# Evaluating a Natural Zeolite as an Amendment for Extensive Green Roof Substrate[1]

**Jennifer M. Bousselot[2], James E. Klett[3] and Ronda D. Koski[4]**
*Colorado State University, Department of Horticulture and Landscape Architecture*
*Fort Collins, CO 80523*

## Abstract

This research examined soilless green roof substrate blends on an existing modular extensive green roof in Denver, Colorado, USA. Substrate blends evaluated include an extensive green roof substrate, Green Grid® and Green Grid® plus varying percentages of ZeoPro™ H-Plus. Plant taxa used included *Sedum acre* L., *Sedum album* L., *Sedum spurium* Marsch-Bieb. 'Dragon's Blood' and *S. spurium* 'John Creech'. Substrate blends were evaluated based on plant taxa growth performance. Data collected included digital images to measure plant area covered using digital image analysis (DIA) and substrate volumetric moisture content (VMC). All data were analyzed over two growing seasons using the GLIMMIX procedure in SAS as multiple comparisons of substrate blends for each taxa, DIA data were analyzed from eight dates and VMC data were analysed from seven dates. The addition of zeolite (ZeoPro™) to the typical extensive green roof substrate improved establishment year plant cover for *S. acre* and *S. album* but hindered overwintering. Conversely, the two cultivars of *S. spurium* did not show a benefit of plant cover from the addition of ZeoPro™ in the first year but did the second year. As the percentage of ZeoPro™ in the substrate increased, VMC also increased.

**Index words:** digital image analysis, volumetric moisture content, zeolite, clinoptilolite, sedum, vegetated roof, substrate.

**Species used in this study:** *Sedum acre* L.; *Sedum album* L.; *Sedum spurium* Marsch-Bieb. 'Dragons Blood'; and *Sedum spurium* Marsch-Bieb. 'John Creech'.

### Significance to the Nursery Industry

Green roofs or vegetated roofs provide the nursery industry with unique opportunities to propagate, produce, and market unique plant taxa that have been proven to be suitable for growth in green roof systems. Improving extensive green roof substrate in ways that enhance green roof plant performance will make this type of green roof system more attractive for use on buildings in urban communities. Increasing the desire for green roofs will in turn increase the demand for plant taxa suitable for planting in extensive green roof systems.

### Introduction

Green roofs are an increasingly utilized device to help mitigate many environmental problems associated with urban communities (10). They have been effectively used worldwide as a mitigation tactic for urban stormwater management and urban heat island (UHI) effect, and for increasing the amount of green space available in urban communities. As a mitigation tactic for urban stormwater management, green roofs help to slow down the rate and reduce the total volume of water running off rooftops after precipitation events; due to the cooling effect of evapotranspiration, green roofs and the air above these vegetated surfaces are cooler when compared to nearby non-vegetated roofs (8, 10, 18). Green roofs also provide vegetated areas amongst expanses of asphalt, concrete, stone, and glass; these vegetated 'islands' add green spaces to urban communities and provide habitat for a variety of insect and animal species (8, 10, 18).

Extensive green roofs [characterized by shallow-depth substrate, generally less than 15 cm (6 in) deep] generally utilize a substrate made up predominantly of lightweight aggregate such as expanded clay, expanded shale, heat-expanded slate, and pumice (volcanic rock) (8). These materials allow for rapid drainage but have low nutrient holding capacity (8, 19, 20). While lightweight aggregates are beneficial for green roof substrate drainage and for satisfying building structural requirements, on their own these lightweight aggregates do not make ideal substrate for most plants. In a recent study, various percentages of heat-expanded slate were evaluated as green roof substrate. However, as the percentage of heat-expanded slate in the substrate increased, performance of the Sedum species, in general, decreased (20).

Organic matter is well known to be beneficial for root growth, however, extensive green roof substrate with high organic matter content (> 20% by volume) has resulted in shrinkage over time (1, 7, 8, 14). This shrinkage is due to the gradual break down of the organic matter. Even coarse organic materials, such as coir and peat moss, will eventually breakdown over the life of the green roof. Thus, use of green roof substrate with high organic matter content would require replenishment of the organic matter component, which is not time- or cost-effective for most green roof systems (20). Therefore most extensive green roof substrate are composed primarily of mineral-based materials (1, 14).

One material that has been used in shallow, well-drained golf greens to improve nutrient holding and water holding capacities is an expanded potassium-calcium clinoptilolite product, commonly referred to as zeolite (15, 17). ZeoPro™ (ZeoponiX, Inc., Boulder, CO), is a type of zeolite that is mined from volcanic deposits. The granules in ZeoPro™ have a diameter range of 0.4–2.4 mm (0.02–0.09 in), and a lattice structure suitable for plant-extractable nutrient and moisture retention.

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[2]Former Graduate Research Assistant.

[3]Professor. jim.klett@colostate.edu. To whom all correspondence should be directed.

[4]Research Associate.

Incorporating ZeoPro™ into a typical mineral-based green roof substrate may improve nutrient holding and water holding capacities. The objective of this study was to evaluate plant growth response to a series of extensive green roof substrate blends containing various percentages of ZeoPro™.

## Materials and Methods

Rooftop experiments were conducted on the roof of the 8th floor of the building that houses the EPA Region 8 Headquarters (1595 Wynkoop, Denver, CO). A 10 cm (3.94 in) deep extensive modular (tray) GreenGrid® (Weston Solutions, Inc., West Chester, PA) system was installed in the fall of 2006. Research modules were placed among the existing modules in the spring of 2008.

The species used to evaluate the ZeoPro™ amendment were the *Sedum* taxa already in use on the green roof: *Sedum acre* (goldmoss stonecrop), *Sedum album* (white stonecrop), *Sedum spurium* (two-lined stonecrop) 'Dragon's Blood' and *S. spurium* 'John Creech'. The *Sedums* were planted as a mixed stand (one plant per taxa per module) in 61 × 61 × 10 cm (24 × 24 × 3.9 in) modules on 30.5 cm (12 in) centers from 128-cell plug trays.

Modules were filled with one of four substrate blends: 3:0 GreenGrid® substrate to ZeoPro™ (0% ZeoPro™ H-Plus, from ZeoponiX, Inc. Boulder, CO), 2:1 GreenGrid® to ZeoPro™ (33% ZeoPro™), 1:2 Green Grid® to ZeoPro™ (66% ZeoPro™) and 0:3 Green Grid® to ZeoPro™ (100% ZeoPro™). Modules for each of the four substrates were replicated ten times. The GreenGrid® substrate is a proprietary blend that is lightweight, well-drained and designed for use in this modular system. It contains various percentages of expanded clay, peat, perlite and vermiculite. Chemical and physical characteristics of the substrate blends can be found in Table 1. Substrate physical properties were analyzed at Hummel & Co, Inc. Laboratory in Trumansburg, NY, and reported on March 2, 2010. All physical properties were tested per ASTM E2399, unless noted. Analytical methods included organic matter [ASTM (*American Society for Testing and Materials*) 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 at pF 1.8 (pF 1.8 is equal to field capacity on the substrate moisture retention curve).

Planted modules were hand watered every 48 hour to saturation and maintained at 23.9C (75F) daytime and 18.3C (65F) nighttime temperatures. Modules were moved from the greenhouse outdoors to acclimate on March 20, 2008, and fertilizer (Scott's Osmocote Pro 19-5-8) was applied at the rate of 41.5 g (1.46 oz) per tray. On March 26, 2008, the trays were installed on the EPA Region 8 green roof in Denver, CO.

During the 2008 growing season, irrigation was supplied by 3.5 liters (0.92 gal) per hour drip emitters spaced every 30.5 cm (12 in). At initiation of study, irrigation was provided at 18.7 mm (0.74 in) per week and then reduced to 8.0 mm (0.31 in) per week on August 15. In order to provide more uniform coverage of water, the irrigation system was changed to an overhead MP rotator (Hunter Industries, San Marcos, CA) system, during the 2009 growing season. With emitters spaced 2.44–3.66 m (8–12 ft) apart, irrigation was provided at 6.4 mm (0.25 in) per week starting July 9. Irrigation initiation in 2009 was delayed due to an unusually moist spring, with precipitation 81.3, 14.2, and 64.4% above normal for April, May and June, respectively. Weather for the 2008 and 2009 growing seasons are summarized in Table 2.

*Data collection*. Plant area covered (plant cover) was determined by taking digital images, similar to a concurrent study evaluating plant species on the green roof (as described in 2). A FujiFilm FinePix S3000 (6× optical zoom 3.2 mega pixels lens) camera was mounted to a 190xprob tripod (Bogen Manfrotto, Ramsey, NJ) with an extendable horizontal arm. Digital image analysis (DIA) was performed using SigmaScan Pro 5.0 (SPAA Science, Chicago, IL) image analysis software. The DIA data were analyzed to evaluate the progression of plant cover over time.

DIA data were collected on eight dates over two years and were analyzed to determine plant cover. Four dates in 2008 at six week intervals [May 14 (Day 49), June 25 (Day 91), August 6 (Day 133) and September 16 (Day 174)] and four dates at six week intervals in 2009 [May 13 (Day 413), June 24 (Day 455), August 5 (Day 497) and September 15 (Day 538)] were evaluated. Winter survival was determined for each plant on May 13, 2009, and was determined via visual observation of the absence or presence of plant growth.

Additionally, volumetric moisture content (VMC) of the substrates was quantified using a ThetaProbe ML2X (Delta-T Devices, Cambridge, UK). The ThetaProbe was inserted

**Table 1. Chemical and physical characteristics of the four substrates.**

| Substrate characteristic | | | 0% ZeoPro™[z] | 33% ZeoPro™ | 66% ZeoPro™ | 100% ZeoPro™ |
|---|---|---|---|---|---|---|
| Organic matter content | | % | 4.9 | 1.8 | 0.6 | 0.3 |
| $NO_3$-Nitrogen (N) | | ppm | 105 | 197 | 158 | 21 |
| Total N | | ppm | 1383 | 1401 | 1466 | 1929 |
| Phosphorus (P) | | ppm | 19 | 21 | 26 | 14 |
| Potassium (K) | | ppm | 251 | 1215 | 1456 | 1597 |
| Bulk density | | $g \cdot c^{-3}$ ($lb \cdot ft^{-3}$) | 0.66 (41.20) | 0.75 (46.82) | 0.90 (56.18) | 0.97 (60.56) |
| Particle sensity | | $g \cdot c^{-3}$ ($lb \cdot ft^{-3}$) | 1.96 (122.36) | 2.01 (125.48) | 2.26 (141.09) | 2.35 (146.71) |
| Saturated hydraulic conductivity | | $cm \cdot s^{-1}$ ($in \cdot s^{-1}$) | 0.0102 (0.0040) | 0.0108 (0.0043) | 0.0101 (0.0039) | 0.0154 (0.0060) |
| At max water capacity | Air content | % | 17.7 | 13.6 | 14.9 | 26.8 |
| | Water content | % | 48.6 | 48.9 | 45.1 | 32.0 |
| At pF[y] = 1.8 (FLL, 2008) | Air content | % | 35.7 | 32.8 | 32.3 | 39.4 |
| | Water content | % | 30.6 | 29.7 | 27.7 | 19.5 |

[z]This substrate was composed of expanded aggregate clay:peat:perlite:vermiculite (50:20:20:10, by vol).

[y]pF = 1.8 is equal to field capacity on the green roof substrate moisture retention curve.

Table 2. **Mean monthly weather data for the 2008 and 2009 growing seasons.**

| | | May | | June | | July | | August | | September | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Weather** | | **2008**[z] | **2009**[y] | **2008**[z] | **2009**[y] | **2008**[z] | **2009**[y] | **2008**[y] | **2009**[y] | **2008**[y] | **2009**[y] |
| Minimum temperature | C | 6.7 | 10.7 | 11.9 | 13.5 | 16.8 | 16.3 | 16.7 | 15.9 | 11.3 | 11.8 |
| | F | 44.1 | 51.3 | 53.4 | 56.3 | 62.2 | 61.3 | 62.1 | 60.6 | 52.3 | 53.2 |
| Maximum temperature | C | 22.6 | 24.7 | 29.4 | 28.3 | 34.4 | 31.8 | 31.7 | 32.0 | 26.5 | 27.6 |
| | F | 72.7 | 76.5 | 84.9 | 82.9 | 93.9 | 89.2 | 89.1 | 89.6 | 79.7 | 81.7 |
| Precipitation | mm | 64.3 | 56.4 | 16.8 | 41.3 | 3.8 | 63.5 | 8.4 | 21.8 | 16.0 | 17.5 |
| | in | 2.53 | 2.22 | 0.66 | 1.63 | 0.15 | 2.5 | 0.33 | 0.86 | 0.63 | 0.69 |
| Irrigation amounts | mm | 160.5 | 4.8 | 97.6 | 13.9 | 114.1 | 56.6 | 87.6 | 82.1 | 68.4 | 66.0 |
| | in | 6.32 | 0.19 | 3.84 | 0.55 | 4.49 | 2.23 | 3.45 | 3.23 | 2.69 | 2.60 |

[z]National Weather Service station (ID: 052223) at Denver Water (1600 W. 12th Avenue, Denver, CO) collected 2.6 km (1.62 m) away from green roof.
[y]Campbell Scientific (Logan, UT) weather station located on the EPA Region 8 green roof (1595 Wynkoop Street, Denver, CO).



into the substrate up to the depth of the probe [5 cm (1.97 in)]. Three readings per module per date were recorded. For the VMC data, four dates in 2008 [May 14 (Day 49), June 25 (Day 91), August 6 (Day 133) and September 16 (Day 174)] and three dates in 2009 [May 27 (Day 426), August 19 (Day 510) and September 15 (Day 538)] were evaluated. *Note*: the 2009 dates for VMC data are different than the dates for DIA data due to technical difficulties with the ThetaProbe.

*Experimental design and data analysis.* The experiment was laid out as a randomized complete block design. There were ten blocks with each of the four treatments per block (Fig. 1).

All 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. Since a few of the overwintering data were 0 and 100%, chi-square tests were used to make

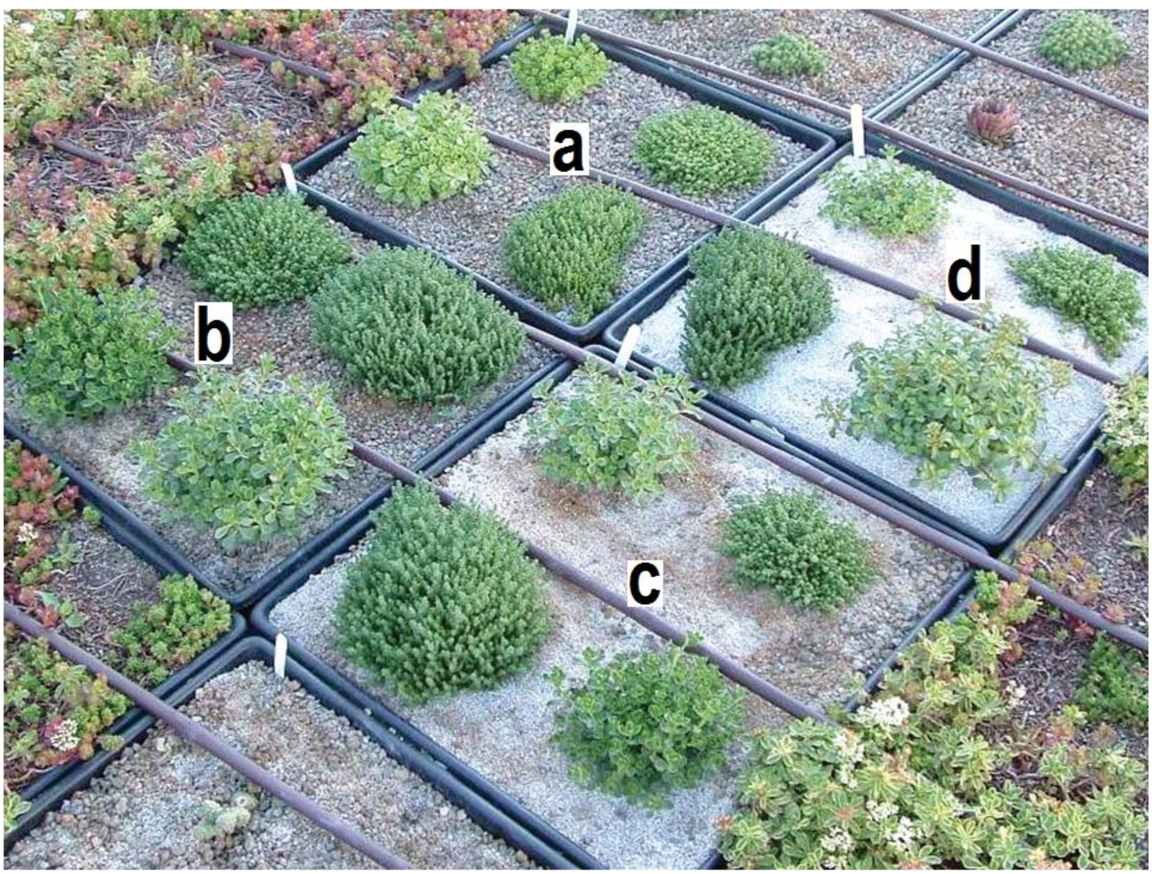


**Fig. 1. Image of one of the ten blocks (taken on July,1, 2008) showing response of the four Sedum taxa to the four substrates (moving counter-clockwise): a) 0% ZeoPro™, (counter-clockwise) b) 33% ZeoPro™, c) 66% ZeoPro™ and d) 100% ZeoPro™.**

pair wise comparisons. All significant differences are at the $p \leq 0.05$ level.

## Results and Discussion

All four *Sedum* taxa responded to the addition of ZeoPro™, however, not all in the same growing season or at the same percentage of ZeoPro™ (Fig. 2). For example, by the end of 2008, *S. acre* had the highest plant cover in the mixed blends (33 and 66% ZeoPro™) and the lowest in the uniform blends (0 and 100% ZeoPro™). While *S. album* increased in plant cover with increasing ZeoPro™ content of the substrate.

However, both *S. acre* and *S. album* had low overwintering percentages, determined as presense or absence of individual plants, as ZeoPro™ content of the substrate increased (Table 3). While winter survival as a percentage was higher in the treatment with no ZeoPro™ than the treatments with ZeoPro™, the *S. acre* and *S. album* plants that did survive had less plant cover over the 2009 growing season when compared to the 2008 growing season (Fig. 2). This is consistent with research that showed that some plants that were not fertilized during the previous growing season survived over the winter but were smaller in size compared to those that were fertilized (20). In the current study, all plants were fertilized at initiation of the study, however, the ZeoPro™ treatments have higher nutrient levels, especially K, than the treatment with no ZeoPro™ (Table 1).

Due to the fact that so few individual plants for either *S. acre* or *S. album* survived over the winter and those that did survive were small, no significant differences in plant cover existed between treatments by the end of the 2009 growing season. Researchers in Michigan have noted good overwintering success for these two species of *Sedum* in the short term, even in some cases noting the dominance of these two species specifically (5, 6, 16). Over a long term study, *S. acre* was relatively more dominant among a mixed stand of species in shade than sun (12). Due to the contrasting results, apparently there are enough climactic differences between regions to influence survivability of these species of sedums such as temperature fluctuations in fall, lack of snow cover during most of winter and early spring in Colorado compared to Michigan and Sweden. In Canadian research, substrate depth greatly influenced overwintering success rates of *S. × hybridum* (2). Similarly, a Swedish study showed dominance of these two species except that *S. acre* decreased in area covered coming out of the second winter of the study, similar to the results of the current study (7).

The two *S. spurium* taxa ('Dragon's Blood' and 'John Creech') showed different results than the other two taxa (*S. acre* and *S. album*). At the end of the 2008 growing season, no significant differences in plant cover existed between treatments for either *S. spurium* cultivar. Although overwintering showed 100% survival across treatments for both *S. spurium* cultivars (Table 3), plants in the 100% ZeoPro™ treatment were reduced in size at the beginning of the second season (note the decrease in plant cover on Day 413 in Fig. 2), which is clearly an effect of overwintering survival. The two cultivars of *S. spurium* may have survived in greater numbers than *S. acre* and *S. album* because *S. spurium* is semi-evergreen while the other two are evergreen.

Due in part to this overwintering phenomenon, the 2009 results for the *S. spurium* cultivars show significant differences by treatment. For *S. spurium* 'Dragon's Blood', the

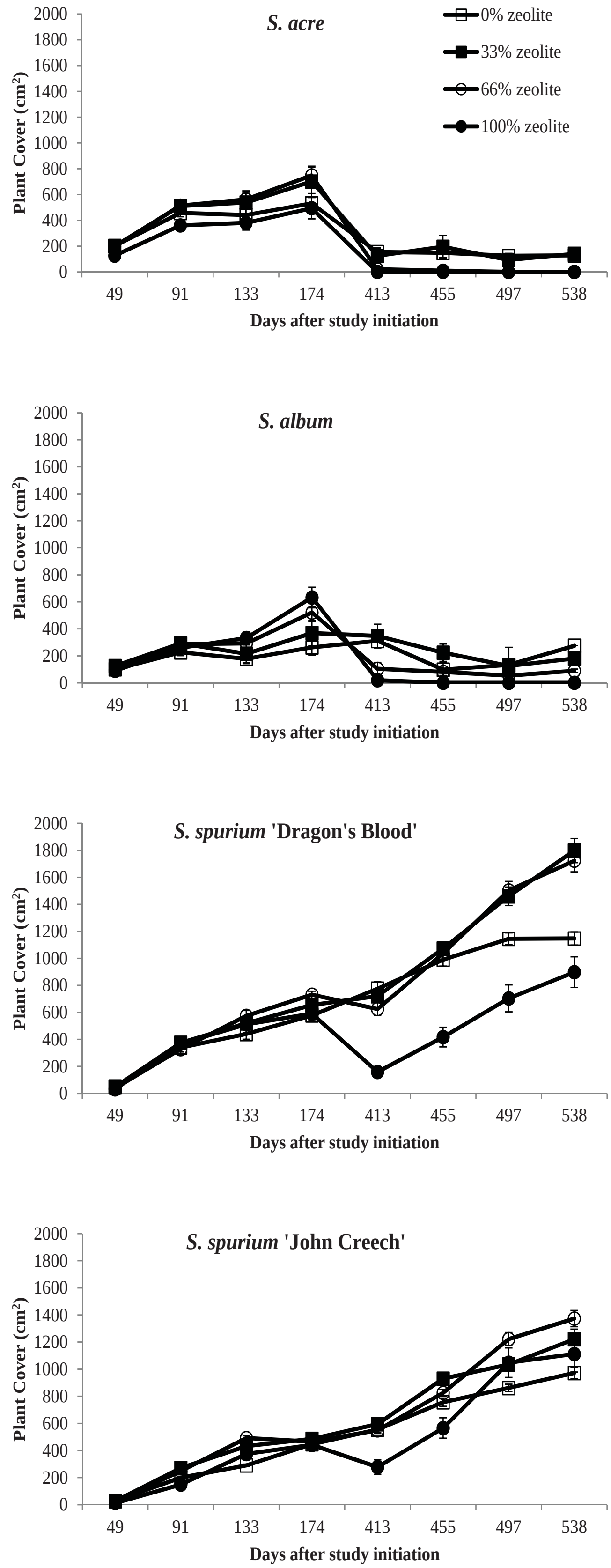


**Fig. 2. Plant cover of four *Sedum* taxa in response to four substrates as determined by digital image analysis (DIA) over eight dates during two growing seasons. Days 49, 91, 133 and 174 are in 2008 and days 413, 455, 497 and 538 are in 2009.**

Table 3. **Overwintering survival data for each *Sedum* taxa at each treatment; ten plants of each taxa were planted in 2008.Overwinter survival was calculated as the number of plants that exhibited regrowth determined on Day 413 (May 13, 2009) of the study.**

| Taxa | 0% ZeoPro™ | 33% ZeoPro™ | 66% ZeoPro™ | 100% ZeoPro™ |
|---|---|---|---|---|
| | Percent survival | | | |
| *S. acre* | 80aA[z] | 40abA | 10bA | 0bA |
| *S. album* | 90aA | 90aB | 50abA | 10bA |
| *S. spurium* 'Dragon's Blood' | 100aA | 100aB | 100aB | 100aB |
| *S. spurium* 'John Creech' | 100aA | 100aB | 100aB | 100aB |

[z]Lower case letters indicate significant differences at the $p \leq 0.05$ level across rows. Upper case letters indicate significant differences at the $p \leq 0.05$ level down columns.

100% ZeoPro™ treatment had significantly lower plant cover from all other treatments through the 2009 growing season except on the last day (Day 538) compared to the 0% ZeoPro™ treatment (Fig. 2). *Sedum spurium* 'John Creech' showed a similar pattern but the 100% ZeoPro™ treatment recovered in plant cover more quickly than the 'Dragon's Blood' cultivar. Therefore, the 100% ZeoPro™ treatment was significantly lower in plant cover from the 33 and 66% ZeoPro™ treatments early in the season, on Days 413 and 455. The 0% ZeoPro™ treatment was only significantly different on Day 413 from the 100% ZeoPro™ treatment.

There are many possible factors which affected survivability of these green roof plants in these different substrate blends, especially during the winter season. Winter VMC and diurnal temperature fluctuation related to media color may influence plant survival. In a greenhouse study, the three species of sedums demonstrated variable rates of dry down with both *S. acre* and *S. album* drying down more rapidly than *S. spurium* 'John Creech' (4). The mean daily minimum temperature of the GreenGrid® substrate during the winter months (December 2008 through March 2009) was –3.0C (27F). However, minimum temperature alone may not be the only problem as *Sedum spectabile* has been shown to not survive –3.0C (27F) temperatures in September but, depending on the cultivar, can survive conditions at less than –20C (–4F) in January (13). Additionally, the root hardiness of these species is unknown in this type of shallow, well-drained system. A longer trial period (greater than two years) may also ultimately affect results such as these (11, 21). Finally, while it has not been formally documented, root size in relation to top growth for some of these species (i.e. *S. acre* and *S. album*) has been found to be noticeably less in luxury nutrient and moisture content situations compared to drier and lower fertility substrate.

*Substrate VMC*. Results of the VMC data indicate that moisture holding capacities of treatments varied by their relative proportion of ZeoPro™ (Table 4). During the first three evaluation dates of 2008, the trend is that the least amount of moisture was present in the 0% ZeoPro™ treatment and the highest was in the 100% ZeoPro™ treatment, which is not consistent with the data provided in Table 1. The field results are consistent with research in turfgrass, which shows higher moisture contents in substrates that contain clinoptilolite than in sand alone (15, 17). The difference between field and laboratory (Table 1 data) results is likely due to the higher ZeoPro™ substrate blends forming a thin crust at the substrate surface, therefore reducing the evaporative losses in the field compared to the 0% ZeoPro™ treatment.

Additionally, a qualitative comparison between irrigation application methods can be made as there were two different systems used in the two years of the study. As noted above, a drip irrigation system was used in 2008 and an overhead rotator system was used in 2009. This means that the overhead rotator system is equally, if not more appropriately, suited to this type of extensive green roof system because it effectively supplies parallel VMC for the plants while only using one third of the water as the drip irrigation system (Table 2). This observation is in agreement with similar irrigation observations discussed in other regions of North America (1, 9).

In conclusion, the addition of ZeoPro™ to the substrate on an extensive green roof improved establishment year growth for *S. acre* and *S. album* but higher concentrations of ZeoPro™ hindered overwintering success of these two species. Conversely, the two cultivars of *S. spurium* did not show benefit from the addition of ZeoPro™ in the first year (2008) but did the second year (2009). Therefore, the data indicate that addition of ZeoPro™ to extensive green



Table 4. **Substrate volumetric moisture content (VMC) on seven dates over two growing seasons.**

| | % Substrate VMC (standard error) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2008 | | | | 2009 | | |
| Treatment | Day 49 | Day 91 | Day 133 | Day 174 | Day 426[z] | Day 510 | Day 538[y] |
| 0% ZeoPro™ | 14.02 (0.77)b[x] | 5.16 (1.11)d | 8.05 (1.62)b | 12.78 (1.13)a | 13.58 (1.08)a | 7.49 (0.84)ab | 9.85 (1.06)a |
| 33% ZeoPro™ | 15.62 (0.51)ab | 7.30 (1.55)cd | 10.12 (1.04)b | 12.83 (0.72)a | 14.00 (1.26)a | 6.42 (0.45)b | 7.32 (0.59)a |
| 66% ZeoPro™ | 14.43 (0.49)b | 9.28 (0.95)bc | 9.46 (1.37)b | 12.65 (0.70)a | 14.53 (0.75)a | 6.86 (0.46)b | 7.96 (0.55)a |
| 100% ZeoPro™ | 17.69 (0.32)a | 12.02 (1.57)a | 10.81 (1.90)a | 12.53 (0.61)a | 15.65 (0.60)a | 9.44 (0.63)a | 9.21 (0.44)a |

[z]Precipitation equaling 31.24 mm (1.23 in) was recorded within 24 hours prior to VMC sampling.

[y]Precipitation equaling 13.46 mm (0.53 in) was recorded within 24 hours prior to VMC sampling.

[x]Lower case letters indicate significant differences at the $p \leq 0.05$ level.

roof substrate is beneficial for certain species of sedum. In general, VMC increased with increasing ZeoPro™ content of the substrate, but laboratory results showed decreasing water holding capacity as ZeoPro™ percentage increased. Additionally, the overhead rotator irrigation system was apparently more efficient than the drip irrigation at supplying similar VMC to plants.

Based on the finding of this study, the authors suggest that if ZeoPro™ is used to amend green roof substrates, it should consist of no more than 33% of the substrate blend.

## Literature Cited


1. Beattie, D. and R. Berghage. 2004. Green roof media characteristics: The basics. *In*: Proc. of 2nd North American Green Roof Conference: Greening Rooftops for Sustainable Communities. The Cardinal Group, Toronto: Portland, OR. June 2–4, 2004. p. 411–416.

2. Boivin, M., M. Lamy, A. Gosselin, and B. Dansereau. 2001. Effect of artificial substrate depth on freezing injury of six herbaceous perennials grown in a green roof system. HortTechnology 11:409–412.

3. Bousselot, J.M., J.E. Klett, and R.D. Koski. 2010. Extensive green roof species evaluations using digital image analysis. HortScience 45:1288–1292.

4. Bousselot, J.M., J.E. Klett, and R.D. Koski. 2011. Moisture content of extensive green roof substrate and growth response of 15 temperate plant species during dry down. HortScience 46:518–522.

5. Durhman, A.K., D.B. Rowe, and C.L. Rugh. 2007. Effect of substrate depth on initial growth, coverage, and survival of 25 succulent green roof plant taxa. HortScience 42:588–595.

6. Durhman, A.K., et al. 2004. Evaluation of Crassulaceae species on extensive green roofs. *In*: Proc. of 2nd North American Green Roof Conference: Greening Rooftops for Sustainable Communities. The Cardinal Group, Toronto: Portland, OR. June 2–4, 2004. p. 504–517.

7. Emilsson, T. 2008. Vegetation development on extensive vegetated green roofs: Influence of substrate composition, establishment method and species mix. Ecological Engineering 33:265–277.

8. FLL. 2008. Guidelines for the planning, execution and upkeep of green-roof sites. Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau, Bonn.

9. Friedrich, C.R. 2005. Principles for selecting the proper components for a green roof growing media. *In*: Proc. of 3rd North American Green Roof Conference: Greening Rooftops for Sustainable Communities. The Cardinal Group, Toronto: Washington, DC. May 4–6, 2005. p. 262–274.

10. Getter, K.L. and D.B. Rowe. 2006. The role of extensive green roofs in sustainable development. HortScience 41:1276–1285.

11. Getter, K.L. and D.B. Rowe. 2009. Substrate depth influences sedum plant community on a green roof. HortScience 44:401–407.

12. Getter, K.L., D.B. Rowe, and B.M. Cregg. 2009. Solar radiation intensity influences extensive green roof plant communities. Urban Forestry and Urban Greening 8:269–281.

13. Iles, J. and N. Agnew. 1995. Seasonal cold-acclimation patterns of *Sedum spectabile* × *telephium* L. 'Autumn Joy' and *Sedum spectabile* Boreau. 'Brilliant'. HortScience 30:1221–1224.

14. Miller, C. 2003. Moisture management in green roofs. *In*: Proc. of 1st North American Green Roof Conference: Greening Rooftops for Sustainable Communities. The Cardinal Group, Toronto: Chicago, IL. May 29–30, 2003. p. 177–182.

15. Miller, G. 2000. Physiological response of bermudagrass grown in soil amendments during drought stress. HortScience 35:213–216.

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

17. Murphy, J.A., H. Samaranayake, J.A. Honig, T.J. Lawson, and S.L. Murphy. 2005. Creeping bentgrass establishment on amended-sand root zones in two microenvironments. Crop Science 45:1511–1520.

18. Oberndorfer, E., J. Lundholm, B. Bass, R.R. Coffman, H. Doshi, N. Dunnett, S. Gaffin, M. Köhler, K.K.Y. Liu, and B. Rowe. 2007. Green roofs as urban ecosystems: Ecological structures, functions, and services. Bioscience 57:823–833.

19. Panayiotis, N., T. Panayiota, and C. Loannis. 2003. Soil amendments reduce roof garden weight and influence the growth rate of *Lantana*. HortScience 38:618–622.

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

21. Thuring, C.C., R.D. Berghage, and D.J. Beattie. 2010. Green roof plant responses to different substrate types and depths under various drought conditions. HortTechnology 20:395–401.