Moisture Content of Extensive Green Roof Substrate and Growth Response of 15 Temperate Plant Species during Dry Down

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Abstract. Success of extensive green roof vegetation depends primarily on associated plant species’ ability to survive the low moisture content of the substrate. As a result of the well-drained nature of the substrate, 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. To effectively select suitable plants, species need to be evaluated in terms of their response to gradual and prolonged dry down of the substrate. A study to determine the relative rates of dry down for 15 species was conducted in greenhouse trials. During dry downs that extended over 5 months, the substrate of succulent and herbaceous species dried down at different rates. The change in moisture content of the substrate was not consistent among succulent and herbaceous plant species during the initial 18 d of dry down. Despite differences in rate of dry down, the succulent species, as a group, maintained viable foliage for over five times longer than the herbaceous species. The revival rates of the succulent species were nearly double those of the herbaceous species. Therefore, not only are succulent species more likely to survive during periods of drought, but these species are more likely to resume growth soon after water is again made available.

Green roofs provide many benefits to urban communities and can be used to help alleviate the negative effects of urbanization (Getter and Rowe, 2006; Oberndorfer et al., 2007). A healthy vegetation layer is essential for achieving these benefits. Therefore, knowledge about plant tolerance to severe moisture stress is essential, especially in a system such as an extensive green roof where moisture is typically a limiting factor for plant health. The substrate used for extensive green roofs is lightweight, well drained, and prone to extreme fluctuations in moisture content. As a result of the characteristics of the substrate, plant species used in extensive green roof systems, among other things, must be able to adapt to periods of low moisture availability in their root zones.

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

To avoid issues associated with *Sedum* monocultures, additional plant species will need to be incorporated into the extensive green roof plant palette. *Sedum* monocultures result in an unvarying, monotone effect (Dunnett and Nolan, 2004). Additionally, similar to row crop monocultures, these systems may have a higher probability of pest problems than a system that has diversity. Many examples can be found in agriculture that illustrate how plant species diversity affects pest populations, particularly

how pest incidence increases in monocultures (Altieri and Letourneau, 1982). Therefore, it would be ideal to avoid potential future issues on extensive green roofs by diversifying plant selection.

Enhancing plant species biodiversity can make extensive green roofs attractive to regionally native arthropod and avian species (Wolf and Lundholm, 2008). Additionally, a diversified plant palette on an extensive green roof may be able to adapt to variable moisture conditions and maximize the evaporative cooling benefit, thus extending the benefits of extensive green roofs (Compton and Whitlow, 2006). Finally, green roofs can be used as an urban location to maintain plant biodiversity (Dunnett and Kingsbury, 2004).

Incorporating native plants into extensive green roof systems has been investigated by others; however, the research in this area suggests that very few plant species can match the growth and survival performance of the non-native *Sedum* species (Dunnett and Nolan, 2004; Durhman et al., 2007; Kircher, 2004; Latocha and Batorska, 2007; Monterusso et al., 2005). This could be because the properties of the soils in which many native plants evolved are significantly different from those of the shallow well-drained, green roof substrate. Native plants should not be considered for use on green roofs based solely on the fact that they are adapted to local conditions (Dunnett, 2006).

Evaluating plants that are native to habitats characterized by growing conditions similar to shallow well-drained extensive green roofs may yield more favorable results. Plant communities that develop on shallow and well-drained soils, which mimic the conditions typical of an extensive green roof, may be sources of additional plant species suitable for extensive green roof culture. For example, plant species native to rocky and well-drained areas in Michigan have been incorporated into the plant palette for extensive green roofs in the Great Lakes region (Durhman et al., 2007). Semiarid areas in Colorado often possess shallow and well-drained soils and receive low annual precipitation often with extended periods of below-normal precipitation. Thus, plant species native to these areas may be well suited for use on extensive green roofs (Getter and Rowe, 2006) because they possess mechanisms that allow them to survive extending periods of suboptimal soil moisture conditions.

Regardless of plant species origin, the establishment, survival, and success of plants in an extensive green roof located in a semiarid region require irrigation (Bousset, 2010). 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).

Selection of plants for use on extensive green roofs should be based on the following criteria: tolerant of soil moisture deficit, low-growing growth habit (beneficial for extensive green roofs to obtain good coverage), evergreen foliage, and a long period of bloom. Plants with an erect growth habit can be used as accent plants (good for contrast with groundcovers in heights and bloom times).

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Plant species considered for use in extensive green roof systems need to be evaluated for their response to gradual and long-term drying of the substrate. Thus, relative rate of dry down for plant species considered for use in such systems is an important characteristic to assess. In semiarid 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 substrate on the growth of 15 plant species and to determine the relative water use for each of the 15 species.

Materials and Methods

Fifteen plant species were used in two dry down trials conducted in a greenhouse in northern Colorado. Environmental conditions for both of the greenhouse trials are summarized in Table 1. Experiments were performed 1 year apart in the Fall of 2008 and 2009.

For both trials, 24 propagules of each species were randomly selected from 128-cell plug trays of each respective species. The substrate was composed of five parts heat-expanded shale (50% by volume of 95- to 63-mm diameter particles, 30% by volume of 63- to 20-mm diameter particles and 20% by volume of greater than 20-mm diameter particles), two parts sphagnum peatmoss, two parts perlite, and one part vermiculite, by volume. The composition of the substrate was consistent across both trials (Table 2).

Individual propagules of each species (Table 3) were planted singly in containers and established for 10 weeks in a greenhouse. The containers used were circular green plastic 152 mm diameter by 108-mm deep pots. Each container was filled with substrate to a depth of 100 mm to equal the depth of the substrate on a typical extensive green roof. Twenty-four replications per species were planted and laid out as a randomized complete block design. Pots were spaced equidistantly at ≈ 250 -mm centers on wire mesh greenhouse benches.

After planting in containers, plants were irrigated to saturation every 48 h; this irrigation regimen was continued during the establishment period until 10 d before initiation of the dry down period. Then, irrigation was tapered to every 72 h between irrigation events for two irrigations and finally to 96 h before the final irrigation just before dry down initiation. At the final irrigation, all plants were irrigated with 450 mL and free drainage was allowed for at least 12 h before taking the first substrate moisture measurement. Fertilizer (Scotts Osmocote Pro 19-5-8; Scotts-Sierra Horticultural Products Co., Marysville, OH) was applied at 5 g per propagule 4 weeks before dry down initiation. Pots containing substrate with no vegetation served as the non-vegetated controls and were used to evaluate evaporation.

Data collection and statistical analysis. For both trials, substrate volumetric moisture content (VMC) was recorded daily for each plant using a ThetaProbe ML2x (Delta-T Devices, Ltd., Cambridge, UK). The probe was inserted to 60-mm depth in the substrate, at

Table 1. Environmental conditions daily means derived from measurements taken at 5-min intervals in the greenhouse trials (SES in parentheses).

Trial	Temperature ^z	Relative humidity ^z	Solar radiation ^y
Greenhouse 2008 ^x	21.85 °C (0.05)	57.73% (0.13)	162.36 W·m ⁻² (1.87)
Minimum/maximum	9.21/35.08 °C	25.08/84.63%	—
Greenhouse 2009 ^w	21.66 °C (0.04)	56.82% (0.16)	163.13 W·m ⁻² (1.91)
Minimum/maximum	10.88/27.35 °C	22.84/90.10%	—

^zHOB0® temperature and RH probe (U12 Onset Computer Corp., Bourne, MA).

^yPrecision pyranometer (SP-110; Apogee Instruments, Inc., Logan, UT).

^xFrom 3 Sept. 2008 to 30 Sept. 2008.

^wFrom 3 Sept. 2009 to 30 Sept. 2009.

Table 2. Physical characteristics of the substrate used in both trials.

Substrate characteristic	Value
Bulk density	0.77 g·cc ⁻¹
Particle density	2.20 g·cc ⁻¹
Saturated hydraulic conductivity	0.0087 cm·s ⁻¹
At maximum water capacity	Air content 13.8%
	Water content 51.1%

Table 3. Plant species evaluated in the study.

Scientific name	Common name	Propagule source
<i>Allium cernuum</i> Roth.	Nodding onion	Gulley Greenhouse, Fort Collins, CO
<i>Antennaria parvifolia</i> Nutt.	Small-leaf pussytoes	Gulley Greenhouse, Fort Collins, CO
<i>Artemisia frigida</i> Willd.	Fringed sage	Gulley Greenhouse, Fort Collins, CO
<i>Bouteloua gracilis</i> (Kunth) Lag. ex Griffiths	Blue grama	Gulley Greenhouse, Fort Collins, CO
<i>Buchloe dactyloides</i> (Nutt.) Engelm.	Buffalo grass	Gulley Greenhouse, Fort Collins, CO
<i>Carex flacca</i> Schreb.	Sedge	Bluebird Nursery, Inc., Clarkson, NE
<i>Delosperma cooperi</i> (Hook. f.) L. Bol.	Hardy ice plant	Gulley Greenhouse, Fort Collins, CO
<i>Delosperma nubigenum</i> (Schltr.) L. Bol.	Yellow ice plant	Gulley Greenhouse, Fort Collins, CO
<i>Penstemon pinifolius</i> Greene	Pineleaf penstemon	Gulley Greenhouse, Fort Collins, CO
<i>Sedum acre</i> L.	Goldmoss stonecrop	Gulley Greenhouse, Fort Collins, CO
<i>Sedum album</i> L.	White stonecrop	Bluebird Nursery, Inc., Clarkson, NE
<i>Sedum lanceolatum</i> Torr.	Lanceleaf stonecrop	Gulley Greenhouse, Fort Collins, CO
<i>Sedum spurium</i> Marsch-Bieb. 'John Creech'	Two-lined stonecrop	Gulley Greenhouse, Fort Collins, CO
<i>Sempervivum</i> 'Royal Ruby'	Hens and chicks	Gulley Greenhouse, Fort Collins, CO
<i>Thymus pseudolanuginosus</i> Ronn.	Woolly thyme	Gulley Greenhouse, Fort Collins, CO

least 10 mm from the edge of the container. Values were collected daily until VMC remained constant, which occurred ≈ 18 d after initiation of the dry down period. 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.

The number of days to top growth dieback for each plant was also determined. The date when no viable green tissue, including both foliage and stems, remained above the substrate surface was recorded and used to determine the number of days to top growth dieback. On the day when no viable green tissue remained above the substrate surface, all plants were rewatered with 450 mL every 48 h. This day was also the starting point to determine their revival ability.

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

Results and Discussion

Results for the greenhouse trials show change of VMC for up to 18 d after initiation

of the dry down period, depending on the species (Fig. 1). This is a much longer period of time when compared with a study conducted in a Michigan greenhouse trial, which found that VMC of a mixture of *Sedums* stopped changing after only 7 d with some species reaching 0% VMC in as little as 1 d (VanWoert et al., 2005). The dissimilarity between studies is most likely the result of differences among species, differences in developmental stages of plants, differences in substrate depth, solar radiation intensity, container type, and possibly substrate moisture-holding capacities.

Plant relative water use, as estimated by removing the evaporative portion (i.e., non-vegetated control) of evapotranspiration, was calculated by taking the daily difference in values and then averaging over the 18 d period for each species (Fig. 2). Relative water use was not consistent within plant type (i.e., herbaceous, succulent). For example, the average relative water use per day for the herbaceous species ranged from -1.53 VMC for *A. parvifolia* to -6.23 VMC for *A. frigida*. Similarly for the succulents, the range was $+2.04$ VMC for *S. 'Royal Ruby'* and -5.56 VMC for *D. nubigenum*. These results for *D. nubigenum* are consistent with other research, which found that, although it is also a succulent, *D. nubigenum* depletes available moisture in

Fig. 1. Mean volumetric moisture content (VMC) of substrate for greenhouse trials by species shown as days after initiation of dry down period. Error bars represent SE.

Fig. 2. Mean difference in volumetric moisture content (VMC) between the non-vegetated control and each species taken daily and averaged over the 18 d of the study. Lower case letters show significant differences at the $P \leq 0.05$ level.

the rhizosphere more quickly than most species of *Sedum* (Nagase and Thuring, 2006).

Delosperma nubigenum was not the only succulent plant to have high relative water use. *Delosperma cooperi* and *S. album* were very similar in relative water use to *D. nubigenum*. This agrees with research studies that evaluated response of common green roof species to substrate moisture deficit; results indicated that some species of succulent plants, especially *D. nubigenum*, use water rapidly while it is available (Berghage et al., 2007; Thuring et al., 2010).

Even *S. acre* used more water than some of the herbaceous plants such as *A. parvifolia*

and *T. pseudolanuginosus*. This is in contrast to other studies that have found *S. acre* to have relatively low water use, especially when compared with the non-vegetated control (Durhman et al., 2006; Lundholm et al., 2010; Wolf and Lundholm, 2008). Differences in experimental design and environmental conditions likely contribute to the dissimilarity between results. In the current study, only one species had lower water use than the non-vegetated control, *S. 'Royal Ruby'*.

In the case of herbaceous plants such as *T. pseudolanuginosus*, others have also found it to be a suitable plant for green roof use as a result of its growth habit and tolerance to low

moisture conditions in its rhizosphere (Sendo et al., 2007). Herbaceous plants such as *A. parvifolia* and *B. gracilis* as well as succulents *D. cooperi* and *S. lanceolatum* were all previously found to be suitable plants for use on extensive green roofs in semiarid climates (Bousselot et al., 2010). As previously documented, knowing species-specific relative water use rates will help in determining irrigation frequency (Durhman et al., 2004, 2006).

Results for number of days to top growth dieback show a clear division between the herbaceous and succulent species (Table 4). There was a nearly sixfold difference in days to dieback for the herbaceous plants versus the succulent species (Table 4). Two of the succulent species (*S. album* and *S. 'Royal Ruby'*) did not have any individuals that died back during either of the 151 d trials (Table 4). These are similar results to a study in Michigan where the succulent species of *Sedums* remained viable for the entire 4-month study period (Durhman et al., 2004). Additionally, *Sedum rubrotinctum* R. T. Clausen has been shown to remain alive for up to 2 years in a greenhouse without irrigation (Teeri et al., 1986).

Once the top growth of an individual plant had died back, the plant was rewatered to determine if the plant had entered into drought-induced dormancy or died. If plants had not died during the 151 d study, water was applied at the end of the study to evaluate their revival rate after an extended period of drought (Table 4). The herbaceous plants had a mean of 23.51% revival, whereas the succulent species had a mean of 44.53% revival (Table 4). Figure 3 shows the differences in plant appearance from

Table 4. Mean number of days to top growth dieback and percent revival after rewating.

Species	Plant type	Days to dieback (SE)	Revival
<i>A. cernuum</i>	s ^z	59.25 (1.77) f [†]	91.67%
<i>A. parvifolia</i>	h	22.79 (0.65) d	31.25%
<i>A. frigida</i>	h	16.08 (0.32) a	8.33%
<i>B. gracilis</i>	h	18.23 (0.71) ab	22.92%
<i>B. dactyloides</i>	h	20.19 (0.90) bc	37.50%
<i>C. flacca</i>	h	20.13 (0.90) bc	27.08%
<i>D. cooperi</i>	s	52.25 (1.44) e	0.00%
<i>D. nubigenum</i>	s	107.06 (3.46) g	2.08%
<i>P. pinifolius</i>	h	20.09 (0.67) bc	0.00%
<i>S. acre</i>	s	107.67 (6.46) g	2.08%
<i>S. album</i>	s	151.00 (0.00) j	58.33%
<i>S. lanceolatum</i>	s	138.71 (2.53) i	54.17%
<i>S. spurium</i> 'John Creech'	s	127.87 (3.72) h	56.25%
<i>S. 'Royal Ruby'</i>	s	151.00 (0.00) j	69.44%
<i>T. pseudolanuginosus</i>	h	20.75 (0.87) c	31.25%
Herbaceous mean		19.75	22.62%
Succulent mean		111.75	41.75%

^zs = succulent; h = herbaceous.

[†]Lower case letters show significant differences at the $P \leq 0.05$ level.

Fig. 3. Example block in the greenhouse showing the change in plant appearance (A) the day after the trial began and (B) Day 12.

the beginning of the study compared with 12 d later.

Based on plant relative water use and revival of species, these results suggest that succulents such as *S. 'Royal Ruby'*, *A. cernuum*, and *S. lanceolatum* would be ideal on an extensive green roof in a semiarid environment with limited moisture content. Additionally, of the species tested here, herbaceous plants such as *A. parvifolia*, *T. pseudolanuginosus*, and *B. dactyloides* are the most likely to survive low moisture content of the substrate and revive once moisture is no longer limiting. Both *A. parvifolia* and *S. lanceolatum* have been successful in other extensive green roof trials in the same semiarid region (Bousselot et al., 2010).

Conclusion

There was no clear division between succulent and herbaceous species in dry down curves because there are differences within plant types. Additionally, relative water use during the 18 d dry down was inconsistent within plant type. However, the general trend was

that succulent species retained more moisture in the substrate for longer than herbaceous species.

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

Literature Cited

- Altieri, M. and D. Letourneau. 1982. Vegetation management and biological control in agroecosystems. *Crop Prot.* 1:405–430.
- Berghage, R., D. Beattie, A. Jarrett, and F. Rezaei. 2007. Green roof plant water use, p. 18–38. In: Berghage R., et al. (eds.). *Quantifying evapotranspiration and transpirational water losses from green roofs and green roof media capacity for neutralizing acid rain*. The Pennsylvania State University, State College, PA.

- Bousselot, J.M. 2010. Extensive green roofs in Colorado: Plant species performance, growing media modifications, and species response to growing media dry down. *Horticulture and Landscape Architecture*, Colorado State University, Fort Collins, CO.
- Bousselot, J.M., J.E. Klett, and R.D. Koski. 2010. Extensive green roof species evaluations using digital image analysis. *HortScience* 45:1288–1292.
- Compton, J.S. and T.H. Whitlow. 2006. A zero discharge green roof system and species selection to optimize evapotranspiration and water retention. In: *Proc. of 4th North American Green Roof Conference: Greening Rooftops for Sustainable Communities*, The Cardinal Group, Toronto, Boston, MA, 10–12 May 2006.
- Dunnett, N. 2006. Green roofs for biodiversity: Reconciling aesthetics with ecology. In: *Proc. of 4th North American Green Roof Conference: Greening Rooftops for Sustainable Communities*, The Cardinal Group, Toronto, Boston, MA, 10–12 May 2006.
- Dunnett, N. and N. Kingsbury. 2004. Planting options for extensive and semi-extensive green roofs, p. 221–236. In: *Proc. of 2nd North American Green Roof Conference: Greening Rooftops for Sustainable Communities*, The Cardinal Group, Toronto, Portland, OR, 2–4 June 2004.
- Dunnett, N. and A. Nolan. 2004. The effect of substrate depth and supplementary watering on the growth of nine herbaceous perennials in a semiextensive green roof. *Acta Hort.* 643: 305–309.
- Durham, A.K., D.B. Rowe, and C.L. Rugh. 2006. Effect of watering regimen on chlorophyll fluorescence and growth of selected green roof plant taxa. *HortScience* 41:1623–1628.
- Durham, 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.
- Durham, A.K., N.D. VanWoert, D.B. Rowe, C.L. Rugh, and D. Ebert-May. 2004. Evaluation of Crassulaceae species on extensive green roofs, p. 504–517. In: *Proc. of 2nd North American Green Roof Conference: Greening Rooftops for Sustainable Communities*, The Cardinal Group, Toronto, Chicago, IL, 29–30 May 2003.
- Emilsson, T. 2003. The influence of substrate, establishment method and species mix on plant cover, p. 305–312. In: *Proc. of 1st North American Green Roof Conference: Greening Rooftops for Sustainable Communities*, The Cardinal Group, Toronto, Chicago, IL, 29–30 May 2003.
- Getter, K.L. and D.B. Rowe. 2006. The role of extensive green roofs in sustainable development. *HortScience* 41:1276–1285.
- Kircher, W. 2004. Annuals and *Sedum*-cuttings in seed-mixtures for extensive roof gardens. *Acta Hort.* 643:301–303.
- Latocha, P. and A. Batorska. 2007. The influence of irrigation system on growth rate and frost resistance of chosen ground cover plants on extensive green roofs, p. 131–137. *Annals of Warsaw University of Life Sciences–SGGW. Horticulture and Landscape Architecture*. Warsaw University of Life Sciences Press, Warsaw, Poland.
- Lundholm, J., J.S. MacIvor, Z. MacDougall, and M. Ranalli. 2010. Plant species and functional group combinations affect green roof ecosystem functions. *PLoS ONE* 5:e9677.
- Miller, C. 2003. Moisture management in green roofs, p. 177–182. In: *Proc. of 1st North American Green Roof Conference: Greening Rooftops for Sustainable Communities*, The Cardinal Group, Toronto, Chicago, IL, 29–30 May 2003.

- 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.
- Nagase, A. and C. Thuring. 2006. Plant responses to drought on extensive green roofs: The effects of temperature, substrate type and substrate depth. In: Proc. of 4th North American Green Roof Conference: Greening Rooftops for Sustainable Communities, The Cardinal Group, Toronto, Boston, MA, 10–12 May 2006.
- 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(10): 823–833.
- Sendo, T., N. Inagaki, M. Kanechi, and Y. Uno. 2007. What kind of plant species are the best for urban rooftop gardening? *Acta Hort.* 762: 333–339.
- Snodgrass, E.C. and L.L. Snodgrass. 2006. Green roof plants: A resource and planting guide. Timber Press, Portland, OR.
- Teeri, J.A., M. Turner, and J. Gurevitch. 1986. The response of leaf water potential and Crassulacean acid metabolism to prolonged drought in *Sedum rubrotinctum*. *Plant Physiol.* 81:678–680.
- Thuring, C.E., 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.
- VanWoert, N.D., D.B. Rowe, J.A. Andresen, C.L. Rugh, and L. Xiao. 2005. Watering regime and green roof substrate design affect *Sedum* plant growth. *HortScience* 40:659–664.
- Wolf, D. and J.T. Lundholm. 2008. Water uptake in green roof microcosms: Effects of plant species and water availability. *Ecol. Eng.* 33:179–186.