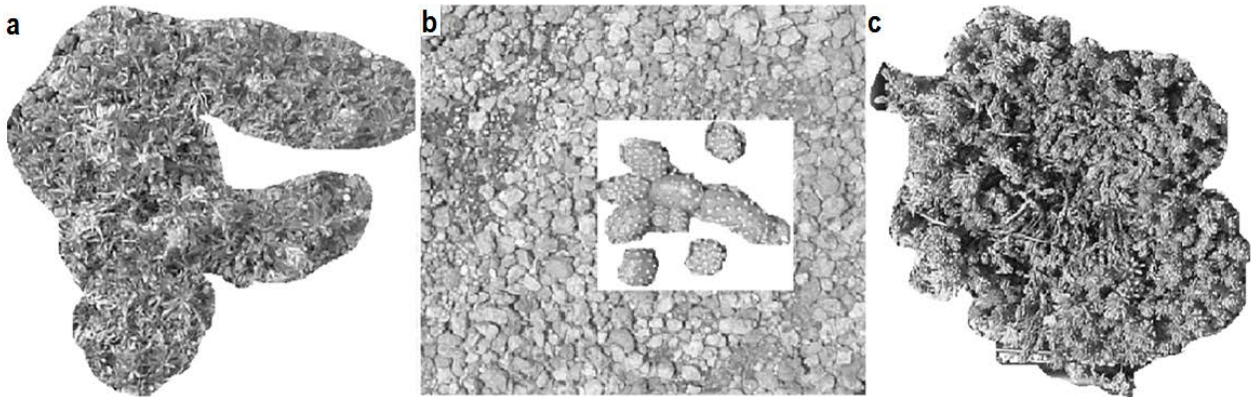


Figure 4-6: Three examples of regrowth patterns.

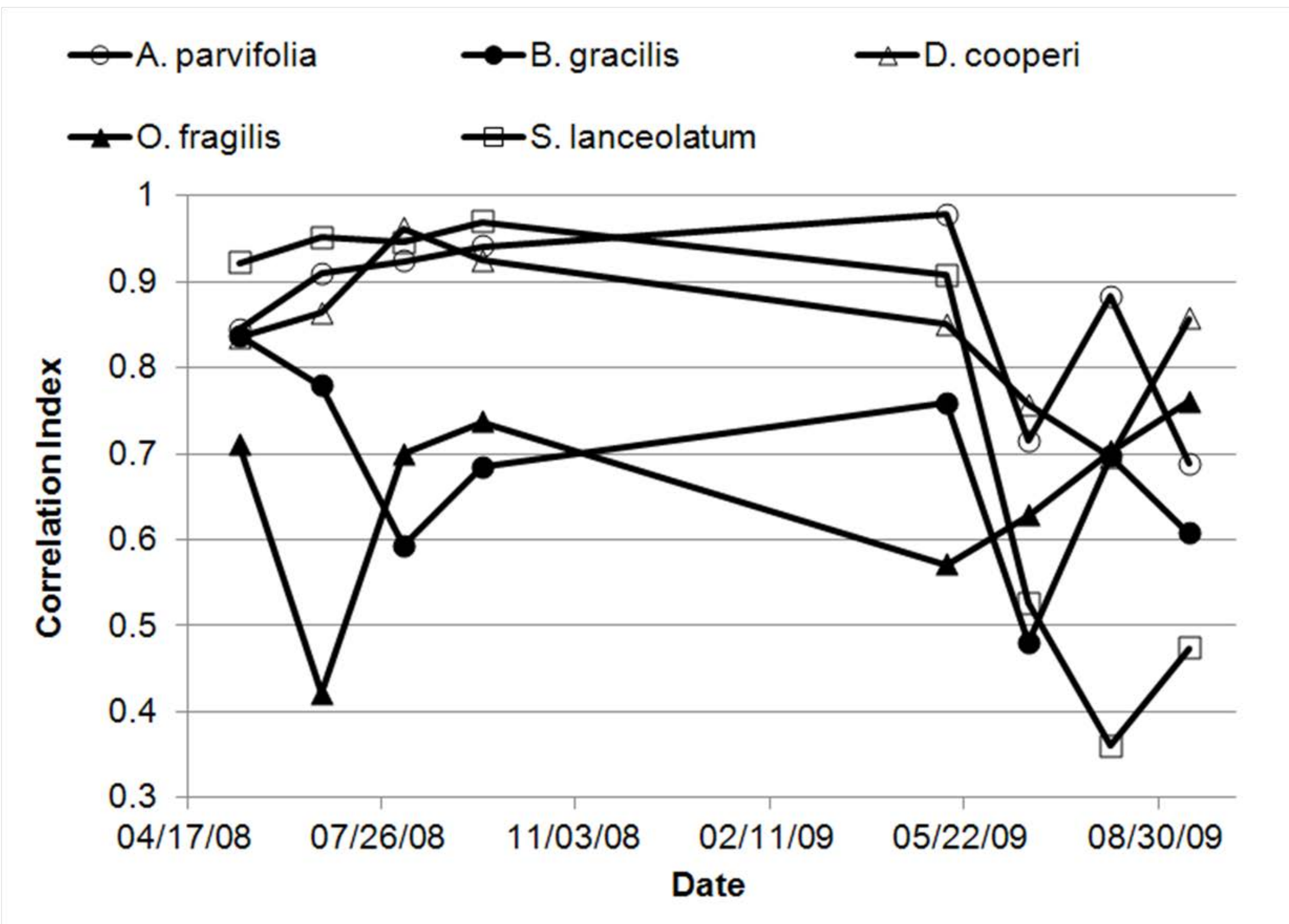


Figure 4-7 Correlation analysis between DIA and C2D plant cover methods.

Both *A. parvifolia* and *D. cooperi* showed continued decline on 6/24/09 (Day 455) relative to 5/13/09 (Day 411). Partly this is overwintering stress, as one would expect increase growth with beginning of growing season. As the irrigation system was damaged in the winter and replaced mid June, 2009, these declines may also be partly attributable to decreased efficiency of the existing irrigation system, however, there was sufficient rainfall in April, 2009 and irrigation with the new system was started immediately after completion of the installation.

On 06/25/08, Day 91, each *O. fragilis* plant in two of the five blocks had pads removed by extension cords that were dragged over the plants. All of the pads that were removed from the parent cactus were replanted near the parent plant. The measurements of those plants on Day 91 potentially yielded superficially larger results (69% for DIA and 77% for C2D) than they would have if the entire plant were intact (b in Figure 4-6). 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. Rooting and regrowth occurred rapidly but may have also increased assessment of overwintering success (64% and 44%, respectively) as multiples plants were being measured, rather than initial plantings. Note also the low correlation value for *O. fragilis* for Day 91 (6/25/08) in Figure 4-7.

In 2009, bloom on *S. lanceolatum* occurred early in the season in three of the five blocks and after the inflorescence senesced (prior to 6/24/09, Day 455), the center of each plant died out leaving an irregular circular area of green around the perimeter of the plant (c in Figure 4-6). Therefore the C2D measurements showed the plant to be much larger than what the DIA quantified, hence the reduced correlation values for 2009 as shown in Figure 4-7.

Biomass Accumulation

Biomass accumulation from harvested plants (Table 4-4) was correlated with the last date of DIA and C2D to evaluate how well plant cover corresponded with individual plant biomass accumulation (Table 4-5). Correlations between DIA and biomass, and C2D and biomass, on final date of DIA and C2D data collection (Day 538 [9/15/ 09]) for the five species (n = 40 except *A. parvifolia* where n = 26). 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 for DIA and 0.18 for C2D); 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 by either plant cover analysis (r = 0.64 for DIA and 0.19 for C2D). In general, DIA had higher correlations to biomass than did C2D.

Table 4-4 Biomass Accumulation by Species

Species	Wet biomass (g)	Dry biomass (g)	Water content (%)
A. parvifolia	39.2	14.7	61.1
B. gracilis	54.0	35.3	33.1
D. cooperi	258.9	42.3	83.5
O. fragilis	522.7	148.4	72.1
S. lanceolatum	181.1	46.0	75.1

Table 4-5 Final Correlations between Plant Cover Analysis Methods and Dry Biomass

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

Conclusions

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 was observed by Monterusso et al. (2005) in the growth index graphs for *Agastache foeniculum*, *Aster laevis*, *Coreopsis lanceolata* and several other species.

On the final date of plant cover comparisons (Day 538 [9/15/09]), the two species with the highest plant cover were *B. gracilis* and *D. cooperi*, with the remaining three species (*A. parvifolia*, *O. fragilis* and *S. lanceolatum*) closely grouped in plant cover. *O. fragilis* had the highest biomass accumulation after two seasons. Based on evaluations over the two consecutive growing seasons, *B. gracilis* and *D. cooperi* were more successful than *A. parvifolia*, *O. fragilis* and *S. lanceolatum*, but all of these species resulted in a net increase in plant cover.

Using DIA to evaluate plant cover and biomass accumulation is especially appropriate for groundcover species (Bousselot et al., 2010).

Chapter 5 Mixed Species Study

Introduction

The Mixed Species Study was set up like the Single Species Study (Chapter 4) except eight different species (Table 5-1) were planted together in each of ten 61 x 122 x 10 cm (2 x 4 x 1/3 ft) modules. One of each species was planted in the modules and plantings were evenly spaced (see Figure 3-3). Five of the modules were planted with the existing green roof growing media (GreenGrid®) and the other five were planted with a 50% by volume zeolite (ZeoPro™ H-Plus) mixed in with the existing growing media. Incorporating zeolite as an amendment was intended to improve the moisture-holding and nutrient-holding capacity of the green roof growing media. One module of each growing media type was placed in each of the five blocks (see Figure 3-2). Similar data as in the previous study was collected.

Table 5-1: Plant Species in the Mixed Species Study

Scientific name	Common name
Allium cernuum	nodding onion
Antennaria parvifolia	small-leaf pussytoes
Bouteloua gracilis	blue grama
Delosperma cooperi	hardy ice plant
Eriogonum umbellatum aureum	Kannah Creek® buckwheat
Opuntia fragilis	brittle pricklypear
Sedum lanceolatum	lanceleaf stonecrop
Sempervivum 'Royal Ruby'	hens and chicks, houseleek

Results

All plants of all species in both growing media treatments survived the 2008 growing season with an exception of one *A. cernuum* plant lost to bird predation. The overwintering success of all remaining plants is documented in Table 5-2 and Table 5-3. In general, Table 5-2 indicates winter survival in the 50% zeolite amendment modules was similar or lower than in the existing growing media modules for each species. Table 5-3 indicates that when herbaceous plants did survive, plant cover (as measured by C2D) of these species was less in the zeolite amended modules. Similar to the Single Species Study (study 1), the two species with the lowest overwintering rates were *A. parvifolia* and *E. umbellatum*. Unlike the Single Species Study where *B. gracilis* had 100% survival, in this study *B. gracilis* showed reduced overwintering survival, just 60% in both media treatments, possibly due to competition from the mixed stand of species. Over winter, succulents increased in plant cover, as there is a slight increase in plant cover for the GreenGrid® media over the 50% zeolite amended media, 44% compared to 36%, though results varied per species. *O. fragilis* and *Sempervivum* 'Royal Ruby' had higher plant cover in the 50% zeolite amendment; the 50% zeolite amendment reduced (60% compared to 100%) the survivorship of *D. cooperi*. Though not as robust, as in the Single Species Study *O. fragilis* increased in plant cover over the winter (Table 5-3).

Table 5-2: Overwintering Results for the Mixed Species Study Evaluated on Day 413 (May 13, 2009)

Species	No amendment	50% zeolite amendment
Allium cernuum	100%	75%
Antennaria parvifolia	40%	40%
Bouteloua gracilis	60%	60%
Eriogonum umbellatum aureum	60%	40%
Herbaceous Mean	65%	54%
Delosperma cooperi	100%	60%
Opuntia fragilis	100%	100%
Sedum lanceolatum	100%	100%
Sempervivum 'Royal Ruby'	100%	100%
Succulent Mean	100%	90%

Table 5-3: Change in Percent Plant Cover for the Mixed Species Study from September 19, 2008 to May 13, 2009

Species	No amendment	50% zeolite amendment
Allium cernuum	25%	- 43%
Antennaria parvifolia	10%	- 63%
Bouteloua gracilis	- 66%	- 75%
Eriogonum umbellatum aureum	64%	0%
Herbaceous Mean	8%	- 45%
Delosperma cooperi	22%	0%
Opuntia fragilis	50%	64%
Sedum lanceolatum	74%	37%
Sempervivum 'Royal Ruby'	32%	46%
Succulent Mean	44%	36%

Plant species cover as measured by C2D is outlined in Figure 5-1 through Figure 5-4. The mean and error bars were calculated based on the surviving plants (error bars represent standard error). Similar to the Single Species Study (Chapter 4), the two species that had the highest plant cover by the end of the study were *B. gracilis* and *D. cooperi*. All other species were much lower in plant cover.

Table 5-4 compares peak plant cover for the amended and non-amended modules. With the exception of *A. parvifolia* plant cover increased in the zeolite amended modules over that of the modules with green roof media during the 2009 growing season. *S. lanceolatum* which is not presented in Table 5-4 actually declined in plant cover from 570 cm^2 on May 13, 2009 to 260 cm^2 on 9/15/09 for the GreenGrid® media, while it increased from 470 cm^2 to 710 cm^2 with the 50% zeolite amendment.

Table 5-4: Comparison of peak plant cover in 2009 in the Mixed Species Study

Species	No amendment		50% zeolite amendment		Percent Difference
	Date	Plant cover (cm2)	Date	Plant cover (cm2)	
Allium cernuum	8/5/09	180	8/5/09	250	25%
Antennaria parvifolia	9/15/09	320	9/15/09	190	-40%
Bouteloua gracilis	8/5/09	1300	8/5/09	1900	34%
Eriogonum umbellatum aureum	9/15/09	490	8/5/09	530	7.7%
Herbaceous Mean					26%
Delosperma cooperi	9/15/09	3950	9/15/09	4120	4.1%
Opuntia fragilis	8/5/09	150	9/15/09	540	72%
Sempervivum 'Royal Ruby'	8/5/09	1040	8/5/09	1550	33%
Succulent Mean					36%

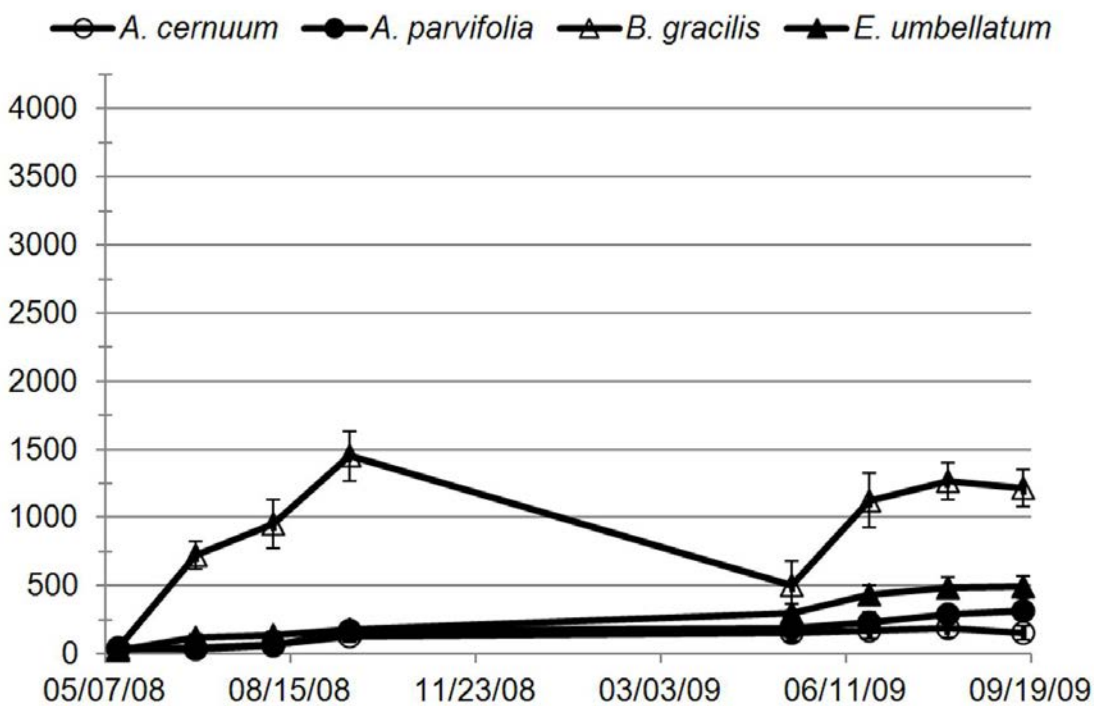


Figure 5-1 Plant cover for herbaceous plants of mixed species study in existing green roof growing media

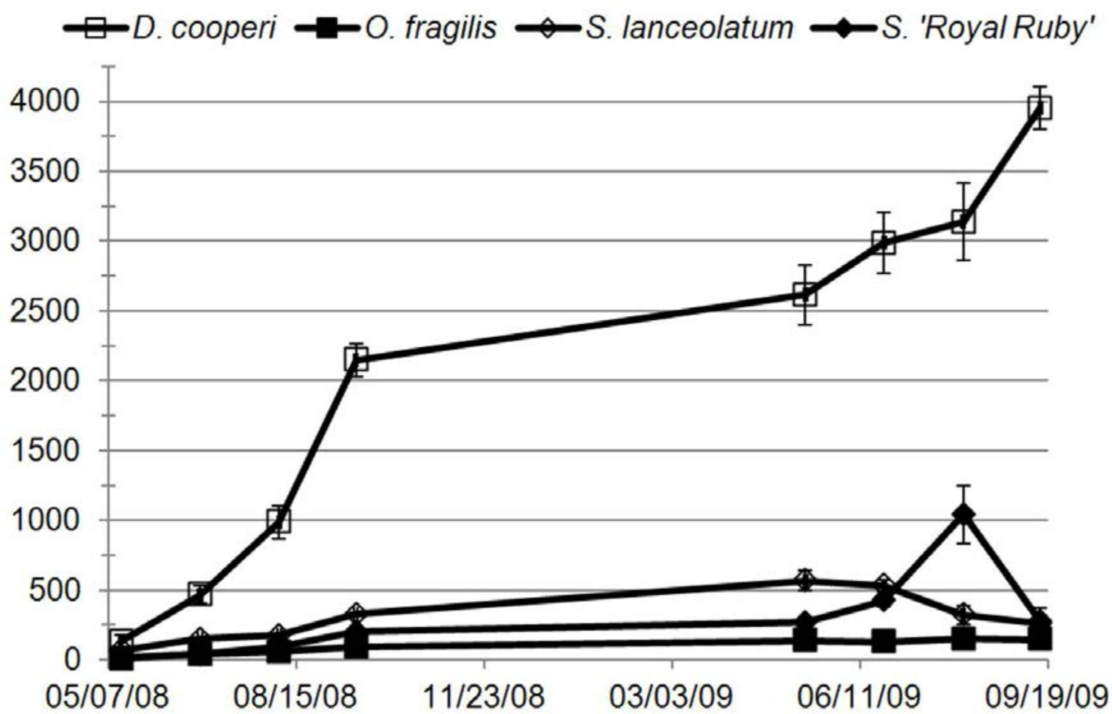


Figure 5-2 Plant cover for succulent plants of mixed species study in existing green roof growing media

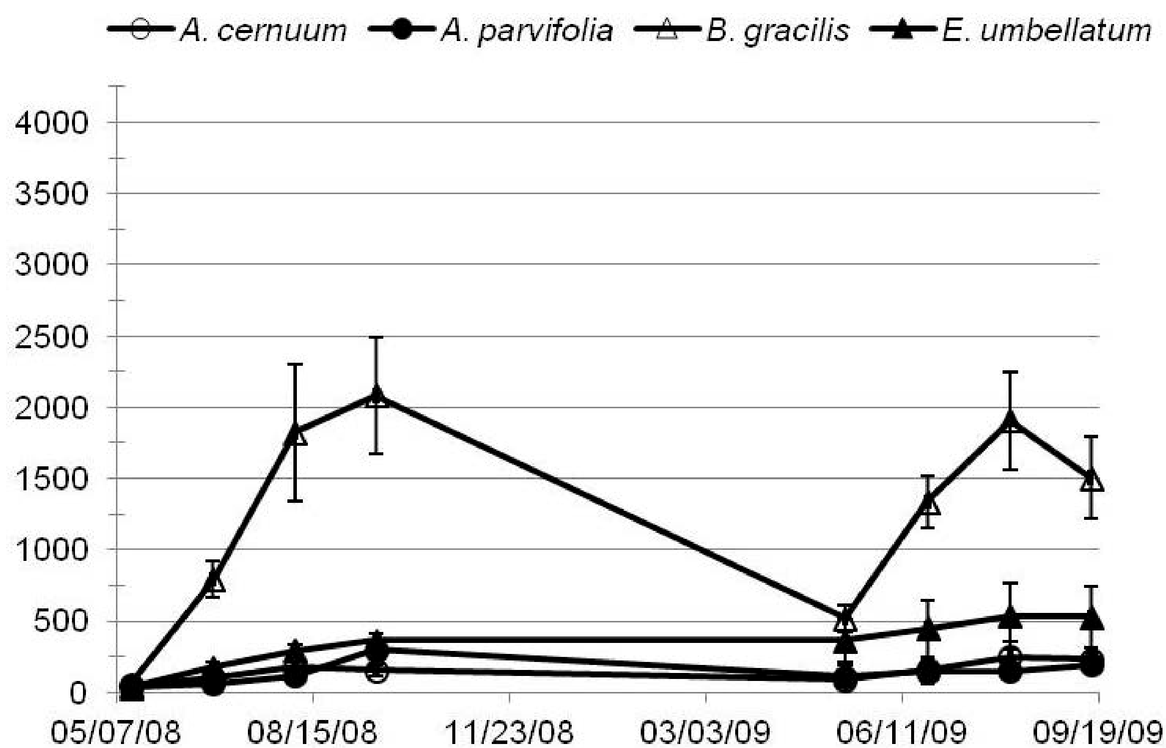


Figure 5-3 Plant cover for herbaceous plants of mixed species study in 50% zeolite amended green roof growing media

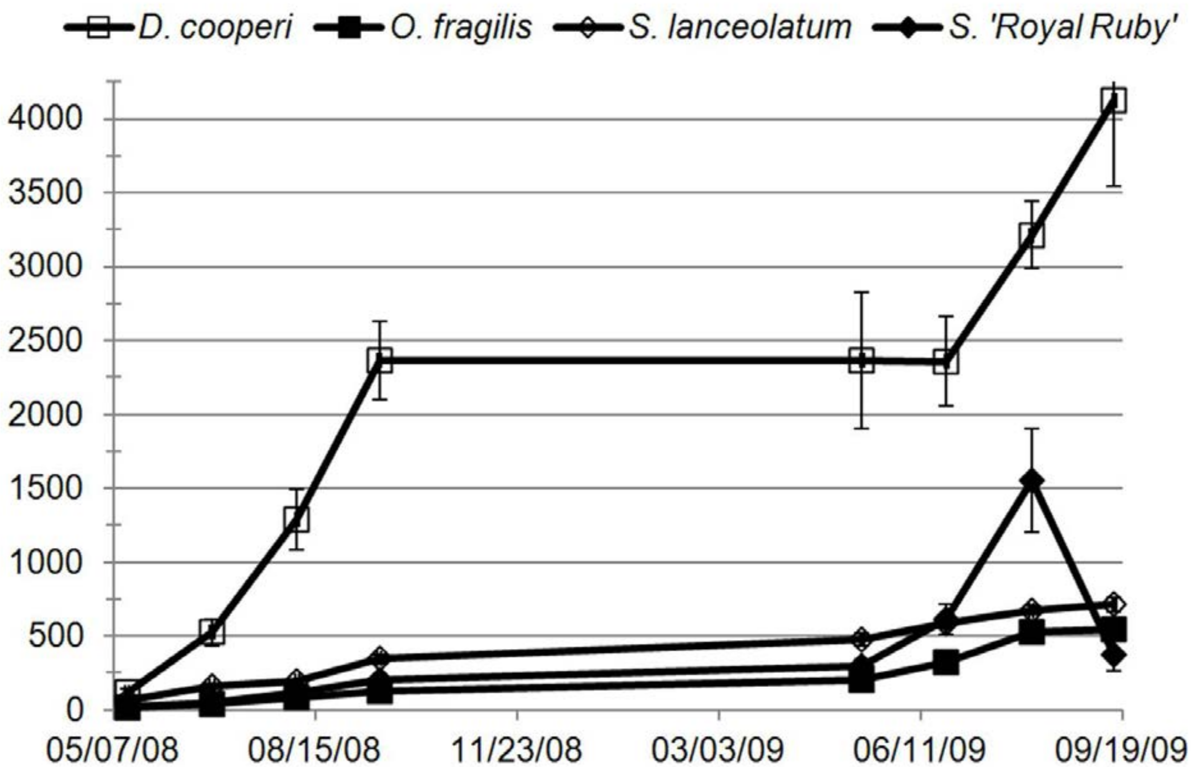


Figure 5-4 Plant cover for succulent plants of mixed species study in 50% zeolite amended green roof growing media

Conclusions

In general, species increased in plant cover during 2008 though the 50% zeolite amendment impacted the over wintering success in some plants. In 2009, typically the plants in the zeolite had greater peak plant cover later in the season with increases of 26% for the herbaceous plants and over 36% for the succulents. Specifically for the two herbaceous species, while *E. umbellatum aureum* had greater survivorship in this study than study 1, overall the addition of zeolite in this amount does not appear to be beneficial and the 50% zeolite amendment appears to be detrimental to *A. parvifolia*, decreasing over winter plant cover and plant cover in general for 2009. For the succulent species, the 50% zeolite amendment was detrimental to survivability of *D. cooperi* and did not improve overwinter plant cover.

There is disparity in survivorship from one study to another as demonstrated by *E. umbellatum aureum* which had greater survivorship in the Mixed Species Study at 60% (no zeolite) compared to 12.5% survival rate for the Single Species Study, and *A. parvifolia*, which had 80% survivorship in the Single Species Study but only achieved 40% survivorship (with and without zeolite amendment) in the Mixed Species Study. This shows that there is much variability in the response of the plants to the differing environmental conditions. *E. umbellatum aureum* potentially benefitted from differing water usage rates of the species used in this study, while during the Single Species Study, water usage and needs of *E. umbellatum aureum* may have hindered survivability.

Some plants can reduce stress of neighboring plants and improve survivability of neighboring plants in harsh habitats. Butler and Orians (2011) observed that *Sedum* species may reduce water loss from green roof media thereby allowing other species to benefit especially during periods of summer water deficit. Cook-Patton and Bauerle (2012) recommended testing in both single and mixed stands as both survivability (e.g. drought tolerance) and beneficial function (e.g. evapotranspiration for stormwater management) of individual species may depend on plant diversity of a green roof.

Chapter 6. Zeolite Amendment Study

Introduction

For the Zeolite Amendment Study, three percentages of zeolite (ZeoPro™ H-Plus) (33%, 66% or 100%) were incorporated into a commercially available extensive green roof growing medium (GreenGrid®). Four taxa (three species, with one species represented by two cultivars) of *Sedum* already on the EPA Region 8 green roof (*S. acre*, *S. album*, *S. spurium* ‘Dragons Blood’ and *S. spurium* ‘John Creech’) were planted into each of the zeolite amended mixtures of growing media and a growing media control to determine which composition is most suitable for plant growth.

Ten replicates of each media mix were set up in a randomized complete-block design, similar to the Single Species Study (Chapter 4), but the primary variables was amount of zeolite amendment in media and four taxa. A main difference between the Single Species Study and the Zeolite Amendment Study is that smaller sized, 61 x 61 x 10 cm (2 x 2 x 1/3 ft) modules were used. Four planting media (one each of the three percentages of zeolite amended growing media and one growing media control) made up one module (see Figure 3-1). Each module was randomly assigned to one of the four positions in each block to minimize environmental variability (see Figure 3-2). Physical and chemical properties of the blends are outlined in Table 6-1.

Table 6-1 Chemical and Physical Characteristics of the Four Growing Media

Growing media characteristic		Control	33% zeolite	66% zeolite	100% zeolite
Organic natter content by mass (loss on ignition)		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 maximum 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] = 1.8 (proportion of large pores FLL, 2008)	Air content	35.7%	32.8%	32.3%	39.4%
	Water content	30.6%	29.7%	27.7%	19.5%

[1] pF is the logarithmic value (base 10) of the water column in cm; soil moisture measurement to define soil suction. At pF = 1.8 is equal to field capacity on the green roof substrate moisture retention curve.

Nitrogen was analyzed as nitrate (NO_{3}-N) but the zeolite contains nitrogen as ammonium ion-N and therefore the 100% treatment showed very little nitrogen content. Nitrogen content increased in the 33% and 66%, likely because the form of nitrogen in the zeolite changed with mixture of organic matter, i.e., changed some ammonium ion-N to into NO_{3}-N. All plants were fertilized at initiation of the study; however, the zeolite treatments had higher nutrient levels, especially K, than the treatment with no zeolite as indicated by the 1597 ppm K in the sample of pure zeolite (Table 6-1).

Results

All four *Sedum* taxa responded to the addition of zeolite, however, responses varied in growing season, overwintering or mixtures of zeolite (Figure 6-1, error bars represent standard error). For example, by the end of 2008, *S. acre* had the highest plant cover in the 33% and 66% amendments and was lower in control and 100% zeolite, while *S. album* increased in plant cover with increasing zeolite content of the growing media.

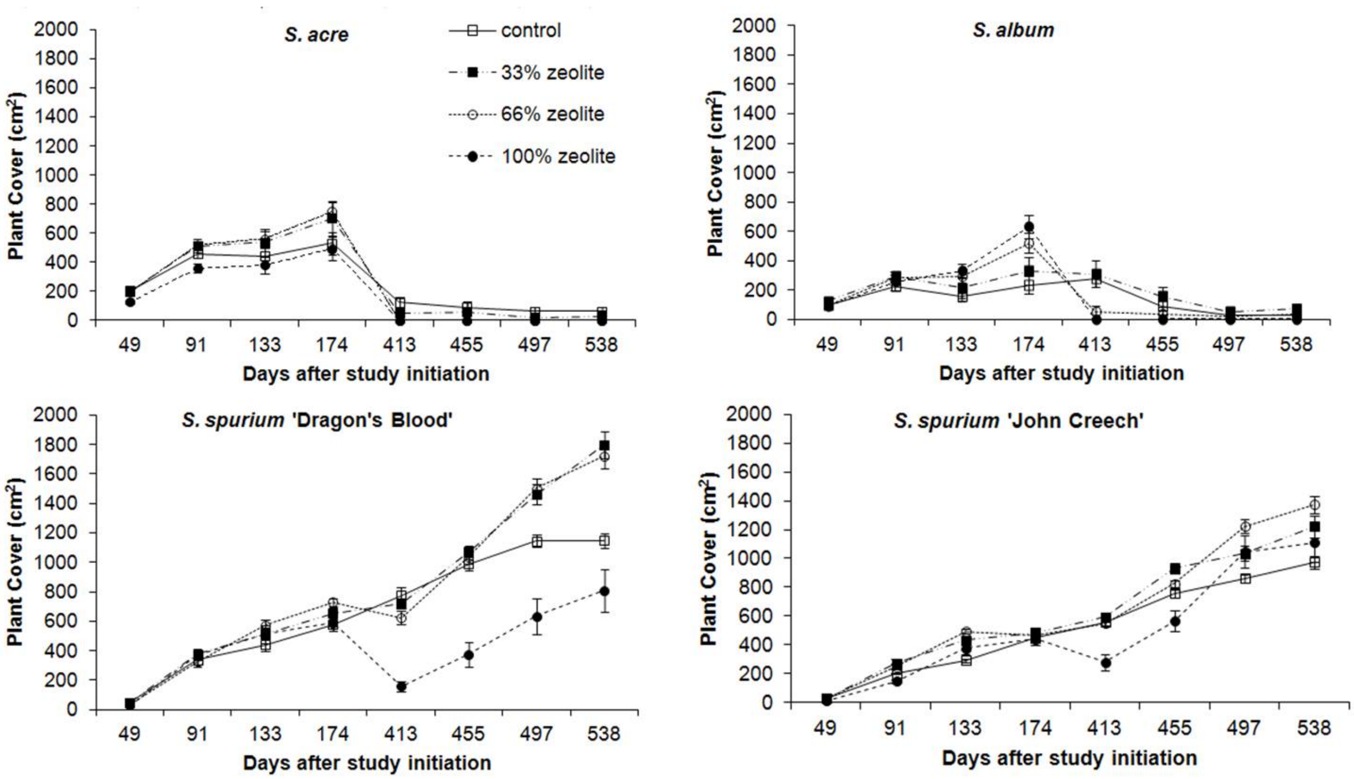


Figure 6-1: Plant cover as determined by DIA over eight dates during two growing seasons.

However, both *S. acre* and *S. album* overwintered poorly as few individual plants survived; this was more pronounced as zeolite content of the growing media increased (Table 6-2). 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 6-1) and were small. 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).

Table 6-2: Overwinter Survival for Each *Sedum* Taxa for Controls and Zeolite Amendments as Determined on May 13, 2009

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

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., 2004; Monterusso et al., 2005; Durhman et al., 2007). Minimum ambient air temperatures below freezing were recorded between October 2008 and April, 2009 with the lowest temperature of -21.6 C° occurring in December, 2008. Due to the contrasting results, apparently there are enough climactic differences between regions to influence survivability of these *Sedums*. However, minimum temperature alone may not be the only problem as another *Sedum*, *S. spectabile* did not survive temperatures of -3.0°C in September but, depending on the cultivar, can survive conditions at less than -20°C in January (Iles and Agnew, 1995).

There are many possible factors which could have affected survivability of these green roof plants in these different growing media blends, especially during the winter season. The minimal precipitation during the winter along with the water holding capacity of the zeolite may have contributed to the desiccation of these two species. Winter VMC and diurnal temperature fluctuation related to media color and albedo may have also influence plant survival. Figure 6-2 shows a block of media treatments clearly showing lighter color of zeolite in relation to GreenGrid® medium. The mean daily minimum temperature of the GreenGrid® growing media during the winter months (December, 2008 through March, 2009) was -3.0°C. The minimum recorded temperature on the surface of the media was -18.76°C which occurred on December 15, 2008 at 7:50 AM while the minimum temperature on the membrane under the substrate of the module was -13.09°C coming two hours later at 9:50 AM.

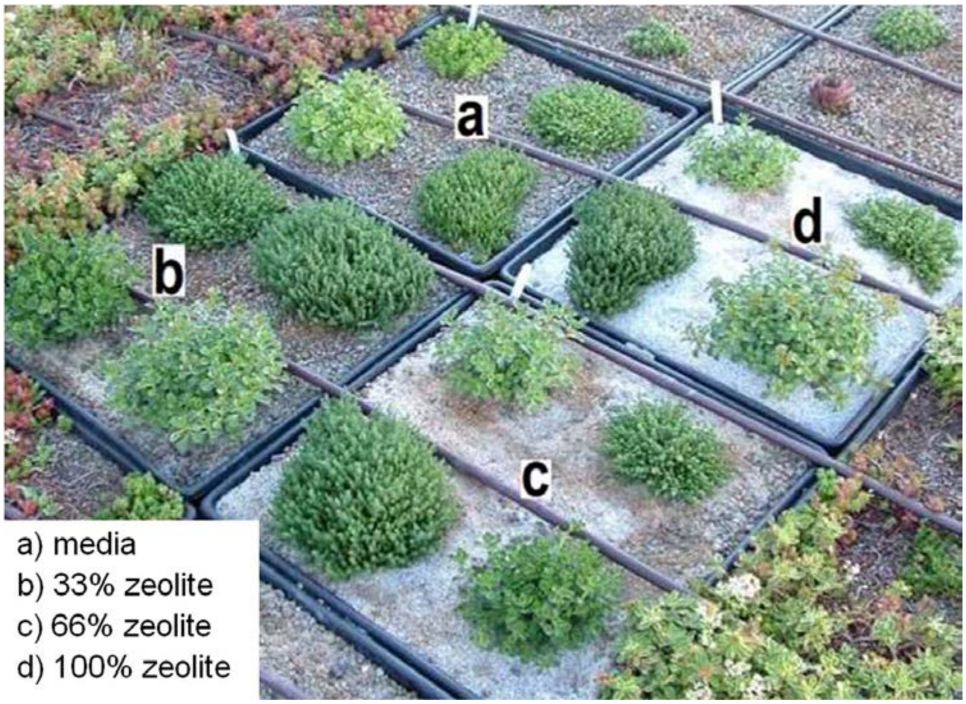


Figure 6-2 Example block on July 1, 2008 showing four media.

Durham et al. (2007) noted that snow cover protects the shoots and buds of alpine plants against water loss during winter. Lack of snow cover in dry areas can desiccate plants (Savonen, 2012). Plants subject to desiccation may leaf out but die later. Watering or irrigating during winter may prevent desiccation (Savonen, 2012); there was only approximately 10 mm of rain per month from November 2008 through February 2009 (Table 4-3). Additionally, the root hardiness of these species is unknown in this type of shallow, well-drained system; 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 higher nutrient and moisture content situations compared to drier and lower fertility growing media. Additionally, the two *S. spurium* taxa which were native to Colorado apparently were competitively better the non-native *Sedum* species at obtaining water resources during the winter.

The two *S. spurium* taxa ('Dragon's Blood and 'John Creech') showed much different results than *S. acre* and *S. album*. At the end of the 2008 growing season, all treatments for both of the *S. spurium* cultivars had similar plant cover. Although overwintering survival was 100% for all amendments and the controls for both *S. spurium* cultivars (Table 6-2), plants in the 100% zeolite were reduced in size at the beginning of the second season (note the decrease in plant cover on Day 413 in Figure 6-1), which is clearly an effect of overwintering and potential desiccation. This was especially noteworthy for the 100% zeolite treatment for both *S. spurium* cultivars.

Conclusions

The survivability of some of the plants in the 100% zeolite indicates that other forms of green roof media may be utilized. However, interaction effects with other plants remain to be tested. As in the Mixed Species Study, some plant species perform poorly in zeolite. Competition for water resources also impacts survivability. Whether *S. acre* and *S. album* survivability could be increased if planted with species other than *S. spurium* cultivars remains to be tested. As the *S. acre* and *S. album* decreased in plant cover even in the control, the introduction of a limited irrigation regime during winters of low rainfall and limited snow cover may also improve survivability of these species in these environmental conditions.

Chapter 7 Analysis of Volumetric Moisture Content

Calculated Evapotranspiration Rates

The evapotranspiration (ET) rates were calculated from monthly data using the Penman-Monteith equation and guidelines of the Food and Agriculture Organization of the United Nations (FAO) (Allen et al., 1998). As per FAO guidelines, the monthly reference evapotranspiration rate (ET_0) was calculated for the 15th day of the month. The monthly value presented in Table 7-1 was derived by multiplying the representative 15th day of the month by the number of days in the month. Values of ET for specific crops can be derived by multiplying a crop coefficient (K_C) to ET_0 to derive individual evapotranspiration rates per crop (ET_C). For many crop and forage plants listed in the FAO guidelines (Allen et al., 1998), $K_C > 1$; however, one of the plants listed in the FAO guidelines that has a $K_C < 1$is the pineapple.

The pineapple, which has its stomata closed during the day, has a K_C of 0.5 for most conditions though this can be as low as 0.3 for mature crop in bare soil (Allen et al., 1998). Crassulacean acid metabolism (CAM) is an adaption by plants to arid conditions to close the stomata during the day while opening their stomata at night, taking up carbon dioxide and storing it as malic acid for photosynthesis (Ting, 1985). Because CAM plants open their stomata at night and close them during the day to minimize water loss, these plants have very high water use efficiency, therefore K_C for CAM plants is expected to be < 1. Similarly many *Sedums* planted on green roofs exhibit CAM particularly when water stressed. The pinapple, of the *Bromeliaceae* family, the *Sedums* of the *Crassulaceae* family and *O. fragilis* of the *Cactaceae* family have all been previously identified as CAM plants (Sayed, 2001). Therefore, ½ ET_0 is also presented in Table 7-1 as potential ET_C value for CAM plants used on green roofs.

Smeal et al. (2010) developed a plant or landscape coefficent for western landscape xeriscape plants which can be applied to ET_0 calculated from the FAO Penman-Monteith equation. This was for a range of plants tested in New Mexico under varying irrigation regime. The mean landscape coefficient measured by Smeal et al. (2010) was 0.3. This value is applied to a specific equation that looks at ET since last day of irrigation and includes a more complete from of analysis (e.g., plan canopy area) (Smeal et al., 2010) However, this has been nominally applied to the normalized monthly ET_0 values as a minimal reference value in Table 7-1. Additionally, irrigation and rainfall rates are presented, along with a qualitative indicator whether irrigation rates and rainfall totals were greater than ET_0.

Table 7-1 Calculated Evapotranspiration Rates and Irrigation and Rainfall Totals

Year	Month	Stephan Boltzman (MJ/m^2-d)	Vapor pressure deficit (kPa)	Evapotranspiration (mm)			Monthly rainfall (mm)	Monthly irrigation rate[2] (mm)	Total irrigation and rainfall	Qualitative monthly deficit[1]
				Calculated monthly reference (ET_0)	½ monthly reference (0.5 x ET_0)	Monthly xeriscape reference (0.3 x ET_0)				
2008	May	--	--	--	--	--	64.3[3]	160.5	224.5	<<[4]
	Jun	37.6	2.15	183	91.6	55.0	16.8[3]	97.6	114.4	<
	Jul	40.2	2.99	196	97.9	58.7	4.3	114.1	118.4	<
	Aug	38.5	2.02	148	74.1	44.4	55.6	87.6	143.2	<
	Sep	35.8	1.46	106	53.0	31.8	28.2	68.4	96.6	<
	Oct	33.3	1.08	75.6	37.8	22.7	17.5	40.8	58.3	<
2009	Mar	31.3	0.96	99.5	49.7	29.8	44.2	3.1	47.3	< >
	Apr	31.7	0.74	91.4	45.7	27.4	108.2	3.9	112.1	<<
	May	35.2	1.32	139	69.3	41.6	53.6	4.8	58.4	< >
	Jun	36.8	1.56	145	72.3	43.4	55.4	13.9	69.3	< >
	Jul	38.4	1.91	162	81.0	48.6	60.2	56.6	116.8	<
	Aug	38.4	2.13	154	77.0	46.2	20.8	82.1	102.9	<
	Sep	35.8	1.46	113	56.3	33.8	16.0	66.0	82.0	<
	Oct	33.3	1.08	59.4	29.7	17.8	45.2	28.2.	73.7	<<

[1] Normalized to monthly total based on meter readings.
[2] << = exceeds monthly ET_0; < = between monthly monthly ET_0, and ½ monthly ET_0; < > = between ½ monthly ET_0, and monthly ET_C, for xeriscaping; > below monthly ET_0, for xeriscaping (not observed); -- = no data.
[3] National Weather Service station (ID: 052223) at Denver Water (1600 W. 12th Avenue, Denver, CO) collected 2.6 km away from Region 8 green roof.
[4] Based on May 2009 ET_0.

Table 7-1 indicates that irrigation rates applied to the roof were generally less than that of the reference ET_0 rates with the potential exception of May, 2008. As May, 2008 was the start of the study, i.e. plants put in position on the roof, irrigation was increased for success of these transplants. Otherwise, when the combination of irrigation and rainfall exceeded ET_0 for the month, it was due to large rainfall totals rather than excessive irrigation. The combination of irrigation and rainfall never fell below the 0.3 x ET_0 rate for xeriscaping. This would be considered the minimal irrigation requirement, while the target for green roof irrigation would be between 0.3 x ET_0 and ½ x ET_0 as many of these plants exhibit CAM. However, herbaceous plants that do not exhibit CAM may have ET rates closer to the ET_0. These plants may require additional irrigation, though as previously noted mixed plantings of *Sedums* and other species may allow the other species to benefit as the *Sedums* reduce water loss from green roof media (Butler and Orians, 2011). Any applied irrigation should also take into account actual rainfall. As data and ET_0 have been normalized to monthly values, irrigation should also take into account periods without rainfall and other intra monthly variation.

From June through October, 2008, ET_0 was 710 mm (28 in.) while from June to October, 2009 ET_0 was 630 mm (25 in.). For the same period, the total irrigation and rainfall was 530.9 (20.9 in.) for 2008 and 444.7 (17.5 in.) for 2009. The combined irrigation and rainfall total exceed the ½ ET_0 for 2008, 350 mm (14 in.), and 2009, 320 mm (13 in.), respectively.

Relative Volumetric Moisture Content Analysis

The cumulative daily rainfall and cumulative daily irrigation and rainfall total for September 2008 and 2009 are shown in Figure 7-1. Cumulative irrigation rates were assumed to smooth the graph as actual irrigation was applied early in the morning only on Mondays and Thursdays.

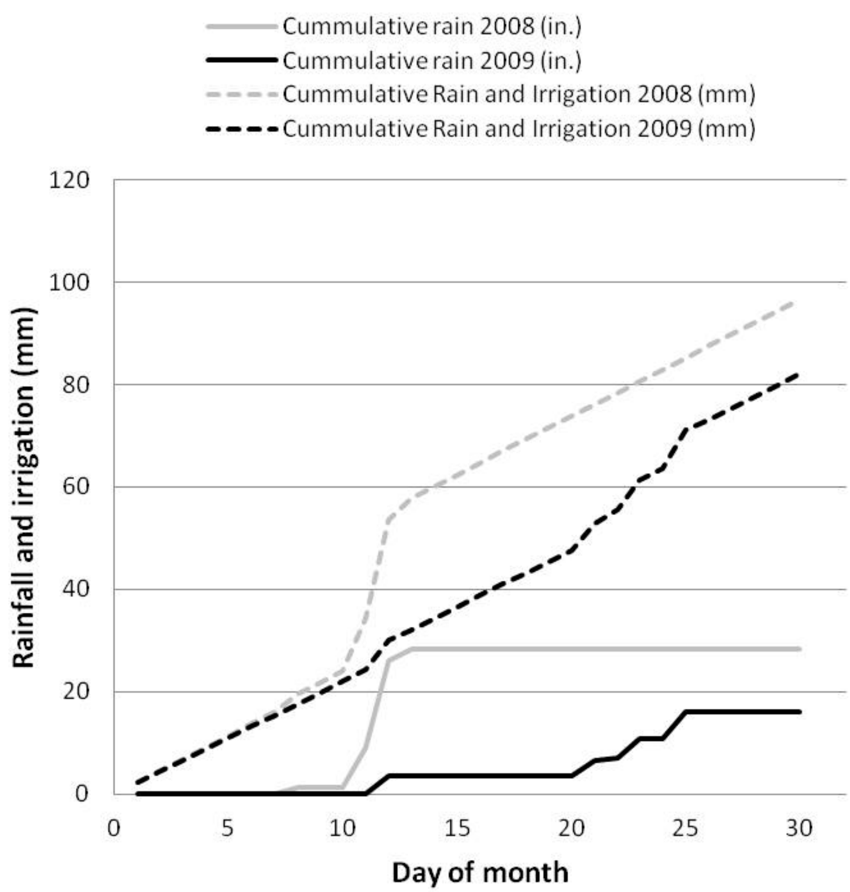


Figure 7-1 Irrigation and rainfall totals for September.

The VMC was measured for studies 1, 2 and 3 on the EPA Region 8 green roof during the month of September in both 2008 and 2009. Delta-T Theta Probe ML2X (Delta-T Devices, Cambridge, UK) were used to take instantaneous readings of growing media VMC. As zeolite is reputed to have good micro-pore space available for holding water, at least compared to other extensive green roof growing media materials, moisture holding capacity of the growing media was expected to increase with zeolite content in the mix. The ability to measure the exact water content due to the micropore structure, in the order of 10^{-10} m diameter, with macroscopic physical probes may be limited. Measurements were made on three separate dates, representing the beginning, middle and end of the month. Additional measurements were made concurrent to plant cover data collection for study 2. Figure 3-3 describes locations of VMC data collection.

Figure 7-2 and Figure 7-3 show average VMC measurements for study 1 for three dates in September for 2008 and 2009. There is a higher VMC around the middle of the month for 2008 (Figure 7-2), but there was a large rainfall event, 17 mm (0.67 in.) on September 12, 2008 (Figure 7-1). In 2009, there were several small rain fall events and the VMC measurements appear more consistent. Besides rainfall patterns, the major difference between 2008 and 2009 is the change in irrigation systems from drip to overhead rotary (spray).

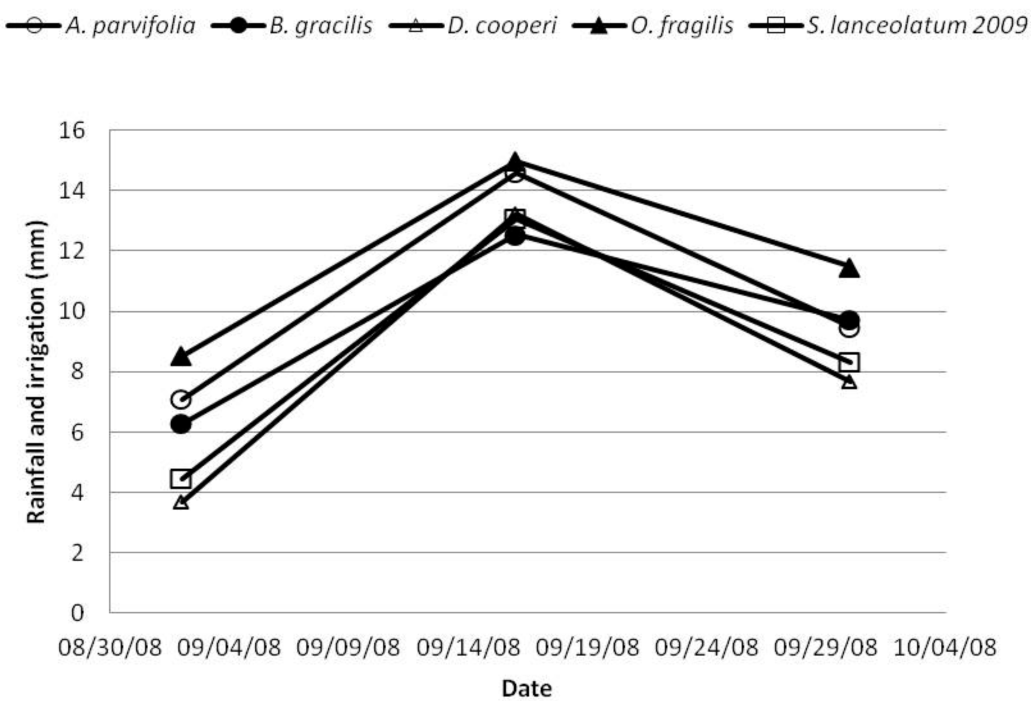


Figure 7-2 Average volumetric moisture content for each species for three dates in 2008.

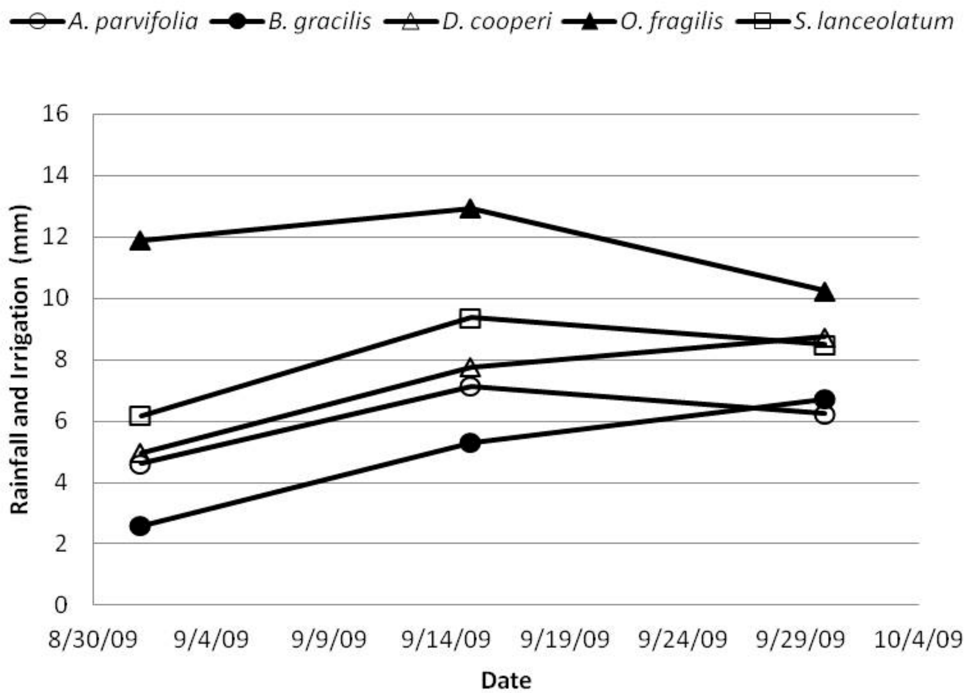


Figure 7-3 Average volumetric moisture content for each species for three dates in 2009.

Results of the factorial MANOVA/ANOVA for the Single Species Study (study 1) are summarized in Table 7-2. Average VMC was used rather than individual data points per module and only four species were analyzed as *A. parvifolia* had missing data and *E. umbellatum aureum* had low survivorship as discussed previously.

Table 7-2 Factorial Analysis of Volumetric Moisture Content for Study 1

Categorical Factors	Multivariate Analysis (VMC and cumulative irrigation and rainfall)		Univariate Analysis (VMC)	
	F value	P value	F value	P value
Species	6.94	0.000001	11.7	0.000002
Block	2.90	0.005	4.6258	0.002
Type of Irrigation	3.57	0.033	6.9661	0.010
Species - Block	1.27	0.19	2.0696	0.028
Species - Type of Irrigation	2.04	0.063	3.1524	0.029
Block - Type of Irrigation	0.92	0.50	1.4027	0.24
Species - Block - Type of Irrigation	0.69	0.85	1.0844	0.38

Figure 7-4, Figure 7-5 and Figure 7-6 show the graphical results for species, block and type of irrigation respectively for the multivariate analysis. Figure 7-7 and Figure 7-8 shows the interaction effects between block and species, and species and type of irrigation.

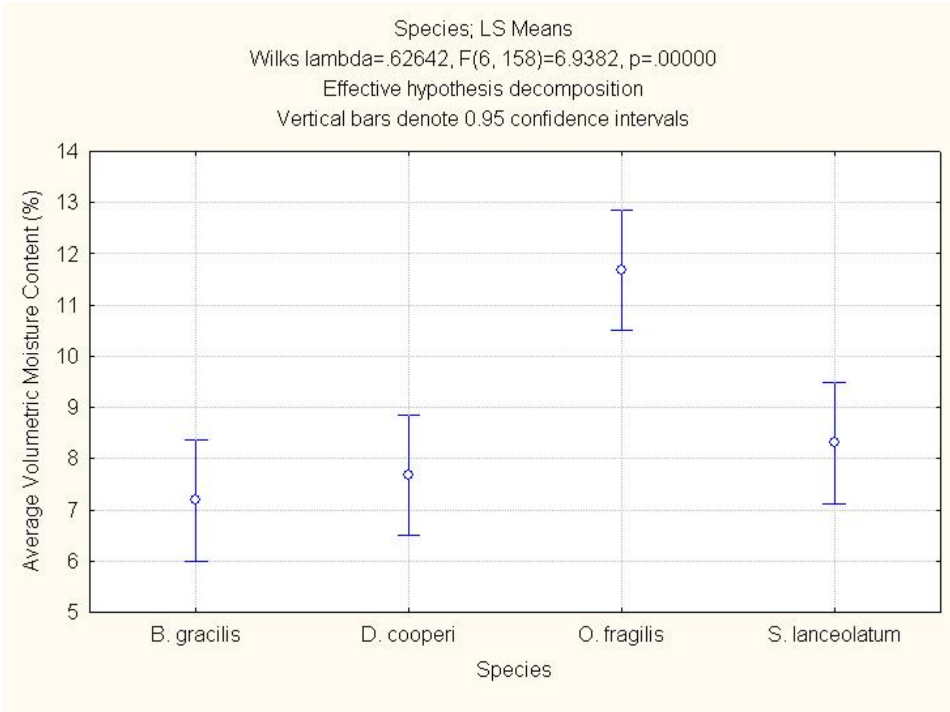


Figure 7-4 Box and whisker plot of effect of species on volumetric moisture content for study 1.

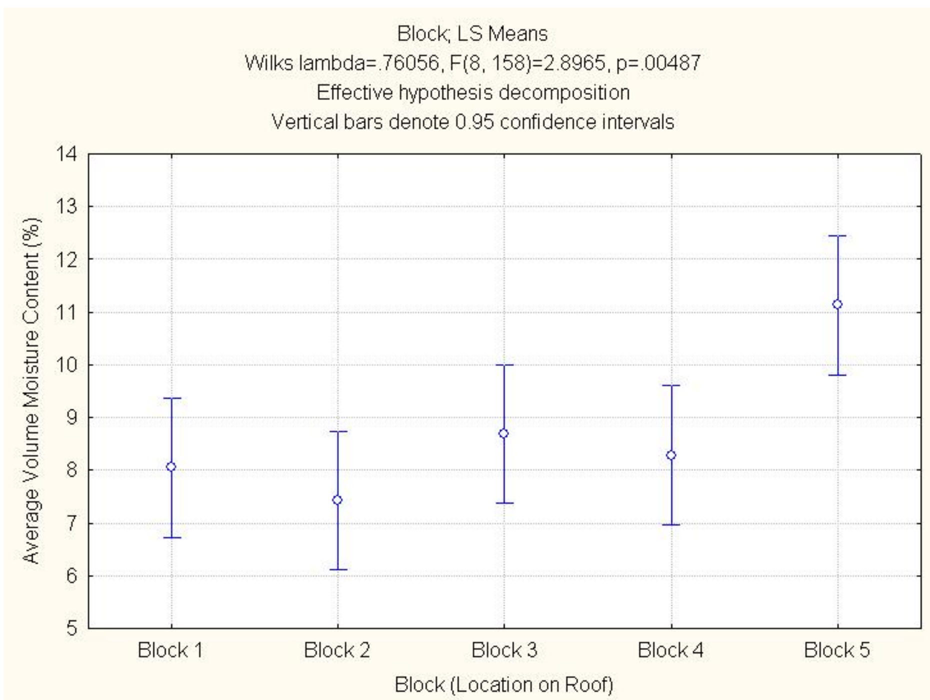


Figure 7-5 Box and whisker plot of effect of block on volumetric moisture content for study 1.

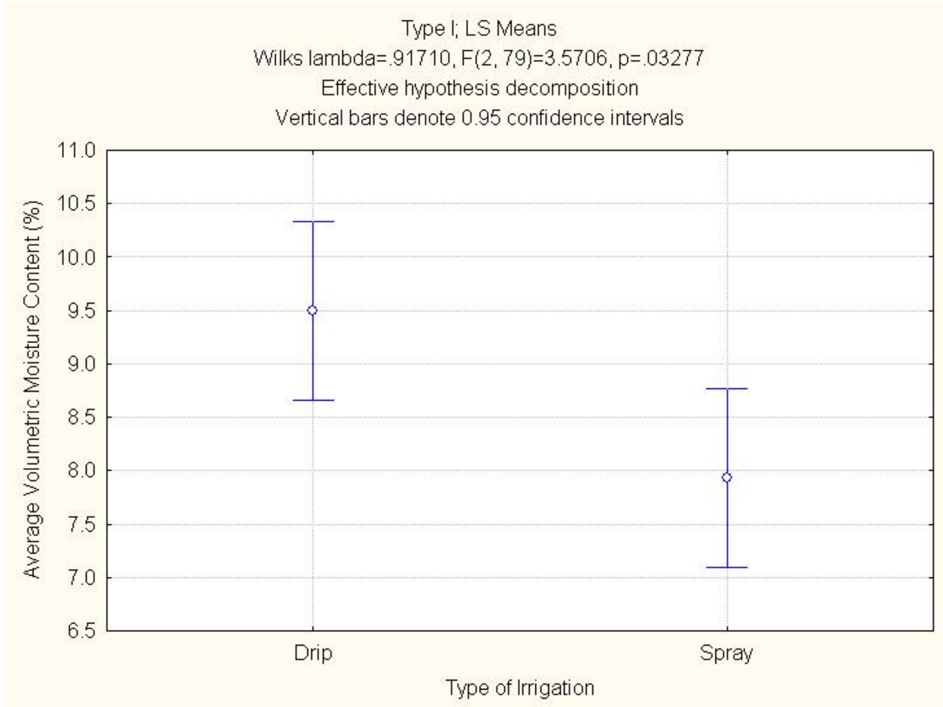


Figure 7-6 Box and whisker plot of effect of block on volumetric moisture content for study 1.

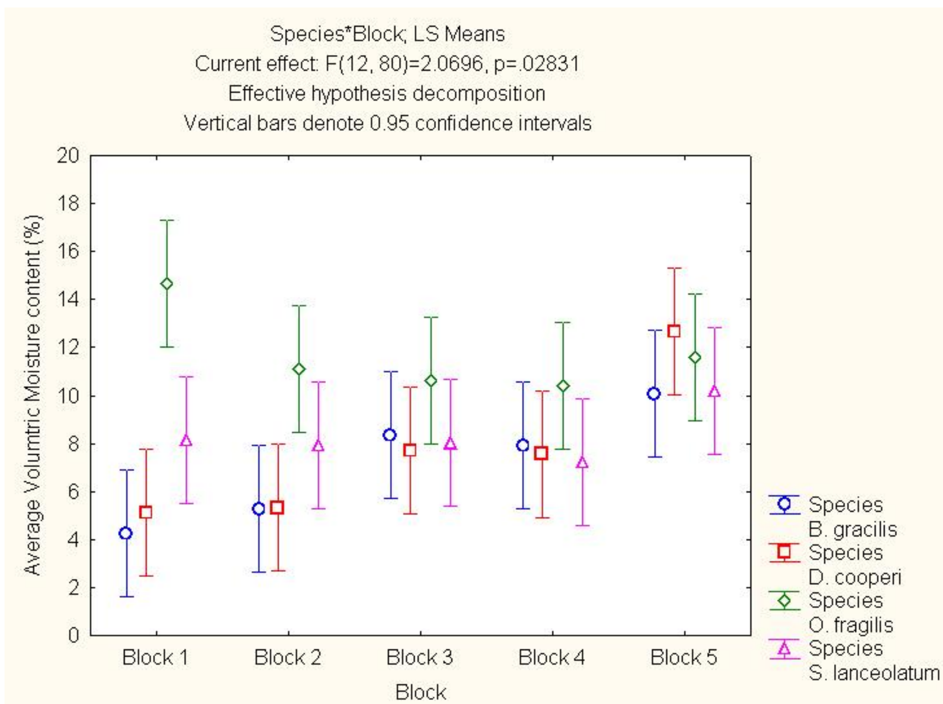


Figure 7-7 Box and whisker plot of effect of block and species on volumetric moisture content for study 1.

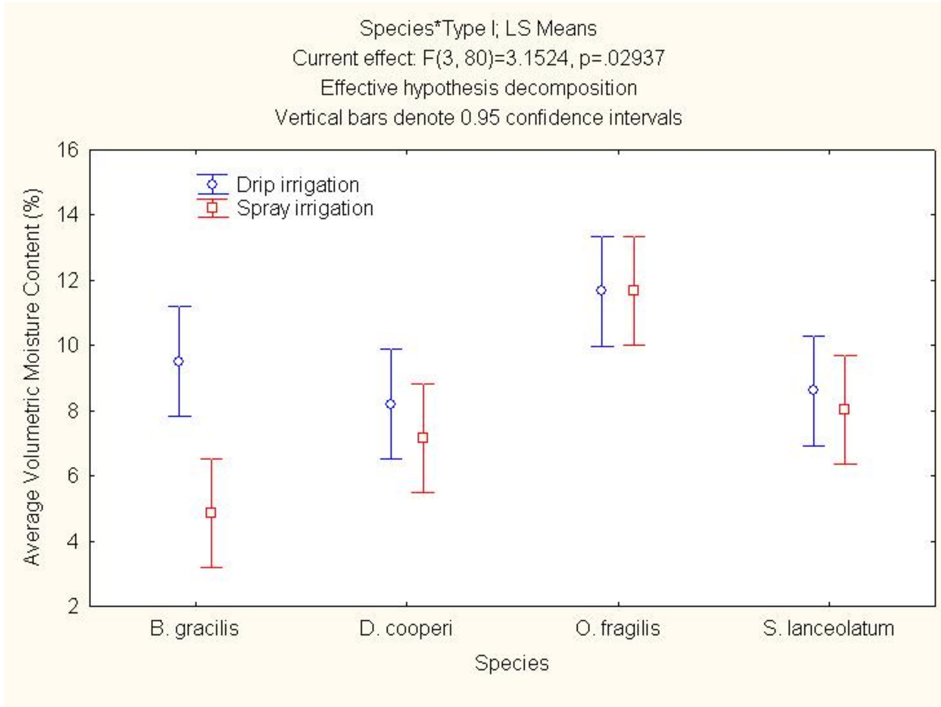


Figure 7-8 Box and whisker plot of effect of species and irrigation type on volumetric moisture content for study 1.

O. fragilis, a cactus, consistently has the highest VMC; this is clear from multivariate analysis (Figure 7-4) and univariate analysis (both Figure 7-7 and Figure 7-8). Block 5 had the highest VMC (Figure 7-5) which is a possible indication of shading in the late afternoon by the upper floors of the building, as block 5 was located on the east side of the building (Figure 3-2). Irrigation was always applied early in the morning. Block 1, which was on the west side of the building, would have had the lowest VMC but *O. fragilis* had its highest VMC for block 1 (Figure 7-7). While Figure 7-6 indicates there is a difference in VMC due to the change in irrigation systems, Figure 7-8 might indicate this difference is mostly due to the reduction of VMC measured in the *B. gracilis* modules. *B. gracilis* had the second lowest biomass at the end of the Single Species Study and lowest measure of water content (Table 4-4). This may imply that overhead rotary irrigation is appropriate for *Sedums* but may not be appropriate for herbaceous species planted in a single stand. As VMC for *O. fragilis* were consistently higher than other species, it would appear that irrigation rates were more than this species need. *O. fragilis* had the highest biomass (Table 4-4) and similar water content to the *Sedums*; there was no difference in VMC for *O. fragilis* (Figure 7-8).

The plant loss of *A. parvifolia* corresponded to block 1 which had the lowest VMC reading (except for *O. fragilis*). A multivariate analysis for cumulative irrigation and rainfall and VMC for the same three categorical variables with *A. parvifolia* and without blocks 1 and 5 yielded only species as significant ($F = 2.28$, $p = 0.026$), with *O. fragilis* having highest VMC while other species were similar. A univariate analysis of VMC indicated effects for species ($F = 3.90$, $p = 0.0069$) and type of irrigation ($F = 4.63$, $p = 0.035$).

Results of the factorial MANOVA/ANOVA for the Mixed Species Study (study 3) are summarized in Table 7-3. There are significant effects for zeolite, which is shown graphically in Figure 7-9, while the interaction effect of zeolite - type of irrigation nearly registered significance for the univariate analysis and this is shown graphically in Figure 7-10. There is no effect based on block location for the Mixed Species Study (study 3). This may be due to varying water usage rates of mixed plants in the modules versus single plant species (study1) where effect was observable, i.e., in the Single Species Study (study 1), all plants in a module would assumably use water at the same rate.

Table 7-3 Factorial Analysis of Volumetric Moisture Content for Study 3

Categorical Factors	Multivariate Analysis (VMC and cumulative irrigation and rainfall)		Univariate Analysis (VMC)	
	F value	P value	F value	P value
Zeolite	8.35	0.00096	14.4	0.00049
Block	0.858	0.55	1.55	0.21
Type of Irrigation	1.27	0.29	0.168	0.69
Zeolite - Block	0.99	0.45	1.79	0.15
Zeolite - Type of Irrigation	2.28	0.12	3.94	0.054
Block - Type of Irrigation	0.98	0.46	1.77	0.15
Zeolite - Block - Type of Irrigation	1.09	0.38	1.98	0.12

Figure 7-9 shows that the 50% zeolite amendment decreased measured VMC. Figure 7-10 shows that drip irrigation had higher measured VMC for no amendment while overhead rotary irrigation had higher VMC for the 50% amendment. As noted earlier in Chapter 5, the zeolite 50% amendment had a slight adverse effect on the overwintering success of plants (Table 5-2 and Table 5-3) as measured on May 13, 2009, while there was a mean increase in plant cover of 26% for herbaceous plants and >36% increase for succulents (Table 5-4) for plants in the 50% zeolite mixture over those in GreenGrid® medium. Block 1 had the lowest survivability in study 3 with a loss of 7 plants (4 in 50% mixture). This potentially implies that zeolite contributed to desiccation of the root zone.

Figure 7-9 Box and whisker plot of effect of zeolite on volumetric moisture content for study 3.

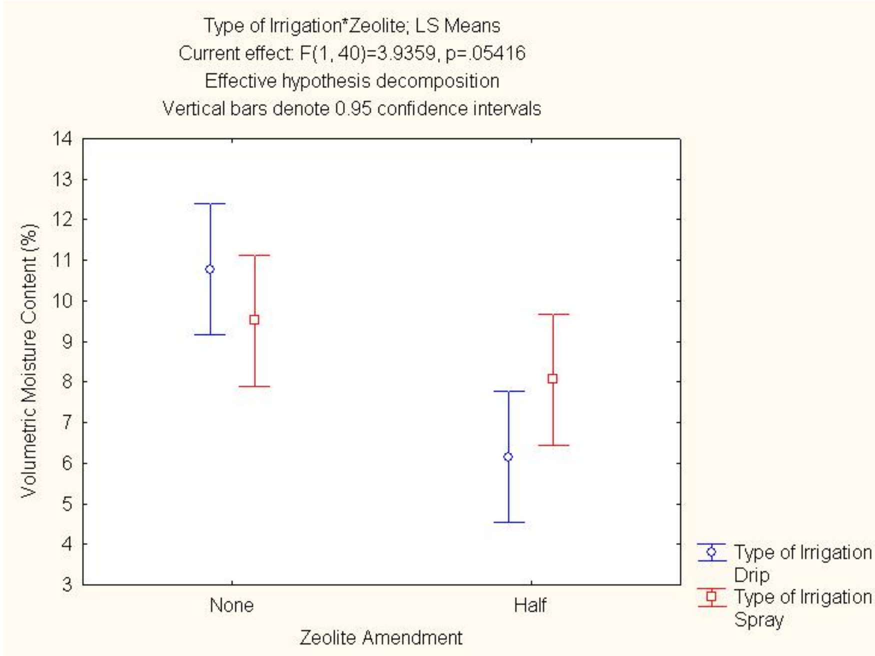


Figure 7-10 Box and whisker plot of effect of bock on volumetric moisture content for study 3.

Results of the factorial MANOVA/ANOVA for the Zeolite Amendment Study (study 2) are summarized in Table 7-4. The only significant effect for the multivariable analysis is the type of irrigation, shown in Figure 7-11. As in the Mixed Species Study (study 3), there is not an observation of statistical difference due to block or location on the roof; this study (2) had different plant species planted in individual plant modules as did the Mixed Species Study (study 3). For the univariate analysis, type irrigation once again has a strong effect, while interaction effects of zeolite amendment –block, Figure 7-12, and zeolite amendment - type of irrigation, Figure 7-13 were statistically significant.

Table 7-4 Factorial Analysis of Volumetric Moisture Content for Study 2

Categorical Factors	Multivariate Analysis (VMC and cumulative irrigation and rainfall)		Univariate Analysis (VMC)	
	F value	P value	F value	P value
Zeolite	1.08	0.38	2.19	0.000000
Block	0.87	0.54	1.78	0.14
Type of Irrigation	21.0	0.000000	41.6	0.000000
Zeolite - Block	1.46	0.090	3.21	0.00086
Zeolite - Type of Irrigation	1.69	0.13	3.47	0.020
Block - Type of Irrigation	1.03	0.42	2.1	0.089
Zeolite - Block - Type of Irrigation	0.56	0.95	1.17	0.32

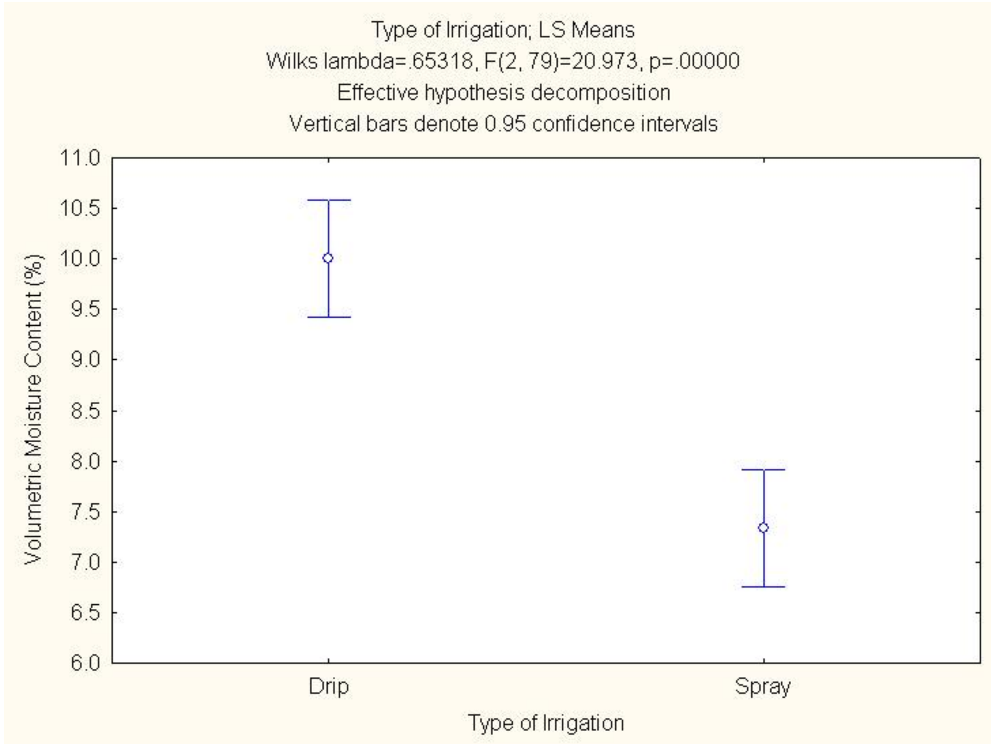


Figure 7-11 Box and whisker plot of effect of type of irrigation on volumetric moisture content for study 3.

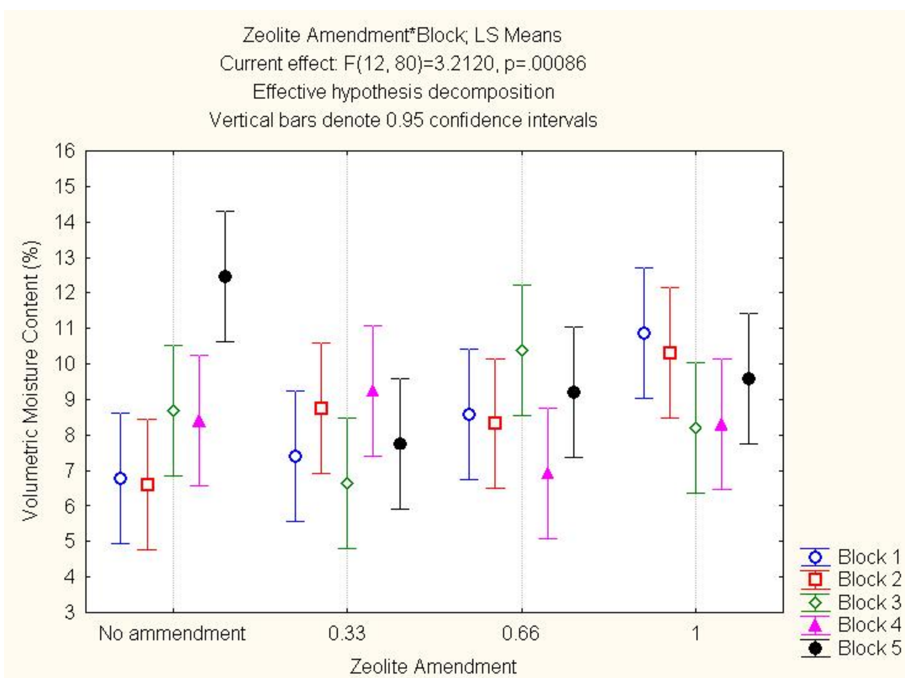


Figure 7-12 Box and whisker plot of effect of block and amendment on volumetric moisture content for study 2.

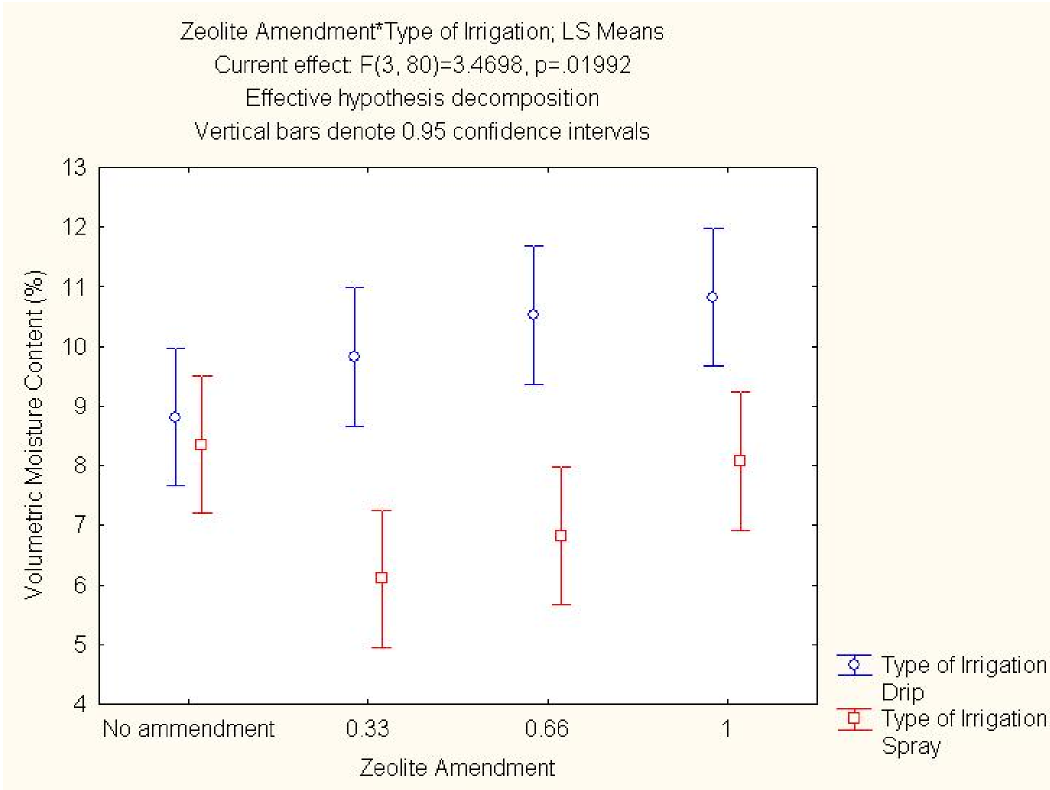


Figure 7-13 Box and whisker plot of effect of amendment and irrigation type on volumetric moisture content for study 2.

Figure 7-12 shows that for the control, GreenGrid® medium, block 5 has the highest VMC; this is similar to interaction effects of Figure 7-7 for the Single Species Study which shows increasing VMC of block 5. Figure 7-13 shows that for the drip irrigation, i.e., the first year of the study in 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, which is inconsistent with the data provided in Table 6-1. As noted earlier the albedo of the zeolite amendment is noticeable (see Figure 6-2) and this may play a role in increasing VMC by lowering temperature of the media. Also, a slight crust tended to form on the surface of substrates containing zeolite, potentially further reducing evaporation.

Figure 7-13 also shows that with overhead rotary irrigation, measured VMC is the same with the control, which is consistent with Figure 7-10, but there is reduced VMC in the zeolite amended modules, which is not consistent with Figure 7-10. The different plant mixtures, zeolite mixtures and varying survivability of plants may have played a role in these differences. Figure 7-13 shows that there is once again an increasing trend of VMC with increasing zeolite content in 2009.

Studies 1, 2 and 3 had significant effects on VMC due to type of irrigation. VMC decreased with overhead rotary irrigation; however, year to year, there was a total 14.6 mm (0.57 in.) less rainfall (12.2 mm, 0.48 in.) and irrigation (2.4 mm, 0.09 in.) in September, 2009 than in September, 2008 (Table 7-1). As shown in Figure 7-2, the VMC in September, 2008 increased in the middle of the month due to rainfall (Figure 7-1), while in Figure 7-3, the response to rainfall in September, 2009 is minimal as measured VMC remains more constant throughout the month.

The drip irrigation system was used in 2008 and an overhead rotary system was used after June, 2009. There were additional VMC data collections for the Zeolite Amendment Study (study 2). Figure 7-14 shows there is much more variability in measured VMC in 2008, particularly 6/25/08 and 8/8/08 date, when the drip irrigation was in use, than in 2009, particularly 8/19/09, when overhead rotary irrigation was in use. Additionally, in August and September of 2008, there was significantly greater rainfall (twice as much) than in August and September of 2009. There was also a noticeable increase in plant cover (Figure 4-2 through 4-5) in August, 2008 for study 1, which had much higher rainfall than July, 2008; July, 2008 was predominantly dependent on irrigation (>90%, Table 7-1) .

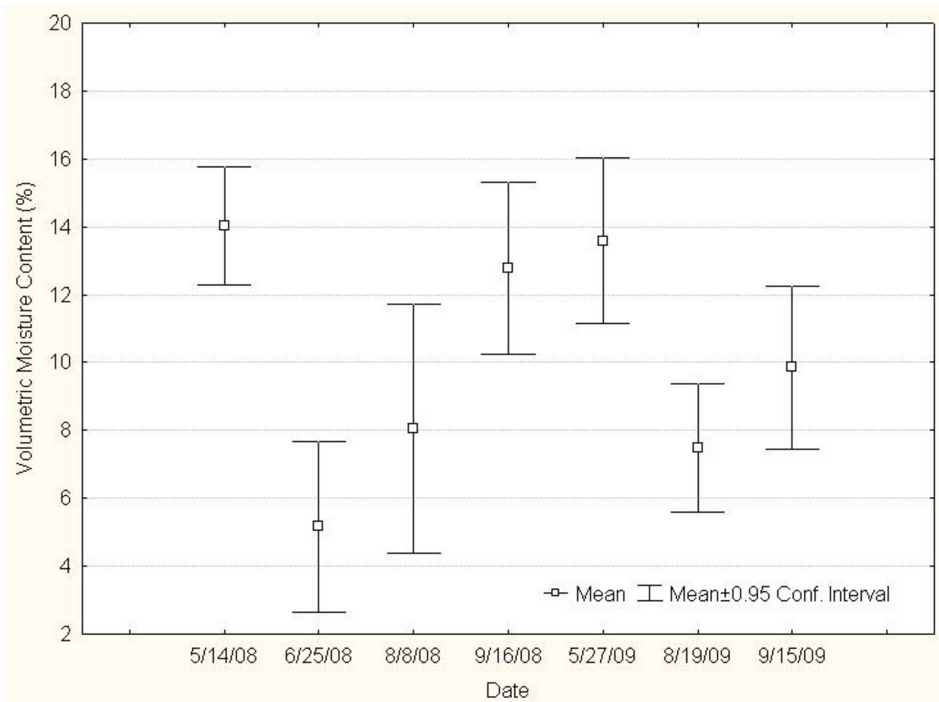


Figure 7-14 Additional volumetric moisture content measurements of the control in study 2.

Results of the factorial MANOVA/ANOVA for the additional VMC data were collected throughout the Zeolite Amendment Study (study 2) and are summarized in Table 7-5. There are significant effects for two categorical variables zeolite and type of irrigation for univariate analysis of VMC. Figure 7-16 show the graphical results for interaction effects of zeolite amendment - block for the univariate analysis.

Table 7-5 Factorial Analysis of Additional Volumetric Moisture Content for Study 2

Categorical Factors	Univariate Analysis - Block (VMC)	
	F value	P value
Zeolite	4.0	0.0085
Block	2.02	0.092
Type of Irrigation	70.1	0.000000
Zeolite - Block	2.01	0.024
Zeolite - Type of Irrigation	2.00	0.11
Block - Type of Irrigation	3.35	0.011
Zeolite - Block - Type of Irrigation	0.521	0.90

Results for the univariate analysis in Table 7-5 using the categorical factor of block are similar to that of the univariate analysis in Table 7-4. Measured effects (p>0.05) were similar, as type of irrigation is the dominant effect, while interaction effects of zeolite – type of irrigation had an effect in the comparison of September 2008 to September 2009 (Table 7-4), it did not an effect in the longer term portion of the study, i.e., May 2008 through September 2009 (Table 7-5). Interaction results of block – type of irrigation was significant in Table 7-5; block 1 had the highest VMC for the drip irrigation and lowest VMC for overhead rotary irrigation (Figure 7-15). In study 1, which did not use zeolite amendment, block 5 had the highest VMC regardless of irrigation system (Figure 7-5). Figure 7-15 implies the overhead rotary irrigation is less variable as VMC ranges from about 6 to 10 while the means for drip irrigation range from 9 to 16.

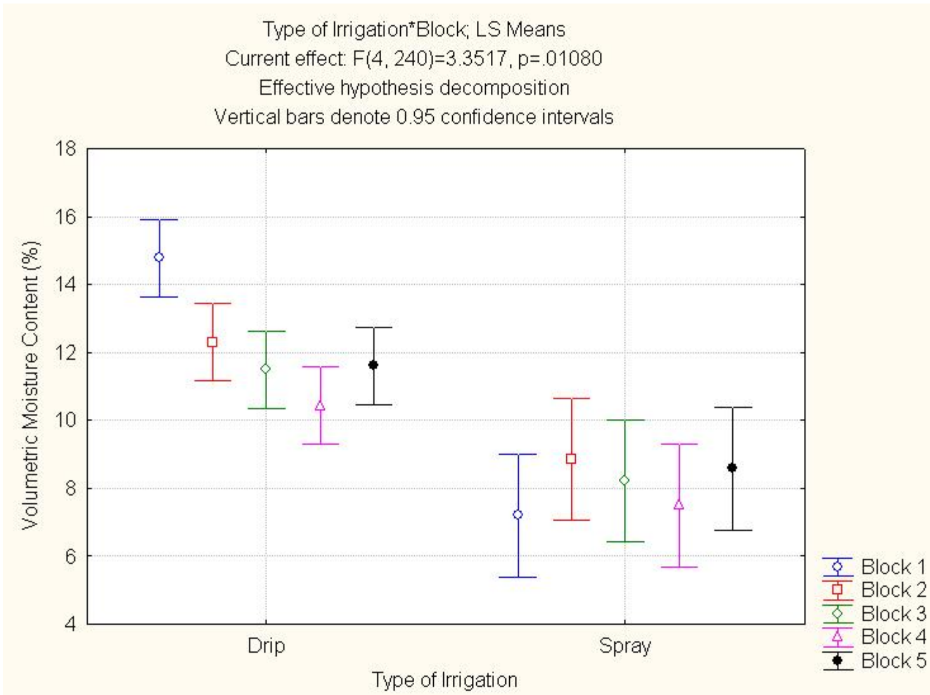


Figure 7-15 Box and whisker plot of effect of block and irrigation type on volumetric moisture content for study 2.

Figure 7-16 shows the interaction effects of zeolite amendment – block which indicates that this disparity in the blocks is potentially an effect of the 100% zeolite amendment, where 5 of the 8 plants were dead and only *S. spurium* 'John Creech' thrived (mean plant cover for this cultivar for block 1 exceeded the mean of all blocks). The control (GreenGrid® medium) retains the previously observed effect of block 5 having the highest VMC as observed in Figure 7-5. Effectively, the overhead rotary irrigation appears to deliver a more uniform cover of irrigation.

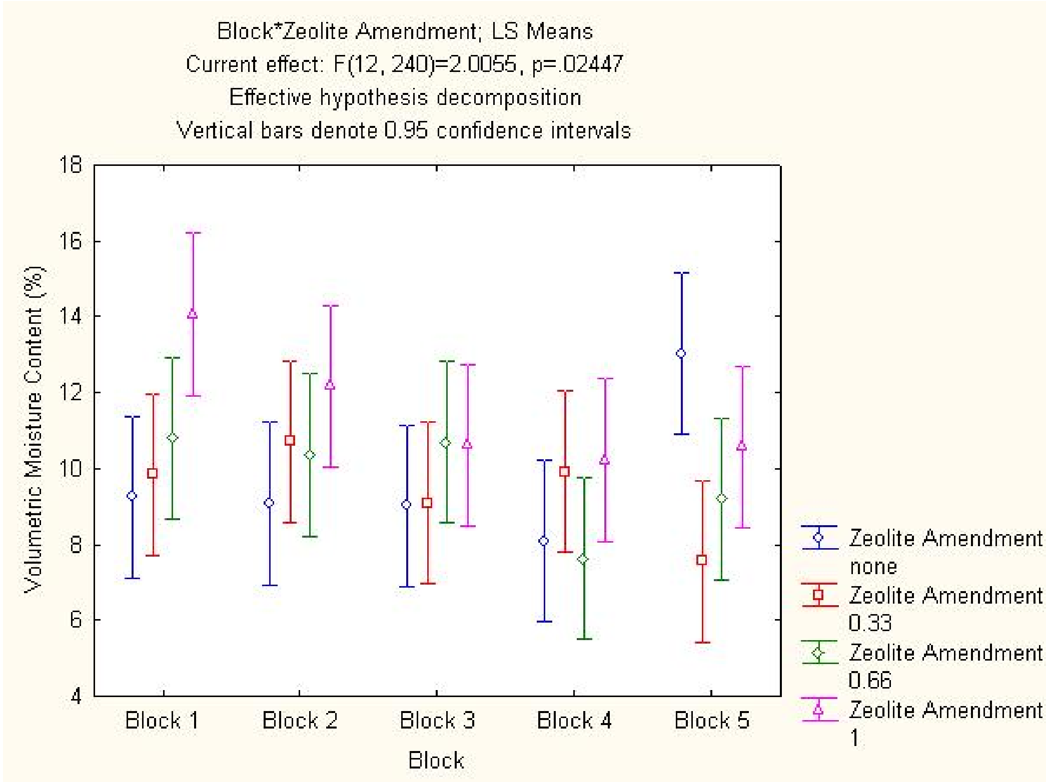


Figure 7-16 Box and whisker plot of effect of amendment and block on volumetric moisture content for study 2.

Comparison of Volumetric Moisture Content and Plant Cover

The MANOVA/ANOVA multivariate analysis in Table 7-6 compared DIA and VMC analysis performed on the same dates (6/25/2008, 8/6/2008, 9/16/2008, 8/19/2009 and 9/15/2009). Results indicate that all interaction effects involving plant and block or type were not significant. While there are several significant interaction effects, most graphical presentation are similar to many of the previous graphs. Figure 7-17 through Figure 7-20 present the interaction effects between plants or block with type of irrigation and zeolite amendment.

Table 7-6 Factorial Analysis of Volumetric Moisture Content and Plant Cover for Study 2

Categorical Factors	Multivariate Analysis	
	F value	P value
Plant	212.068	0.000
Type of Irrigation	237.413	0.000
Block	6.085	0.000
Zeolite	23.463	0.000
Plant - Type of irrigation	217.995	0.000
Plant – Block	0.793	0.75
Type of Irrigation – Block	10.750	0.000
Plant – Zeolite	7.010	0.000
Type of Irrigation - Zeolite	11.213	0.000
Block - Zeolite	4.114	0.000
Plant - Type of Irrigation - Block	0.680	0.88
Plant - Type of Irrigation – Zeolite	8.067	0.000
Plant - Block – Zeolite	0.848	0.81
Type of Irrigation - Block – Zeolite	2.012	0.0026
Plant - Type of Irrigation - Block – Zeolite	0.660	0.99

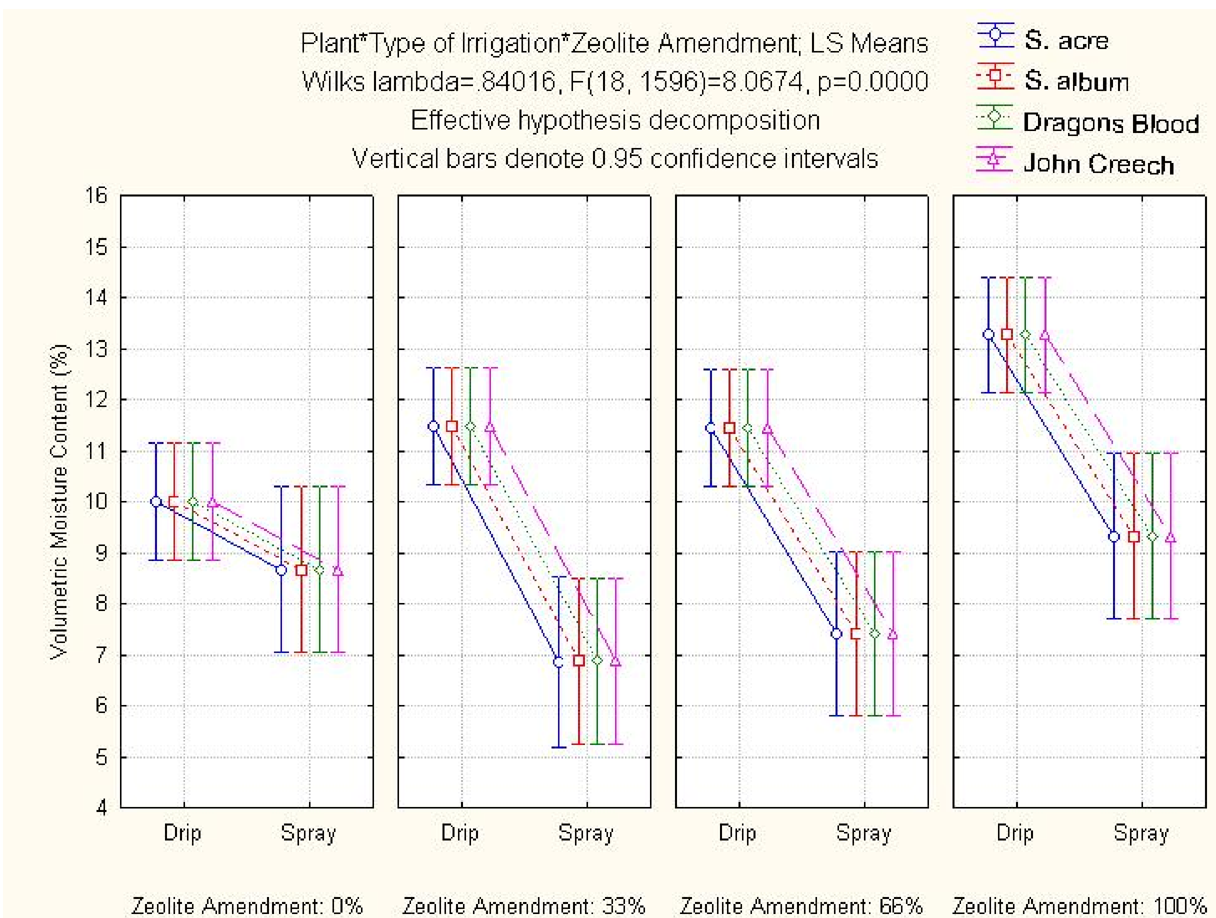


Figure 7-17 Box and whisker plot of effect of plant, irrigation type and zeolite amendment on volumetric moisture content.

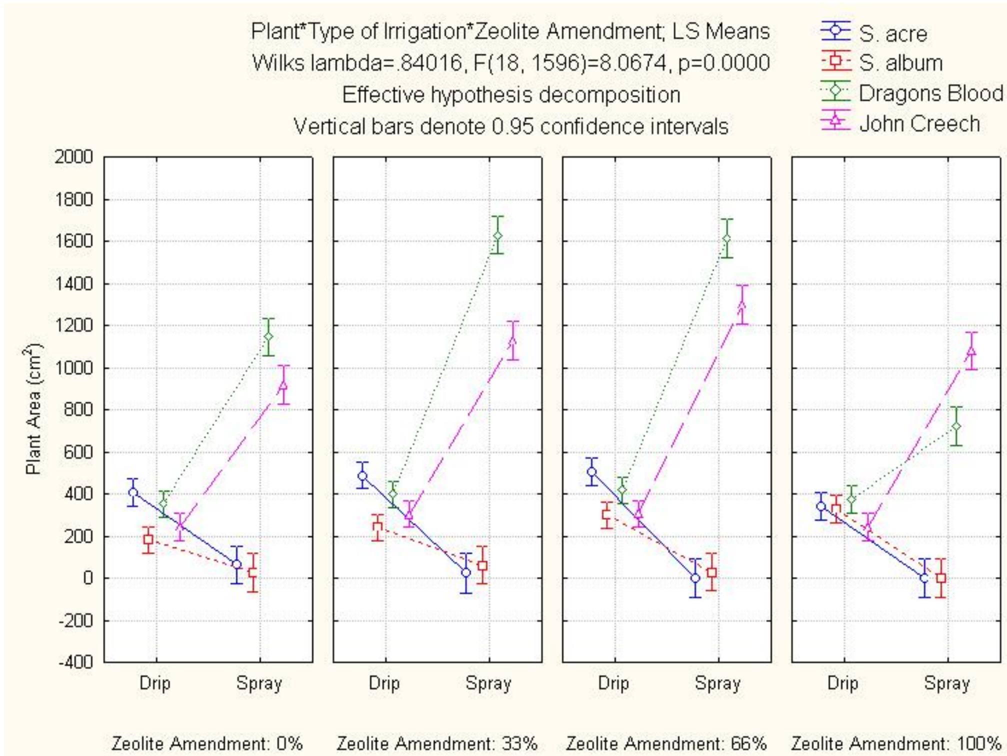


Figure 7-18 Box and whisker plot of effect of plant, irrigation type and zeolite amendment on plant area.

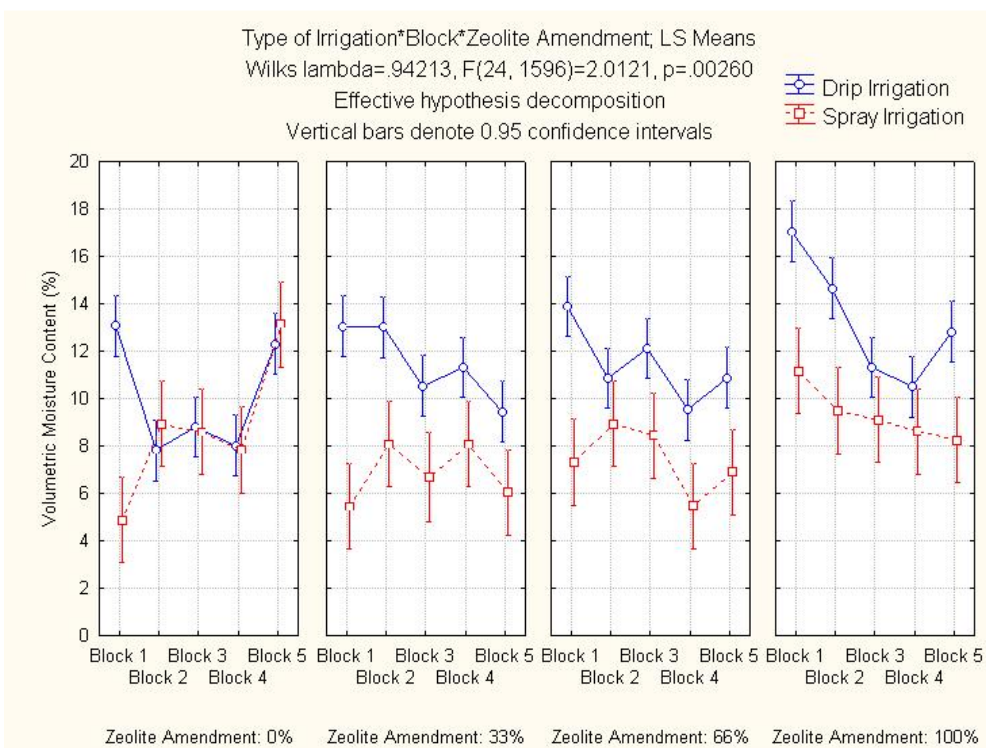


Figure 7-19 Box and whisker plot of effect of block, irrigation type and zeolite amendment on volumetric moisture content.

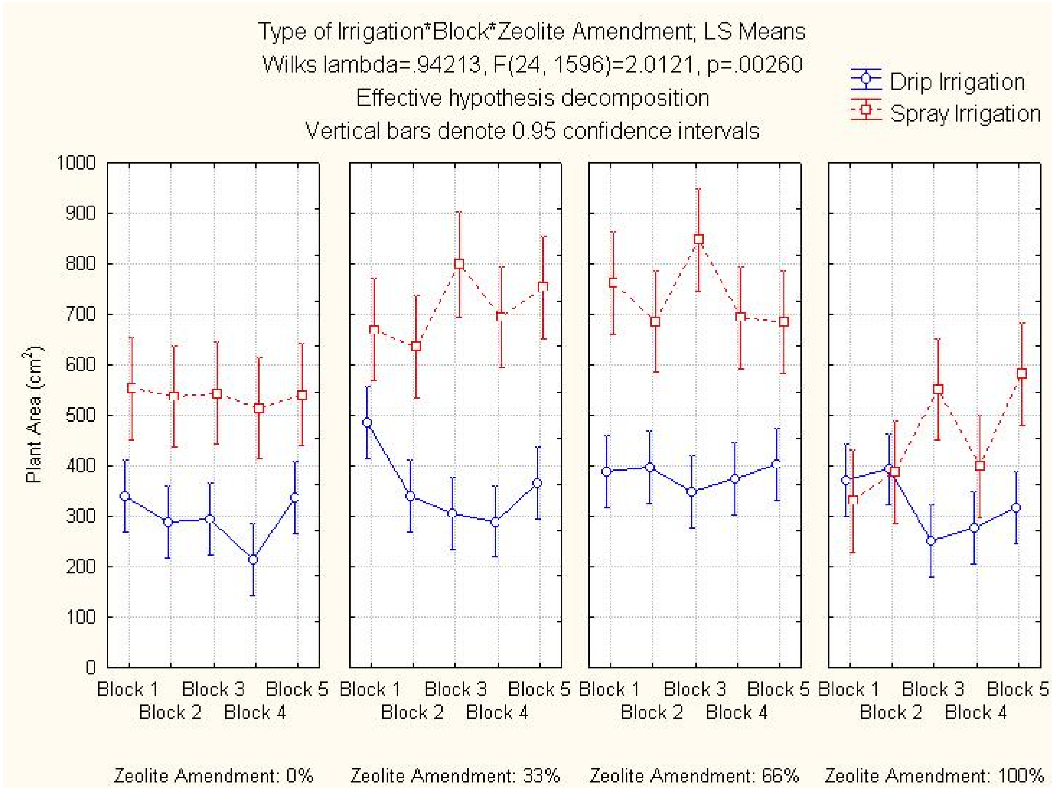


Figure 7-20 Box and whisker plot of effect of block, irrigation type and zeolite amendment on volumetric moisture content.

Figure 7-17 shows there is a less observed VMC for the overhead spray irrigation for all levels of zeolite amendment, while Figure 7-18 shows there is increased plant cover for *S. spurium* cultivars 'Dragons Blood' and 'John Creech'. Particularly of interest is that while the VMC drops for the 33% and 66% zeolite amendment, there is correspondingly higher plant cover for *S. spurium* cultivars 'Dragons Blood' and 'John Creech'. Figure 7-19 shows there is less VMC for the 33% through 100% zeolite amendment for the overhead rotary irrigation across all five blocks. Figure 7-20 shows there is increased plant cover in all cases except block 1, 100% zeolite amendment, with much higher plant cover for 33% and 66% zeolite amendment for the overhead rotary irrigation across the five blocks. This may help explain some of the disparity in comparing reduced VMC observed for Zeolite Amendment Study (study 2) in Figure 7-13 compared to increased VMC for 50% zeolite amendment for Mixed Species Study (study 3).

The implication is that overhead rotary irrigation overall increased plant cover even though there were reductions in observed VMC. The original drip irrigation system was fitted with emitters spaced roughly 30 cm (1 ft) apart. Observations indicated only a small cone of moisture formed beneath each emitter, with dry media intervening between emitters, and considerable amounts of water draining through the medium to discharge drains. This is in part due to the soil-less media which preferentially allows water to move though it vertically rather than laterally. The replacement overhead rotary irrigation system more uniformly distributed moisture across the green roof planting media. The overhead rotary irrigation was more readily available to the shallow rooted *Sedums*. This implies the overhead rotary irrigation is better suited to the green roofs.

The analysis also implies that the zeolite amendments i.e. 33%, 50% and 66% appear to increase plant growth for certain plants, so lower VMC measurements in these cases imply this moisture is available to the plants for uptake. The overhead rotary irrigation values were taken at the end of the 2009 year implying that there will be greater time for growth and this is being compared to the drip irrigation which included measurements earlier in the season for 2008, i.e., May and June when plant growth would have been minimal. However, there was the extreme die-off of *S. acre* and *S. album* which is also included in this overall analysis and plant cover still dramatically improved with overhead rotary irrigation as displayed in Figure 7-18 and Figure 7-20. Less irrigation was applied in 2009 with the overhead rotary irrigation, than in 2008 with the drip irrigation system. Year to year for the months July through September, there was 10% more rainfall in 2009 and 32% less irrigation.

Conclusions

The overhead rotary irrigation system appears more appropriately suited to an extensive green roof system planted with *Sedums* because it effectively supplies irrigation to the media over a wider area than the drip irrigation system. This observation is in agreement with observations discussed in other regions of North America (Beattie and Berghage, 2004; Friedrich, 2005).

While both varieties of *S. spurium* in study 2 benefitted from change to overhead rotary irrigation across all levels of zeolite amendment, *S. acre* and *S. album* had low overwintering survival and had continued decline though the 2009 with application of overhead rotary irrigation even for the control (no zeolite amendment). Even though desiccation during the winter has been identified as one probable the cause for die-off of *S. acre* and *S. album*, this may also imply that some plants might be affected by changing irrigation type. Further work needs to be done to confirm effects of zeolite amendment in affecting VMC and confirming this moisture is available to a variety of plants.

Additional analysis of plant biomass may be warranted. *Sedums* have shallow rooted systems which would seem more well suited for overhead rotary irrigation while some herbaceous species tend to have more of a tap root which might benefit from drip irrigation, i.e., if properly placed next to plant. Assessing root mass in addition to top growth may provide further insight into choosing the right irrigation system for the individual type of plants.

Chapter 8 Moisture Deficit Study

Introduction

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 withstand periods of low moisture availability in their root zones. The survival and growth 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). Additionally, a diversified plant community on an extensive green roof may be able to respond to variable moisture conditions and maximize the evaporative cooling benefit, thus extending the benefits of extensive green roofs (Compton and Whitlow, 2006).

Due to the porous and well-drained nature of the typical 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 plants 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 medium (Table 8-1) on the growth of fifteen plant species, and to determine the relative water use for each of the fifteen species (Table 8-2).

Table 8-1 Physical Characteristics of the Growing Medium Used in all Three Trials.

Growing Media Characteristic		Value
Composition by volume	Five parts heat-expanded shale	50% 63 – 95 mm diameter 30% 20 - 63 mm diameter 20% < 20 mm diameter
	Two parts sphagnum peatmoss	--
	Two parts perlite	--
	One part vermiculite	--
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 %

The media used in this study was based on mixing specs from GreenGrid®. Greenhouse and outdoor studies used the same media. Media physical properties were analyzed at Hummel & Co, Inc. Laboratory in Trumansburg, NY, USA, and reported on March 02, 2010. All physical properties were tested per ASTM E2399. Analytical methods included organic matter (ASTM F1647, method 1, loss on ignition), dry density, particle density (ASTM D5550), saturated hydraulic conductivity (permeability), total porosity, and air and water filled porosity at maximum water capacity.

Table 8-2 Species Evaluated in Greenhouse and Outdoor Trials.

Species	Trials
Allium cernuum Roth. (nodding onion)	greenhouse
Antennaria parvifolia Nutt. (small-leaf pussytoes)	greenhouse, outdoors
Artemisia frigida Willd. (fringed sage)	greenhouse, outdoors
Bouteloua gracilis (Kunth) Lag. ex Griffiths (blue grama)	greenhouse
Buchloe dactyloides (Nutt.) Engelm. (buffalograss)	greenhouse, outdoors
Carex flacca Schreb. (heath sedge)	greenhouse
Delosperma cooperi (Hook. f.) L. Bol. (hardy ice plant)	greenhouse, outdoors
Delosperma nubigenum (Schltr.) L. Bol. (yellow ice plant)	greenhouse
Penstemon pinifolius Greene (pineleaf penstemon)	greenhouse, outdoors
Sedum acre L. (goldmoss stonecrop)	greenhouse
Sedum album L. (white stonecrop)	greenhouse, outdoors
Sedum lanceolatum Torr. (lanceleaf stonecrop)	greenhouse, outdoors
Sedum spurium Marsch-Bieb. (two-lined stonecrop) 'John Creech'	greenhouse, outdoors
Sempervivum (hens and chicks) 'Royal Ruby'	greenhouse, outdoors
Thymus pseudolanuginosus Ronn. (woolly thyme)	greenhouse
Non-vegetated control	greenhouse, outdoors

The green house studies were performed in 2008 and 2009 extending 151 days until dieback conditions for all plants were observed. The outdoor trial was performed only in 2009 and was truncated to 43 days due to freezing temperatures. The greenhouse studies used individual plantings in circular green plastic containers 15.2 cm diameter by 10.8 cm deep pots with media depths of 10 cm. Containers were randomly placed on wire mesh greenhouse benches equidistantly apart at 2.5 cm (1 in.) as part of a complete block design of 24 replicates. The outdoor studies used the same type of modules used on the Region 8 green roof and like the Single Species Study there were 8 replicates in each module.

All plants were established for 10 weeks in a greenhouse. Irrigation was to saturation every 48 h until ten days before the start of the dry-down study. Irrigation was reduced to every 72 h and then 96 h just before the final irrigation. For final irrigation, 450 mL was applied and allowed to freely drain. The first VMC was at least 12 hr after the final irrigation. In addition, each plant received 5 g of Fertilizer (Scotts Osmocote Pro 19-5-8; Scotts-Sierra Horticultural Products Co., Marysville, OH) four weeks before dry down study began.

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 herbaceous (Figure 8-1) and succulent (Figure 8-2) species (error bars represent standard error). Figure 8-1includes the non-vegetated control. A dry down period of 18 days 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, container type, growing media moisture holding capacities and measurement techniques.

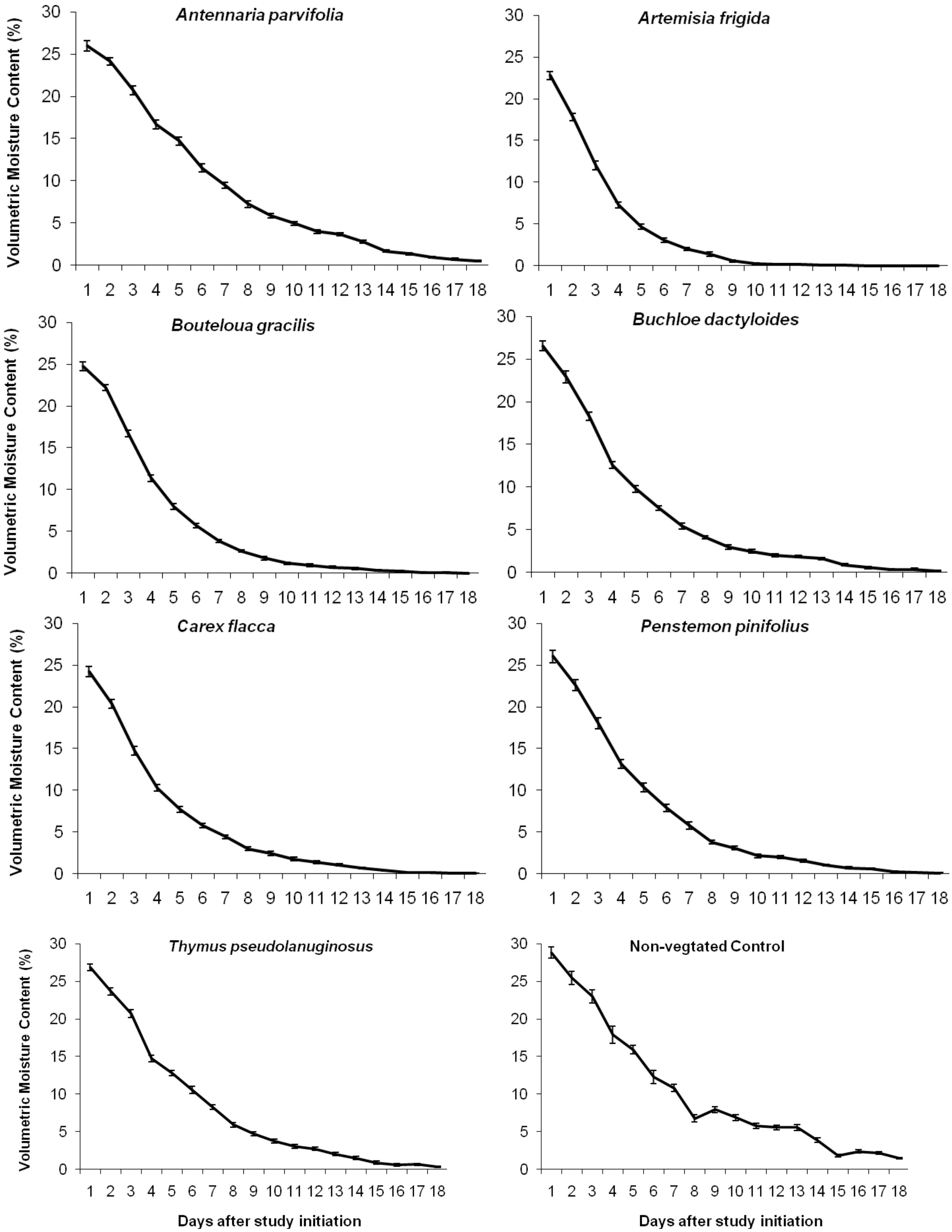


Figure 8-1: Mean volumetric moisture content measurements of growing media for herbaceous plants in greenhouse trials

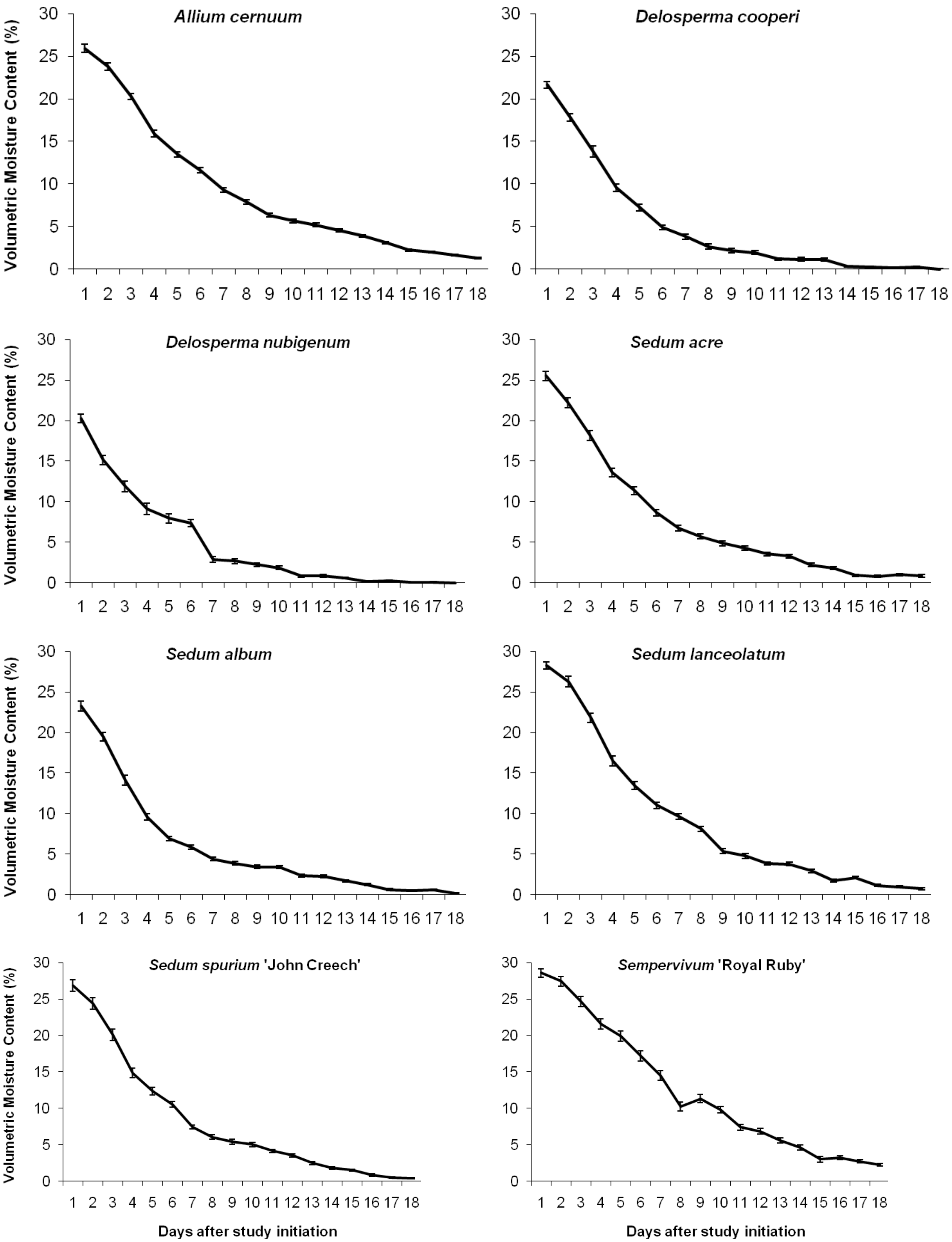


Figure 8-2: Mean volumetric moisture content measurements of growing media for succulent plants in greenhouse trials

Figure 8-3 shows the differences in plant appearance from the beginning of the study compared to 12 days into the study.

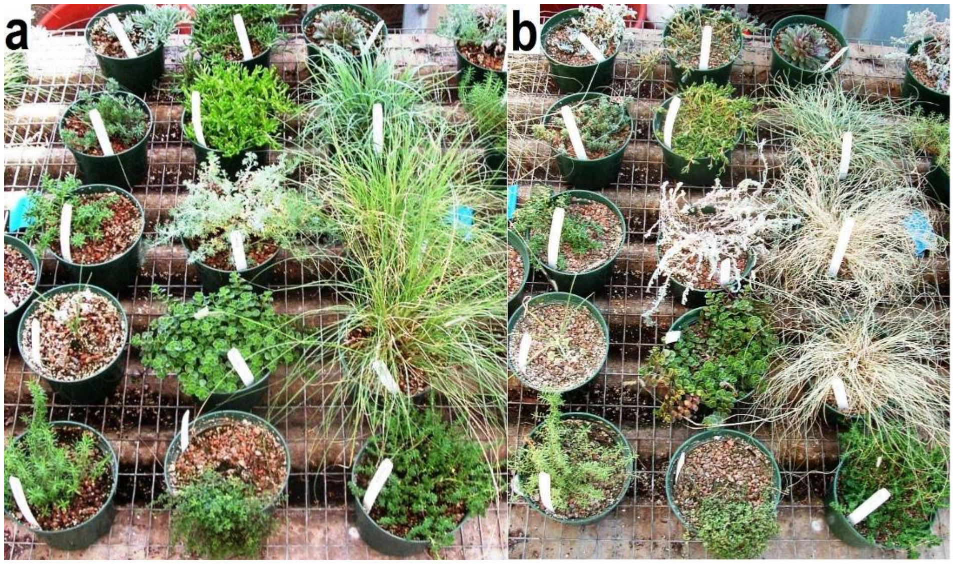


Figure 8-3: Example block showing the change in plant appearance a) the day after the trial began and b) day 12.

The mean relative water use for each species was estimated from substrate VMC data by subtracting the VMC of the non-vegetated control from the container VMC for each day and is presented in Table 8-3 along with number of days to top growth dieback and percent of plants revived after watering. Top growth die back was defined as when there was no viable green tissue, i.e. foliage and stems, above the substrate surface. When plants reached this state, plants were watered with 450 mL every 48 hrs to measure to determine if the plant had entered into dormancy or died. If plants had not died during the 151 day study, 450 ml of water was applied at the end of the study to evaluate if they could recover from an extended period of drought.

Table 8-3 Mean Relative Water Use, Days to Top Growth Dieback and Percent Revival after Watering in Greenhouse Trials

Species	Plant type	Mean relative water use (SE)	Days to dieback (SE)	Revival
Antennaria parvifolia	herbaceous	-1.53% (0.19) c[1]	22.79 (0.65) d	31.25%
Artemisia frigida	herbaceous	-6.23% (0.74) k	16.08 (0.32) a	8.33%
Bouteloua gracilis	herbaceous	-4.63% (0.46) hi	18.23 (0.71) ab	22.92%
Buchloe dactyloides	herbaceous	-3.56% (0.35) f	20.19 (0.90) bc	37.50%
Carex flacca	herbaceous	-4.77% (0.50) hij	20.13 (0.90) bc	27.08%
Penstemon pinifolius	herbaceous	-3.63% (0.32) fg	20.09 (0.67) bc	0.00%
Thymus pseudolanuginosus	herbaceous	-2.26% (0.20) de	20.75 (0.87) c	31.25%
Herbaceous mean		-3.80%	19.75	22.62%
Allium cernuum	succulent	-1.13% (0.25) b	59.25 (1.77) f	91.67%
Delosperma cooperi	succulent	-5.24% (0.60) ij	52.25 (1.44) e	0.00%
Delosperma nubigenum	succulent	-5.56% (0.69) ijk	107.06 (3.46) g	2.08%
Sedum acre	succulent	-2.72% (0.31) e	107.67 (6.46) g	2.08%
Sedum album	succulent	-4.48% (0.60) gh	151.00 (0.00) j	58.33%
Sedum lanceolatum	succulent	-1.22% (0.27) bc	138.71 (2.53) i	54.17%
Sedum spurium 'John Creech'	succulent	-2.00% (0.22) cd	127.87 (3.72) h	56.25%
Sempervivum 'Royal Ruby'	succulent	+2.04% (0.36) a	151.00 (0.00) j	69.44%
Succulent mean		-2.54%	111.75	41.75%

[1]Lower case letters show significant differences at the p≤ 0.05 level

Table 8-3indicates that only one species, *Sempervivum* 'Royal Ruby', had lower water usage than the non-vegetated control which potentially implies CAM. Results for number of days to top growth die back show a clear division between the herbaceous and succulent species. There was a nearly six-fold difference in days to dieback for the herbaceous plants versus the succulent species (Table 8-3). The herbaceous plants had a mean revival of 22.62% while the succulent species had a mean revival of 41.75% (Table 8-3).

Two of the succulent species (*S. album* and *Sempervivum* 'Royal Ruby') did not have any replications that died back during any of the 151-day trials (Table 8-3); however, while *S. album* and *S.* 'Royal Ruby' survived the initial dry down period, once rewatering commenced, some individuals died. These are similar results to a study in Michigan where the succulent species of *Sedums* remained viable for the entire four month study period (Durhman et al., 2004). Another *Sedum*, *S. rubrotinctum* has been shown to remain alive for up to two years in a greenhouse without irrigation (Teeri et al., 1986).

Outdoor Trial

Results for the outdoor trials show change of VMC for up to 18 days after initiation of dry down period, depending on the herbaceous (Figure 8-4) and succulent (Figure 8-5) species (error bars represent standard error). The results of the outdoor trial had similar trends to the greenhouse trials concerning rate of dry down of the herbaceous and succulents. In general, the growing media of succulent plants dried down more slowly than the herbaceous plants, although exceptions did occur. This can been seen in Table 8-4 which shows results of simple rate analysis (liner regression). It indicates that the succulants loose water at a slightly slower rate than the herbaceous plants and at a rate similar to that of media. Butler and Orians (2011) observed that sedums may reduce water loss from the green roof media.

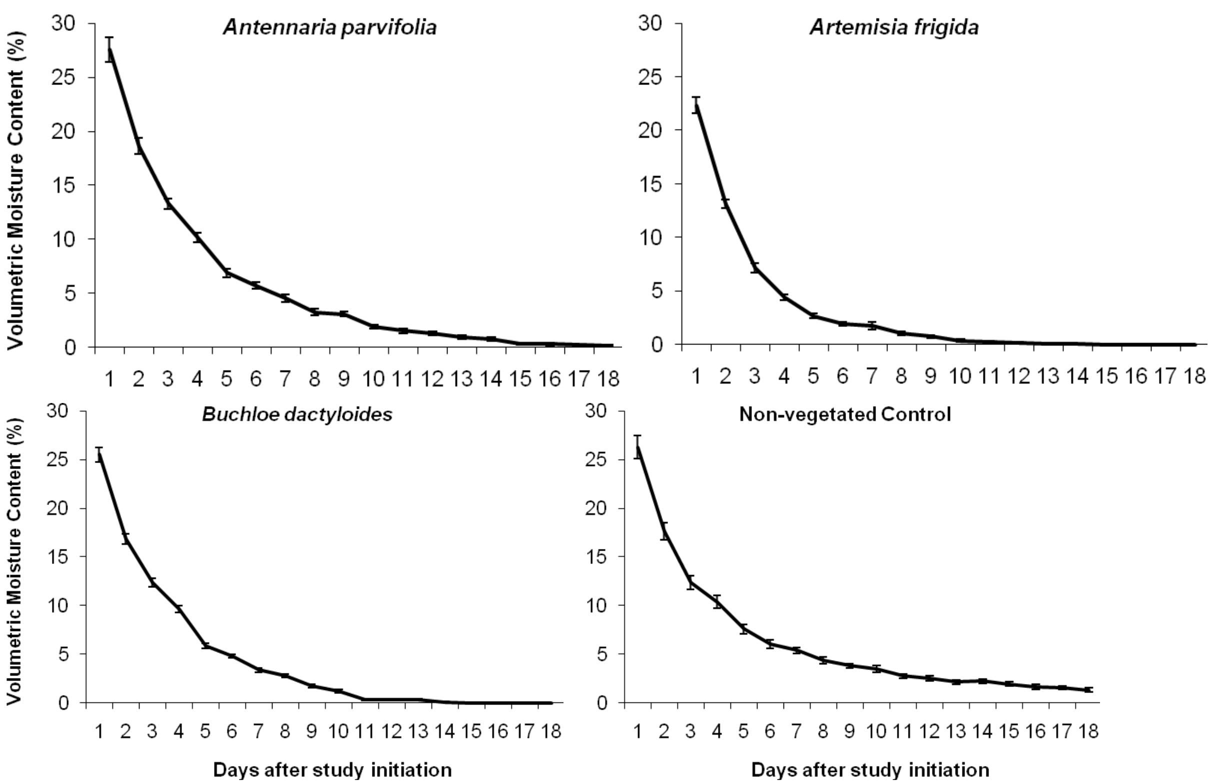


Figure 8-4: Mean volumetric moisture content measurements of growing media for herbaceous plants in outdoor trials

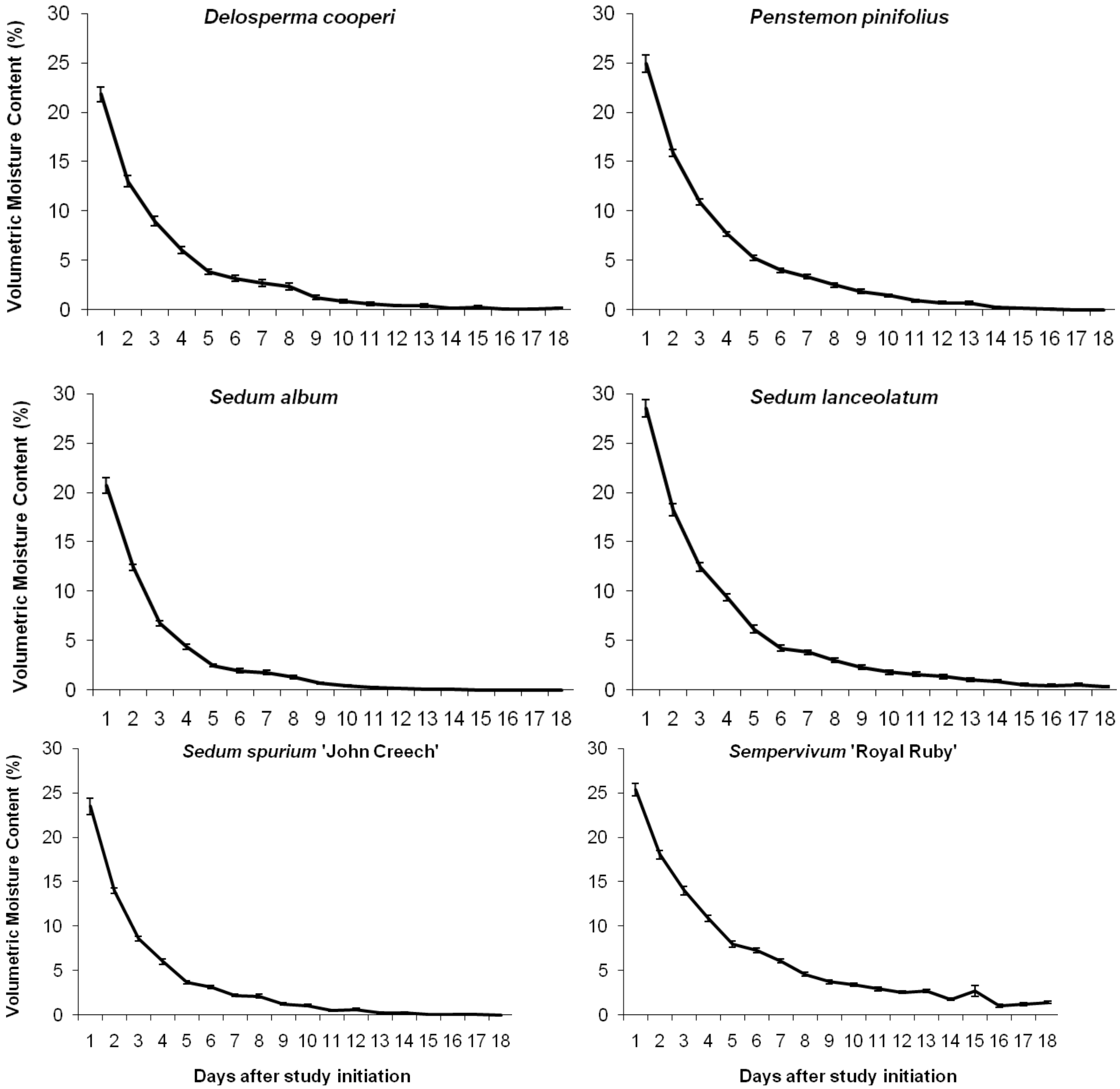


Figure 8-5: Mean volumetric moisture content measurements of growing media for succulent plants in outdoor trials

Table 8-4 Mean Relative Water Use, Days to 50% Volumetric Moisture Content Loss and Rate of Loss in Outdoor Trials

Species	Plant type	Days to 50% or greater VMC loss	Rate of water loss	
			3 day (r^2)	6 day (r^2)
Antennaria parvifolia	Herbaceous	3	- 7.1 (0.98)	- 4.2 (0.92)
Artemisia frigida	Herbaceous	3	- 7.6 (0.97)	- 3.9 (0.86)
Bouteloua gracilis	Herbaceous	3	- 6.6 (0.97)	- 4.0 (0.92)
Herbaceous mean		3.0	- 7.1 (0.98)	- 4.0 (0.90)
Delosperma cooperi	Succulent	3	- 6.4 (0.88)	- 3.5 (0.88)
Penstemon pinifolius	Succulent	3	- 7.0 (0.97)	- 4.0 (0.90)
Sedum album	Succulent	3	- 6.9 (0.99)	- 3.6 (0.86)
Sedum lanceolatum	Succulent	3	- 8.1 (0.98)	- 4.6 (0.91)
Sedum spurium 'John Creech'	Succulent	3	- 7.5 (0.98)	-3.9 (0.86)
Sempervivum 'Royal Ruby'	Succulent	4	- 5.7 (0.97)	- 3.5 (0.90)
Succulent mean		3.2	- 6.9 (0.84)	- 3.9 (0.89)
Non-vegetated control		3	- 6.9 (0.98)	- 3.8 (0.90)

The number of days to dieback and revival rates were quantified for the outdoor trial (Table 8-5). This table shows the mean difference in growing media VMC from the non-vegetated control, days to top growth dieback and percent revival after re-watering. The growing media of *A. parvifolia* retained more moisture for a longer period of time than did the growing media of most of the succulent species, except *Sempervivum* 'Royal Ruby', which is similar to what occurred in the greenhouse trials though *S. lanceolatum* retained slightly more moisture in the greenhouse trials. Once again only the species *Sempervivum* 'Royal Ruby' had a mean lower water usage than the non-vegetated control. The freezing temperatures prematurely truncated the study preventing the longer surviving succulent species from completing the dieback process as was done in the greenhouse trials. Therefore, results for the succulent species 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 8-5 Mean Relative Water Use, Days to Top Growth Dieback and Percent Revival after Watering for Outdoors Trial

Species	Plant type	Mean relative water use (SE)	Days to dieback (SE)	Revival[x]
Antennaria parvifolia	Herbaceous	-0.71% (0.21) b[1]	31.4 (0.24) c	54.17%
Artemisia frigida	Herbaceous	-3.21% (0.31) de	20.0 (0.31) a	50.00%
Buchloe dactyloides	Herbaceous	-1.57% (0.15) bc	27.7 (0.25) b	41.67%
Herbaceous mean		-1.83%	27.58	41.67%
Delosperma cooperi	succulent	-2.62% (0.25) d	NA[2]	NA
Penstemon pinifolius	succulent	-1.82% (0.08) c	31.2 (0.42) c	20.83%
Sedum album	succulent	-3.35% (0.36) e	NA	NA
Sedum lanceolatum	succulent	-0.94% (0.23) bc	NA	NA
Sedum spurium 'John Creech'	succulent	-2.57% (0.20) d	NA	NA
Sempervivum 'Royal Ruby'	succulent	+0.23% (0.15) a	NA	NA
Succulent mean		-1.85%	NA	NA

[1] Lower case letters show significant differences at the $p \leq 0.05$ level
[2] NA = Not applicable (due to truncation of study from freezing temperatures.)

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 had lower solar radiation due to filtration through the greenhouse covering (Table 8-6). Lower solar radiation in the greenhouse would lower ET rates as compared to higher solar radiation and outdoor winds which would increase 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).

Table 8-6 Environmental Conditions Daily Means Derived from Measurements in the Greenhouse and Outdoor Trials

Trial	Dates	Temperature (°C)	Relative humidity (%)	Maximum solar radiation ($W \cdot m^{-2}$)
Greenhouse	9/03/2008 to 9/30/2008	21.9 (0.05)	57.7 (0.13)	162 (1.87)
Greenhouse	9/03/2009 to 9/30/2009	21.7 (0.04)	56.8 (0.16)	163 $W \cdot m^{-2}$ (1.91)
Outdoor	8/20/2009 to 9/30/2009	16.7 (0.13)	58.8 (0.28)	311 $W \cdot m^{-2}$ (4.36)

[1] Standard errors in parenthesis.

The number of days to dieback took longer outdoors than in the greenhouse. There were differences in the amount of growing media not covered by plant canopy. Also, it is likely that the cooler nighttime temperatures outdoors (than in the greenhouse) would reduce nighttime evaporation. As the modules used outdoors had a greater rooting volume to draw moisture from (Figure 8-6), theoretically additional moisture from those areas of the module without vegetation between the plants was available. Figure 8-6 shows *Sempervivum* 'Royal Ruby' in greenhouse containers (a) and outdoor containers (b). In general, revival rates were also greater outdoors than indoors, potentially due to increased root zone.

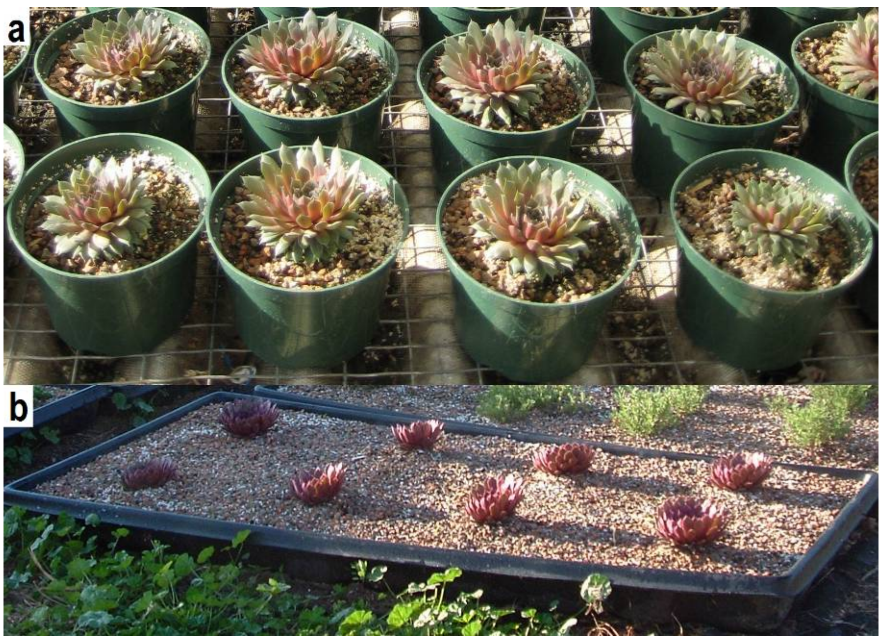


Figure 8-6 Photo examples of different containers used in green house (a) and outdoor (b) trials

Note: images are not of the same scale

Recommendations

Due to the differences in dry down rates and number of days to dieback between succulents and herbaceous species, the frequency of irrigation 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 6 cm (2.5 in.) (VanWoert et al., 2005). This study would concur with that recommendation as all succulents remained viable for at least 28 days following an irrigation event. 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 (Bousselot et al., 2011).

The herbaceous plants in this study will require more frequent irrigation than the succulents. If days to dieback are an indication of tolerance of low VMC, then irrigation should be provided more often than every 16 days for herbaceous species, which was the mean days to dieback for the earliest species to dieback, *A. frigida*. Even if VMC drops below wilting point (point where water is not longer available to plants), these species should be able to remain viable temporarily until moisture is again supplied. Therefore, irrigation frequency recommendations for the herbaceous species in this study are at least every 14 days (Bousselot et al., 2011).

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