Effect of Substrate Depth on Initial Growth, Coverage, and Survival of 25 Succulent Green Roof Plant Taxa

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Abstract. Because of greater interest in green roofs in the United States, it is critical to increase the number and geographic range of proven plant resources for long-term survival on rooftops. Successful plant taxa for extensive green roofs must establish themselves quickly, provide high groundcover density, and tolerate extreme environmental conditions. Furthermore, dead load weight restrictions on many buildings may limit the substrate depth that can be applied. The objective of this study was to evaluate the effect of substrate depth on initial establishment and survival of 25 succulent plant taxa for green roof applications in the midwestern United States. Survival, initial growth, and rate of coverage were compared for plants grown in three substrate depths (2.5, 5.0, and 7.5 cm) on 24 roof platforms. Plant coverage was determined from image analysis of weekly digital photographs. Results indicate deeper substrates promote greater survival and growth; however, in the shallowest depth of 2.5 cm, several species continued to persist. Of the 25 species initially planted, only 47% survived in the deepest substrate of 7.5 cm. Recommended species at the depths tested for climates similar to southern Michigan include *Phedimus spurius* Raf. ‘Leningrad White’, *Sedum acre* L., *S. album* L. ‘Bella d’Inverno’, *S. middendorffianum* L., *S. reflexum* L., *S. sediforme* J., and *S. spurium* Bieb. ‘Summer Glory’. Subsidiary species that are present at specific substrate depths but may not exhibit an ability to cover large areas include *S. dasyphyllum* L. ‘Burnatii’, *S. dasyphyllum* L. ‘Lilac Mound’, *S. diffusum* W., *S. hispanicum* L., and *S. kamschaticum* Fisch. The primary deterrent for these subsidiary species was little to no survival at 2.5 cm. Deeper substrates promoted greater survival and growth for nearly all species tested.

Vegetated green roofs provide numerous benefits to the built environment such as a reduction in stormwater runoff, building insulation, and mitigation of the urban heat island effect (DeNardo et al., 2005; Getter and Rowe, 2006; Liu, 2004; VanWoert et al., 2005a). Many extensive (shallow) green roofs consist primarily of low-maintenance succulent perennial species such as *Sedum* L., *Delosperma* N.E.Br., and *Sempervivum* L.; grasses like *Festuca* L.; and herbaceous plants such as *Allium* L. and *Dianthus* L. (Dunnett and Kingsbury, 2004; Dunnett and

Nolan, 2004; Köehler, 2003; Snodgrass and Snodgrass, 2006). As more green roofs become established in the United States, it is critical to increase the number and geographic range of proven plant resources for long-term survival on rooftops.

Likely candidates can be found in extreme environments such as rock outcroppings or under alpine conditions. Species classified as chamaephytes grow in alpine regions where snow cover protects the shoots and buds against water loss. Chamaephytes are shrubs and herbs with vegetative shoots that lie along the ground and remain intact at the beginning of an unfavorable season (Raunkiaer, 1934). *Sedum* are classified as passive chamaephytes because response during unfavorable conditions results in shorter internodal length and reduced shoot lengths. In terms of growth habit, their low-growing, spreading groundcover characteristics make them ideal for covering extensive green roofs. Plants that cover the substrate in a short period of time reduce potential erosion problems and inhibit weeds. Species that are long-lived, reseed themselves, or spread vegetatively should continue to provide 100% coverage as long as environmental conditions

are favorable. German guidelines require at least 60% vegetative coverage to be approved as a green roof (FLL, 1995).

In addition to morphologic and growth habit characteristics, many succulents are ideal for extensive green roofs because they are physiologically adapted to withstand harsh environmental conditions (Gebauer, 1988). Some have been documented to exhibit Crassulacean acid metabolism (CAM), a metabolic pathway that enables them to adapt to water-stressed environmental conditions (Gebauer, 1988; Sayed, 2001; Ting, 1985). CAM plants usually have fewer stomata than C₃ and C₄ plants, and these stomata can open at night for the uptake of CO₂, thus reducing daytime water loss. In a controlled greenhouse study, Durhman et al. (2006) found that several species of *Sedum* survived and maintained active photosynthetic metabolism even after 4 months without water. Another drought-resistant mechanism of CAM plants is to store water in the succulent leaves (Sayed, 2001).

In northern climates, winter cold hardiness is a major factor in overwintering survival. In Madrid, Spain, researchers found that when subjected to 10 °C for 11 h, *S. forsterianum* Sm. and various strains of *S. album* L. suffered, but *S. micranthum* Bast., *S. rupestre* L., and *S. ochroleucum* Chaix all survived at a substrate depth of 3.5 cm (Gómez-Campo, 1996). In North America, Boivin et al. (2001) reported that, for the six species tested in Quebec, greater freezing injury occurred at shallow substrate depths of 5 cm compared with 9 cm or 11.5 cm. Monterusso et al. (2005) compared 18 native forbs and grasses with nine species of *Sedum* over three seasons (2001–2004) on a roof platform in Michigan. All nine of the *Sedum* thrived, but only four of the 18 native taxa were found to be acceptable in 10 cm of substrate. It is important to note that although Quebec experiences colder winters than Michigan, the Quebec study was conducted on a heated building, whereas the Monterusso study and this study took place on unheated roof platforms.

The U.S. Dept. of Agriculture (USDA) has developed a plant hardiness zone map to quantify average annual minimum temperature data for the purpose of predicting plant survival. Many ornamental plant species have been assigned to a range of hardiness zones where they are most likely to survive. However, some of the species and cultivars examined in this study have not been previously reported for use on Michigan green roofs and do not have published USDA hardiness zones. Thus, this study offers new plant recommendations for locations with similar climates.

Successful candidates for extensive green roofs exhibit characteristics such as rapid establishment, high groundcover density, tolerance to extreme environmental conditions, and successful winter recovery (ASTM, 2006; Getter and Rowe, 2006). Substrate depth can influence all of these factors. Long-term persistence is also important because

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green roofs are dynamic systems. However, this article concentrates on initial establishment. Therefore, the objective of this study was to evaluate 25 succulent plant species for green roof applications in the midwestern United States by measuring the effect of substrate depth on initial growth rates, coverage, and survival.

Materials and Methods

An initial growth and coverage study was conducted on raised roof platforms at the Horticulture Teaching and Research Center at Michigan State University (MSU), East Lansing, Mich. The study was a split-plot completely random design with substrate depth as the main plot factor and species as the subplot factor. Each species was replicated eight times within each substrate depth for a total of 600 plants.

Platforms. Twenty-four 123 cm × 123-cm raised-roof platforms were constructed. Each pressure-treated wood platform was built per the same ASTM International standards that would be required for a commercial building and equipped with layers of insulation, waterproofing, a green roof drainage system, root barrier, substrate, and a 2% slope for drainage. In each plot, excess water drained through three drilled holes at the base of the slope ≈3 cm in diameter and covered by a mesh filter screen. The tops of each individual wood frame plot were bordered with flexible meter tape for rescaling and orientating the images.

Platforms included a green roof drainage layer (XF108) and vegetation carrier (XF301; Wolfgang Behrens Systementwicklung, GmbH, Groß Ipener, Germany). The drainage layer consisted of a geotextile fabric with attached nylon coil. The nylon coils faced down when installed and the total thickness of this layer was ≈1.5 cm. A water retention fabric layer, ≈0.75 cm thick, was added with the capacity to hold up to 800 g·m⁻² of water. The water retention fabric layer was composed of a recycled synthetic fiber mixture of polyester, polyamide, polypropylene, and acrylic fibers. The vegetation carrier consisted of a geotextile fabric with nylon coils attached and filled with substrate.

Substrate. Substrate depths of 2.5 cm, 5.0 cm, and 7.5 cm were randomly assigned to the 24 platforms. Substrate consisted of 40% heat-expanded slate (gradation of 3 to 5 mm) (PermaTill; Carolina Stalite Company, Salisbury, N.C.), 40% U.S. Golf Association grade sand (Osburn Industries, Taylor, Mich.), 10% Michigan Peat (Osburn Industries, Taylor, Mich.), 5% Dolomite (Osburn Industries), 3.33% composted yard waste (Renewed Earth, Kalamazoo, Mich.), and 1.67% composted turkey litter (Herbruck's, Saranac, Mich.). Substrate proportions are based on volume. At the time of planting, electrical conductivity and pH of the media were 3.29 mmho·cm⁻¹ and 7.9, respectively. All treatments had 100 g·m⁻² of Nutricote type 100, 18N-6P-9K controlled-release fertilizer (Agrivert, Webster, Texas)

hand-applied 47 d after planting on 28 July 2003 and the following summer on 29 July 2004 at the same rate.

Plant species. Stem and leaf cuttings of 25 Crassulacean plant species were excised from stock plants growing in the MSU Plant Science Greenhouses on 11 June 2003. Length of the unrooted cuttings ranged from 2 to 4 cm but were uniform in size within species. Cuttings were stored overnight at 5 °C and propagated the next day on the outdoor platforms (day 1). Cuttings were placed on 20-cm centers with 25 individual species per plot. The location of individual cuttings within each plot was randomly assigned. Species included *Graptopetalum paraguayense* subsp. Rose, *Phedimus spurius* Raf. 'Leningrad White', *Rhodiola pachyclada* L., *R. trollii* L., *Sedum acre* L., *S. album* L. 'Bella d'Inverno', *S. clavatum* C., *S. confusum* Hemsley, *S. dasyphyllum* L. 'Burnati', *S. dasyphyllum* L. 'Lilac Mound', *S. diffusum* W., *S. hispanicum* L., *S. kamtschaticum* Fisch., *S. mexicanum* Britt., *S. middendorffianum* L., *S. moranense* Kunth, *S. pachyphyllum* Clausen, *S. reflexum* L., *S. sediforme* J., *S. 'Rockery Challenger'* H., *S. 'Spiral Staircase'* H., *S. spurium* Bieb. 'Summer Glory', *S. surculosum* var. *luteum* Cos., *S. × luteoviride* C., and *S. × rubrortinctum* C.

During the first 22 d of the study, the platforms were covered with a shade cloth. To help acclimate the plants, the shade cloth was removed, except on bright sunny days, up until day 31, at which time it was removed permanently.

Irrigation. During the establishment period, plots were overhead-irrigated with Rain Bird (Azusa, Calif.) Xerigation XS-180 spray heads fixed to 30.5-cm Polyflex risers. The risers were placed at increments measuring 120 cm. For the first 20 d, the plots were irrigated for 5-min cycles at 0700, 1100, 1400, 1700, and 2000 hr. Each 5-min cycle applied enough water to saturate each plot, misting ≈4.0 mm (30 ml) per plot. Irrigation duration was reduced to 2-min cycles from days 21 to 41. After day 41, automated irrigation ended but occurred periodically to maintain plant health the first year. In the second growing season, supplemental irrigation was not used.

Weed species. During the establishment period, numerous weed seedlings emerged and included *Cirsium arvense* L. *Eleusine indica* L., *Eragrostis cilianensis* All., *Mollugo verticillata* L., *Panicum capillare* L., *Populus deltoides* Marshall, *Salix nigra* Marsh., and *Senecio vulgaris* L. Emerging weeds were hand pulled up to day 33. They were then allowed to grow until day 86, at which time all weeds were removed. Thereafter, plots were managed to remain weed-free for ease of data collection to maintain the original goals of measuring growth rates for desired planted species.

Data collection. Measurements of two-dimensional plant coverage were recorded by taking weekly digital images (32 MB, 1800 × 1200 pixel, fine quality). A portable camera stand was constructed to raise a camera ≈163 cm above the platforms. A digital

camera (FUJIFILM MX-2900 zoom, 2.3 mega pixels; Fuji Photo Film Co., Ltd., Tokyo, Japan) equipped with an F3.3/F7.6 wide conversion lens was suspended on the camera stand. The focal distance was set at 22 mm and the focal range set at 0.9 m. Although planted on 12 June 2003, images were first taken on 8 July (day 27). Weekly analysis occurred during the initial growing season defined as the time up until the plants entered dormancy in late fall and a hard frost occurred on 28 Oct. 2003 (day 139). Data collection resumed the next spring on 24 Mar. 2004 (day 287). This method was used until 19 May 2004 (day 343) when it became too difficult to distinguish individual species because plant canopies began to overlap.

Survival rates were recorded during establishment, after the first growing season, the next spring, and at the end of the second growing season (Table 1). The establishment period was defined as the period up to 7 d after supplemented irrigation ended when 90% of the individuals had rooted. Persistence for the first year was scored on 28 Oct. 2003 (day 139) after a hard frost. To consider overwintering success, presence of individuals at day 139 were compared with their presence on 12 May 2004 (day 336). A final assessment of persistence during the second growing season was made on day 482 after a hard frost on 5 Oct. 2004.

Image analysis. Plant growth rates and horizontal vegetative coverage were determined in a nondestructive method by using SigmaScan Pro 5.0 image analysis software (SPSS Science, Chicago). Vertical height was not measured. Coverage (plant community development) in each plot was measured to compare growth relative to substrate depth (Fig. 1). Digital images were analyzed to determine the percentage of the total horizontal vegetative canopy attributed to each individual. Image area was delineated for the quadrat area using the two-point rescaling function, and then individual plants were analyzed using the manual trace mode (Olmstead et al., 2004). Manual trace mode was necessary because the software program could not automatically distinguish color, intensity, and hue differences between plant materials and substrate. A preliminary test established the accuracy of the method of taking weekly images, analyzing them in an image analysis program, and converting to actual centimeters squared. By measuring paper images of a known area (10 cm²), it was determined that the measurements were 94% accurate relative to actual size.

Vegetative growth was recorded by weekly image analysis beginning on day 27 (8 July 2003), after the 26 d establishment period when individual cuttings rooted. Because of snow cover, analysis of weekly images resumed the next spring on day 287 (24 Mar. 2004). Because it became too difficult to distinguish individual species boundaries, image analysis collection ended on day 342 (18 May 2004).

As a result of size variability among propagules after the 26 d establishment

Table 1. Survival of 25 taxa (*Graptopetalum*, *Phedimus*, *Rhodiola*, and *Sedum*) cultivated at three substrate depths (2.5, 5.0, and 7.5 cm) over two growing seasons (2003–2004).^z

Taxa	Survival (%)											
	2.5 cm				5.0 cm				7.5 cm			
	48	139	336	482	48	139	336	482	48	139	336	482
<i>G. paraguayense</i>	100 Aa	100 Aa	0 Ba	0 Ba	100 Aa	100 Aa	0 Ba	0 Ba	100 Aa	100 Aa	0 Ba	0 Ba
<i>P. spurius</i> Leningrad White	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa
<i>R. pachyclada</i>	62 Ab	37 Bb	0 Ca	0 Ca	100 Aa	87 Aa	0 Ba	0 Ba	87 Aa	87 Aa	12 Ba	12 Ba
<i>R. trollii</i>	100 Aa	62 Bb	0 Cb	0 Cb	100 Aa	100 Aa	0 Bb	0 Bb	100 Aa	100 Aa	25 Ba	25 Ba
<i>S. acre</i>	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa
<i>S. album</i> Bella d'Inverno	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa
<i>S. clavatum</i>	12 Aa	0 Aa	0 Aa	0 Aa	25 Aa	0 Ba	0 Ba	0 Ba	12 Aa	0 Aa	0 Aa	0 Aa
<i>S. confusum</i>	100 Aa	100 Aa	0 Ba	0 Ba	100 Aa	100 Aa	0 Ba	0 Ba	100 Aa	100 Aa	0 Ba	0 Ba
<i>S. dasyphyllum</i> Burnatii	100 Aa	87 Aa	0 Bc	0 Bc	100 Aa	100 Aa	50 Bb	50 Bb	100 Aa	100 Aa	100 Aa	100 Aa
<i>S. dasyphyllum</i> Lilac Mound	100 Aa	50 Bb	0 Cb	0 Cb	100 Aa	75 Bab	25 Cab	12 Cb	100 Aa	100 Aa	87 Aa	87 Aa
<i>S. diffusum</i>	100 Aa	100 Aa	0 Bc	0 Bc	100 Aa	100 Aa	25 Bb	25 Bb	100 Aa	100 Aa	75 Ba	75 Ba
<i>S. hispanicum</i>	100 Aa	87 Aa	25 Bb	12 Bb	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa
<i>S. kamtschaticum</i>	87 Aa	87 Aa	12 Bb	0 Ba	100 Aa	100 Aa	100 Aa	87 Aa	100 Aa	100 Aa	100 Aa	100 Aa
<i>S. mexicanum</i>	100 Aa	100 Aa	0 Ba	0 Ba	100 Aa	100 Aa	0 Ba	0 Ba	100 Aa	100 Aa	0 Ba	0 Ba
<i>S. middendorffianum</i>	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa
<i>S. moranense</i>	100 Aa	100 Aa	0 Ba	0 Ba	100 Aa	100 Aa	0 Ba	0 Ba	100 Aa	100 Aa	0 Ba	0 Ba
<i>S. pachyphyllum</i>	100 Aa	100 Aa	0 Ba	0 Ba	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa
<i>S. reflexum</i>	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa
<i>S. Rockery</i> Challenger	87 Aa	87 Aa	0 Ba	0 Ba	100 Aa	87 Aa	0 Ba	0 Ba	100 Aa	100 Aa	0 Ba	0 Ba
<i>S. sedifforme</i>	100 Aa	100 Aa	75 Bb	75 Bb	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa
<i>S. Spiral</i> Staircase	100 Aa	100 Aa	0 Ba	0 Ba	100 Aa	100 Aa	0 Ba	0 Ba	100 Aa	100 Aa	0 Ba	0 Ba
<i>S. spurium</i> Summer Glory	100 Aa	100 Aa	75 Bb	75 Bb	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	87 Aa	87 Aa	87 Aa
<i>S. surculosum</i> var. <i>luteum</i>	50 Ab	0 Bb	0 Ba	0 Ba	75 Aa	0 Bb	0 Ba	0 Ba	62 Aab	25 Ba	0 Ba	0 Ba
<i>S. x luteoviride</i>	100 Aa	100 Aa	0 Ba	0 Ba	100 Aa	100 Aa	0 Ba	0 Ba	100 Aa	100 Aa	0 Ba	0 Ba
<i>S. x rubrotinctum</i>	100 Aa	100 Aa	0 Ba	0 Ba	100 Aa	100 Aa	0 Ba	0 Ba	100 Aa	100 Aa	0 Ba	0 Ba

^zSurvival reported at 48, 139, 336, and 482 d after initiation of study corresponding to 29 July 2003, 28 Oct. 2003, 12 May 2004, and 5 Oct. 2004, respectively.

Mean separation in rows for each species by least significant difference ($P \leq 0.05$). Uppercase letters denote comparisons over time within individual substrate depths ($n = 8$) (comparisons within columns 1–4, 5–8, and 9–12). Lowercase letters denote comparisons of different substrate depths on specific dates ($n = 8$) (Comparisons of columns 1, 5, and 9; 2, 6, and 10; 3, 7, and 11; and 4, 8, and 12).

period and at the beginning of the second season, the increase in area was calculated to show vegetative groundcover relative to starting size. During 2003, this increase was defined as final area of coverage on day 139 (28 Oct.) minus the initial coverage when image analysis was first used on day 27 (8 July). Likewise, this value was calculated the second season (2004) as the final area on day 342 (18 May) minus the initial on day 287 (23 Mar.) that spring. Measurements for each species were averaged across the eight replications at each species depth. Growth rate was defined using the area of coverage graphs to measure the slope of area divided by time.

Statistical analysis. Data were analyzed separately for 2003 and 2004 years. Significant differences between species growth and depth on specific weeks were determined using multiple comparisons (least significant differences) with Tukey-Kramer adjustments (PROC MIXED, SAS version 8.02; SAS Institute, Cary, N.C.). Survival percentages were compared using a mixed model in which time and depth were factors and species was nested in depth. Survival data did not require a log transformation because it was observed to be normally distributed. Overall coverage of vegetation analyzed at the end of the study was tested using least significant differences (PROC GLM, SAS version 8.02; SAS Institute).

Results and Discussion

Survival. In general, plants grown in the deeper substrate depths of 5.0 and 7.5 cm exhibited higher survival rates than those grown at the 2.5-cm depth (Table 1). All individual cuttings did not survive the propagation period; however, no single species experienced complete mortality for all eight replications at any depth. *Rhodiola pachyclada*, *S. clavatum*, *S. kamtschaticum*, *S. 'Rockery Challenger'*, and *S. surculosum* var. *luteum* exhibited less than 100% propagation survival on some substrate depths after supplemental irrigation was ended. In addition, *S. clavatum* and *S. surculosum* var. *luteum* displayed less than 100% propagation survival at all three depths.

At the end of the first season (day 139), plant mortality was most prominent at the 2.5-cm depth where survival percentage declined for *R. pachyclada*, *R. trollii*, *S. dasyphyllum* 'Lilac Mound', and *S. surculosum* var. *luteum*. Individuals grown in the 7.5-cm depth were least affected by the end of the first season because only *S. surculosum* var. *luteum* experienced a significant decline in survival. Regardless of depth, *S. clavatum* did not survive the first growing season and *S. surculosum* var. *luteum* only survived at the 7.5-cm depth.

In addition to initial establishment and growth, plant hardiness of the shoots and root systems are critical for longevity, stability, and appearance of extensive green roofs (Boivin et al., 2001; Durhman et al., 2004; Getter and Rowe, 2006). Substrate depth appeared to influence plant cold hardiness

with deeper substrate depths of 5.0 and 7.5 cm supporting greater overwintering survival than those grown at the 2.5-cm depth. At the shallow substrate depth of 2.5 cm, only nine of the 25 species overwintered compared with 12 and 14 species for the 5.0- and 7.5-cm depths, respectively. Deeper substrates likely provided greater moisture retention and root protection from temperature fluctuations and allowed for more vertical space for plant roots to grow before reaching the root barrier. A more stable environment allows plants to grow stronger and healthier, which affects their ability to survive harsh climatic conditions of drought and temperatures. However, even with deeper substrates, mortality during winter could be the result of death of the root systems, which are generally not as cold-tolerant as the tops of plants (Wu and Cosgrove, 2000).

In this study, one must remember that the plants were growing on roof platforms so the ambient air temperature was the same above and below the green roof. This would make the root systems more susceptible to freezing. The winter of 2003–2004 was typical for East Lansing with a minimum temperature of -24.3°C recorded at the research site and 141 d with a minimum temperature below 0°C (Fig. 2). On the roof of a heated building, the rooting substrate would be warmed somewhat from heat transfer from the building below. If freezing of root systems was the cause of death, then one would expect that if a particular species survived on a roof platform, then it would also survive on the roofs of unheated and heated buildings.

Rhodiola pachyclada, *R. trollii*, *S. dasyphyllum* 'Burnatii', *S. dasyphyllum* 'Lilac Mound', *S. diffusum*, *S. hispanicum*, *S. kamtschaticum*, *S. sediforme*, and *S. spurium* 'Summer Glory' all increased their survival rates when grown in deeper substrates. No plants of *Sedum dasyphyllum* 'Burnatii' survived at 2.5 cm, but survival increased to 50% and 100% at 5.0 and 7.5 cm, respectively. Similarly, *S. hispanicum* and *S. kamtschaticum* exhibited a dramatic increase in survival rates when the depth was increased from 2.5 to 5.0 cm. At the end of the second season, all plants of five species were still alive regardless of substrate depth. Knowledge of how a species will perform at various substrate depths is important when choosing plant species for a green roof where substrate depth must be kept to a minimum because of building weight restrictions.

Results for *S. acre*, *S. album*, *S. kamtschaticum*, *S. middendorffianum*, *S. reflexum*, and *S. spurium* support previous research that these species can survive on extensive green roofs in the midwestern United States (Monterusso et al., 2005; Rowe et al., 2006a, 2006b). In addition, all *P. spurium* 'Leningrad White' and *S. sediforme* survived regardless of substrate depth. Species such as *S. mexicanum*, which exhibited high coverage values and a fast rate of establishment during the first growing season but no winter survival, may be more suited for green roofs in warmer climates.

Growth rate. Substrate depth affected growth rate, although not immediately (Fig. 1). This is probably because the developing root systems were not yet large enough to exploit the entire depth of the substrate. Growth after establishment varied across species. Depending on substrate depth, several species established and grew quickly early in the season. Differences in initial growth rates could be attributed to individuals' propagation potential, aggressiveness to establish in an open area, and resource allocation.

When image analysis first began on day 27 (8 July 2003) until day 55 (5 Aug. 2003), *S. album* 'Bella d'Inverno' ($1.6\text{ cm}^2\text{d}^{-1}$) was

the only species that exhibited a growth rate greater than 1.5 cm^2 in coverage per day at a depth of 2.5 cm. This value improved to three species at a 5.0 cm with *S. album* 'Bella d'Inverno' (1.9), *S. mexicanum* (1.7), and *S. spurium* 'Summer Glory' (1.8) all exhibiting growth greater than $1.5\text{ cm}^2\text{d}^{-1}$. At 7.5 cm, eight species were above this value: *P. spurium* 'Leningrad White' (2.5), *S. acre* (2.0), *S. album* 'Bella d'Inverno' (3.5), *S. diffusum* (1.7), *S. hispanicum* (1.5), *S. mexicanum* (3.2), *S. middendorffianum* (1.6), and *S. spurium* 'Summer Glory' (2.2).

Between days 55 and 125 (14 Oct. 2003), three, eight, and 14 species exhibited a growth rate greater than $1.5\text{ cm}^2\text{d}^{-1}$ at the

Fig. 1. Growth of 25 taxa (*Graptopetalum*, *Phedimus*, *Rhodiola*, and *Sedum*) cultivated on green roof platforms at three depths (2.5, 5.0, and 7.5 cm). Growth was calculated from digital image analysis. Data collected once a week for 20 weeks, resumed the next spring on week 41, and ended on week 49 when plants were too dense to discriminate. Error bars represent standard error. Break in x-axis denotes winter.

Fig. 1. Continued

2.5-, 5.0-, and 7.5-cm depths, respectively. At 2.5 cm, species included *S. album* 'Bella d'Inverno' (2.2), *S. diffusum* (1.7), and *S. mexicanum* (1.7). At 5.0 cm, *S. acre* (3.3), *S. album* 'Bella d'Inverno' (3.7), *S. diffusum* (4.7), *S. hispanicum* (2.8), *S. mexicanum* (4.0), *S. middendorffianum* (1.7), *S. reflexum* (1.5), and *S. sediforme* (1.9) fit into this category. At 7.5 cm, the list included *P. spurius* 'Leningrad White' (2.9), *S. acre* (5.6), *S. album* 'Bella d'Inverno' (7.5), *S. dasyphyllum* 'Burnati' (2.7), *S. diffusum* (4.3), *S. hispanicum* (4.0), *S. kamtschaticum* (1.6), *S. mexicanum* (7.2), *S. middendorffianum* (2.8), *S. moranense* (1.6), *S. reflexum* (2.7), *S. sediforme* (2.9), *S. spurius* 'Summer Glory' (2.1), and *S. × rubranticum* (1.6). From day 125 to the first hard frost on day 139 (28 Oct. 2003), *S. acre* (1.8) was the only species at any depth that

had a growth rate greater than $1.5 \text{ cm}^2 \cdot \text{d}^{-1}$. This occurred at a depth of 7.5 cm.

After winter, growth resumed for most species the second season. There was little or no observable vegetation present on day 287 for deciduous species such as *S. kamtschaticum* and *R. pachyclada*. However, because regeneration occurred later in spring, growth rates improved. Some species had vegetative dieback in the plant's center (semideciduous), although surrounding tissues were actively recovering from winter injury or growing. For this observation, plant material that looked healthy (turgid or leaf color similar to the previous year's growth) was recorded. Species that exhibited dieback included *S. dasyphyllum* 'Burnatii', *S. dasyphyllum* 'Lilac Mound', *S. hispanicum*, and *S. album* 'Bella d'Inverno'. However, by May,

winter injury was no longer observed. One interesting observation was *S. middendorffianum*, *S. spurius* 'Summer Glory', and *S. kamtschaticum* had much faster growth rates in the second year compared with their performance the prior year. *Sedum acre* and *S. album* 'Bella d'Inverno' had consistently increasing growth rates.

During this second season, there was zero to minimal growth at 2.5 cm between days 286 (23 Mar. 2004) and 314 (20 Apr. 2004) with *S. middendorffianum* displaying the highest growth rate of $0.6 \text{ cm}^2 \cdot \text{d}^{-1}$. At 5.0 cm, *S. middendorffianum* (4.7) was still the only species with a growth rate above $1.5 \text{ cm}^2 \cdot \text{d}^{-1}$. At a depth of 7.5 cm, *P. spurius* 'Leningrad White' (2.5), *S. acre* (3.3), *S. album* 'Bella d'Inverno' (2.3), *S. kamtschaticum* (3.3), *S. middendorffianum* (14.7), *S. reflexum* (3.7), and *S. spurius* 'Summer Glory' (2.2) all exhibited rapid early growth. Other species such as *S. mexicanum*, *S. moranense*, and *S. × rubranticum* that displayed rapid growth the previous year were absent at this stage because they did not survive the winter.

During the next 28 d up until day 342 (18 May 2004), rapid growth occurred for *P. spurius* 'Leningrad White' (2.2), *S. acre* (2.6), *S. album* 'Bella d'Inverno' (4.3), *S. middendorffianum* (3.6), *S. reflexum* (1.9), and *S. spurius* 'Summer Glory' (2.5) at 2.5 cm and *P. spurius* 'Leningrad White' (4.2), *S. acre* (8.9), *S. album* 'Bella d'Inverno' (9.0), *S. kamtschaticum* (6.9), *S. middendorffianum* (11.0), *S. reflexum* (5.4), and *S. spurius* 'Summer Glory' (7.8) at 5.0 cm. At 7.5 cm, these values were even higher: *P. spurius* 'Leningrad White' (8.9), *S. acre* (14.6), *S. album* 'Bella d'Inverno' (15.8), *S. hispanicum* (9.6), *S. kamtschaticum* (10.6), *S. middendorffianum* (15.8), *S. reflexum* (9.1), and *S. spurius* 'Summer Glory' (6.6). After day 342, it became too difficult to distinguish species by image analysis from digital photographs because some species were beginning to grow over the top of others to form multiple canopy layers. However, visual observations confirmed that plants continued to spread throughout the second growing season (Durham, 2005). *Sedum acre*, *S. album* 'Bella d'Inverno', and *S. middendorffianum* displayed the most growth and exhibited the highest percentage of cover by day 482 (5 Oct. 2004).

Across all species, plant vigor (i.e., the fastest growth rates) was greatest at the deepest substrate depth of 7.5 cm. Although the 2.5-cm depth did not promote growth to the same extent as the deeper substrates, plants remained alive. This agrees with the work of VanWoert et al. (2005b) who reported that watering was necessary every 14 d to support growth of a mixture of sedum in a green roof substrate with a 2-cm media depth but only once every 28 d when the substrate depth was increased to 6 cm. Although growth was diminished, these plants survived 88 d without water (VanWoert et al., 2005b). Over time, growth rates within depths varied across plant species,

Fig. 1. Continued

especially for some species including *S. acre*, *S. album* 'Bella d'Inverno', *S. diffusum*, *S. hispanicum*, *S. mexicanum*, and *S. middendorffianum* (Fig. 1). This is attributable in part to favorable growing conditions such as amount and duration of rainfall and temperatures (Fig. 2).

Coverage. As expected, those species that exhibited the fastest growth rate covered the greatest area when image analysis ended on day 343 (Fig. 1). Species with the greatest amount of coverage included *P. spurius* 'Leningrad White', *S. acre*, *S. album* 'Bella d'Inverno', *S. hispanicum*, *S. middendorffianum*, and *S. reflexum*. An exception was *S. mexicanum*, which exhibited high coverage values and a fast rate of establishment across all depths during the first growing season. However, it was not able to survive winter and completely disappeared by the second season. In fact, at the end of the first season, *S. mexicanum* covered a greater area than all other species except for *S. album* 'Bella d'Inverno'.

For most species, coverage was significantly different at each depth with the greatest area of coverage occurring for plants growing in 7.5 cm of substrate (Fig. 1). By day 343, plants growing in 2.5, 5.0, and 7.5 cm of substrate had reached 47%, 74%, and 96% coverage, respectively ($P \leq 0.05$). The 47% coverage on the 2.5-cm depth had still not reached the minimum 60% coverage to be approved as a green roof according to German FLL standards (FLL, 1995). The most vigorous spreader, *S. middendorffianum*, covered 1242 cm² at a depth of 7.5 cm but only

670 cm² and 220 cm² at 5.0 and 2.5 cm, respectively (Fig. 1). However, not all species exhibited a significant difference in coverage between depths of 5.0 and 7.5 cm. *Sedum spurium* 'Summer Glory' covered 377 and 452 cm² at 5.0 and 7.5 cm, respectively, but only 108 cm² at a depth of 2.5 cm.

Increases in coverage within each season also mirrored overall coverage and was dependent on substrate depth (Table 2). Similar to total coverage, during the image analysis phase of the second season, the increase in horizontal growth for *Sedum spurium* 'Summer Glory' at depths of 5.0 (229 cm²) and 7.5 cm (245 cm²) was not different but was much greater than horizontal growth at 2.5 cm (65 cm²). There were also differences among seasons. Some species such as *S. dasyphyllum* 'Burnatii', *S. dasyphyllum* 'Lilac Mound', and *S. sedifforme* did not expand further or decreased in coverage regardless of substrate depth (Table 2) during the second growing season. This may be the result of increased competition during the second season from plants that were more vigorous. Fast establishment and substrate coverage are desirable characteristics for green roof plant taxa. Fast initial growth is important because the faster the plants cover the substrate surface, the fewer the number of plants required and the less expensive they will be to purchase and install.

Life form characteristics influenced species survival, growth, and coverage. Raunkiaer (1934) classified the genus *Sedum* as passive chamaephytes, meaning evergreen

or deciduous vegetative shoots lay along the ground and remain intact at the beginning of the unfavorable season. Evergreen species such as *S. acre* and *S. album* retain their vegetation over the Michigan winter. Additionally, their vegetative shoots quickly root and grow in different areas of the plots early in the growing season. In the spring, they have an obvious spatial advantage by predominating a particular area within the plot. In contrast, deciduous plants like *S. kamtschaticum* are not frost-tolerant and above-ground shoot tissues die in late fall with adverse weather conditions, although new vegetative growth occurs from regenerative buds in the spring. However, this influences the coverage present early in the season. They are at a disadvantage because they must compete spatially against evergreen species; however, their growth rates are comparable later in the growing season (Fig. 1).

Although not apparent in this study, improved coverage and presence at the end of the second growing season by *S. hispanicum* was attributable mainly to its prolific reseeding ability in late summer, especially compared with other species tested. In the second year, *S. hispanicum* flowered throughout June and July with seedlings emerging by the beginning of August. Other species that reseeded in the second season include *S. acre* and *S. album* 'Bella d'Inverno'. Overall, plants selected for this trial generally reproduce easily by asexual means of stem or leaf cuttings without the use of commercial rooting compounds (Stephenson, 2002). Over time, original plants could have easily reestablished themselves in the plots by vegetative means, thereby increasing their coverage and presence at the end of the study.

Conclusion

Most of the species examined within this study have not been previously reported for use on green roofs in the Michigan climate. Furthermore, some of these species and cultivars do not have published USDA hardiness zones. Therefore, this study offers new plant recommendations for use on green roofs. Of the 25 species initially planted, only 47% survived in the deepest substrate of 7.5 cm. Recommended species at the depths tested for climates similar to southern Michigan include *P. spurius* 'Leningrad White', *S. acre*, *S. album* 'Bella d'Inverno', *S. middendorffianum*, *S. reflexum*, *S. sedifforme*, and *S. spurium* 'Summer Glory'. Subsidiary species that are present at specific substrate depths but may not exhibit an ability to initially cover large areas include *S. dasyphyllum* 'Burnatii', *S. dasyphyllum* 'Lilac Mound', *S. diffusum*, *S. hispanicum*, and *S. kamtschaticum*. The primary deterrent for these subsidiary species was little to no survival at 2.5 cm. Deeper substrates promoted greater survival and growth for nearly all species tested; however, in the shallowest depth of 2.5 cm, several species were observed to form stable

Fig. 2. Daily maximum and minimum temperatures (°C) and precipitation (millimeters) during the experimental study (12 June 2003 through 06 Oct. 2004). Weather data were taken using the Michigan Automated Weather Network's East Lansing weather station (located adjacent to the research site).

Table 2. Increase in coverage (cm²) as calculated from image analysis from days 27 to 139 (8 July 2003 to 28 Oct. 2003) and 287 to 343 (24 Mar. 2004 to 19 May 2004).

Taxa	Increase in area of coverage (cm ²) within each season					
	2003 Depth (cm)			2004 Depth (cm)		
	2.5	5	7.5	2.5	5	7.5
<i>G. paraguayense</i>		26 a	46 a			
<i>P. spurius</i> Leningrad White	47 b	106 b	281 a	61 b	127 ab	320 a
<i>R. pachyclada</i>	-2 a	6 a	23 a			19
<i>R. trollii</i>	-3 a	-1 a	3.6 a			12
<i>S. acre</i>	128 c	288 b	472 a	67 c	265 b	501 a
<i>S. album</i> Bella d'Inverno	210 c	330 b	641 a	118 c	260 b	507 a
<i>S. clavatum</i>						
<i>S. confusum</i>	7 a	31 a	83 a			
<i>S. dasyphyllum</i> Burnatii	9 c	106 b	205 a		7 a	8 a
<i>S. dasyphyllum</i> Lilac Mound	-9 a	21 a	42 a		-14 a	17 a
<i>S. diffusum</i>	149 b	384 a	355 a		32 a	66 a
<i>S. hispanicum</i>	98 c	224 b	342 a	6 b	3 b	289 a
<i>S. kamtschaticum</i>	12 b	73 ab	121 a	-1 c	222 b	387 a
<i>S. mexicanum</i>	150 c	338 b	599 a			
<i>S. middendorffianum</i>	58 c	144 b	237 a	118 c	441 b	855 a
<i>S. moranense</i>	38 b	57 b	128 a			
<i>S. pachyphyllum</i>	26 b	77 ab	109 a			
<i>S. reflexum</i>	50 b	133 ab	235 a	46 c	175 b	359 a
<i>S. Rockery Challenger</i>	30 a	42 a	42 a			
<i>S. sedifforme</i>	76 b	155 ab	234 a	-20 a	-13 a	-10 a
<i>S. Spiral Staircase</i>	29 a	66 a	85 a			
<i>S. spurium</i> Summer Glory	35 b	124 ab	197 a	65 b	229 a	245 a
<i>S. surculosum</i> var. <i>luteum</i>			17			
<i>S. × luteoviride</i>	12 a	48 a	84 a			
<i>S. × rubrotinctum</i>	48 b	100 ab	124 a			

Mean separation in rows among depths within each growing season for each taxa were tested using least significant difference with Tukey-Kramer adjustments ($P \leq 0.05$) ($n = 8$). Tests were separated by year before analysis. Blanks denote no surviving plants for specific species.

communities. In choosing a green roof system, it is important to consider both substrate depth and plant species growth factors for sustained growth.

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