Substrate Depth Influences *Sedum* Plant Community on a Green Roof

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Abstract. Because the waterproofing membrane beneath green roofs is estimated to last at least 45 years, long-term plant performance beyond initial establishment is critical. Plants that survive initially on a green roof may not exist in the long term because of variability in climate and other factors. This study evaluated the effect of green roof substrate depth on substrate moisture, plant stress as measured by chlorophyll fluorescence, and plant community development and survival of 12 *Sedum* species over 4 years in a midwestern U.S. climate during 4 years of growth. Plugs of 12 species of *Sedum* were planted on 8 June 2005 and evaluated biweekly for absolute cover (AC). Most species exhibited greater growth and coverage at a substrate depth of 7.0 cm and 10.0 cm relative to 4.0 cm. For the species evaluated, substrate depths of at least 7.0 cm are highly recommended. AC of *Sedum* was significantly greater at this substrate depth than at 4.0 cm. Mean volumetric moisture content of the three substrate depths followed the same pattern as AC. When averaged over time, the 4.0-cm substrate depth held less moisture than depths of 7.0 or 10.0 cm, whereas the 7.0- and 10.0-cm substrate depths were statistically the same. Species exhibiting the greatest AC at all substrate depths were *S. floriferum*, *S. sexangulare*, *S. spurium* ‘John Creech’, and *S. stefco*. In general, species that are less suitable at these substrate depths are *S. ‘Angelina’*, *S. cauticola* ‘Lidakense’, *S. ewersii*, *S. ochroleucum*, and *S. reflexum* ‘Blue Spruce’.

In 2007, 223,666 m² (2,407,525 ft²) of green roofs, or vegetated roofs, were installed in North America representing a 30% increase over 2006 (Green Roofs for Healthy Cities, 2008). By placing plants on rooftops, the vegetated footprint that was previously destroyed during building construction is at least partially replaced. Increased adoption of this roofing technology may be the result of the many benefits they provide such as improved stormwater management (Carter and Jackson, 2007; Getter et al., 2007; Hilten et al., 2008; Jarrett and Berghage, 2008), energy conservation (Sailor, 2008; Santamouris et al., 2007), mitigation of the urban heat island effect (Takebayashi and Moriyama, 2007), increased longevity of roofing membranes (Kosareo and Ries, 2007), a better return on investment than traditional roofs (Clark et al., 2008), reduced noise and air pollution (Van Renterghem and Botteldooren, 2008; Yang et al., 2008), increased urban biodiversity (Baumann, 2006; Brenneisen, 2006) as well as providing a more aesthetically pleasing environment to experience (Getter and Rowe, 2006; Oberndorfer et al., 2007).

For green roofs to be successful as well as to meet client expectations, plant selection is

critical. Species selected must survive extremes in roof microclimate. Green roofs are likely to experience drought and severe fluctuations in root zone temperatures as a result of shallow substrates as well as high temperatures and windy conditions. These conditions combined with heat radiating from the building will likely alter hardiness zones and soil moisture content, thus impacting which species are able to survive.

Successful candidate species for extensive green roofs [i.e., green roofs with substrate depths of 10.0 cm (3.93 in) or less] must exhibit characteristics such as easy propagation, rapid establishment, and high groundcover density (Dunnett and Kingsbury, 2004; Getter and Rowe, 2006; Snodgrass and Snodgrass, 2006). Low-growing plants that spread and cover the substrate in a short period of time reduce potential erosion problems, inhibit weeds, and provide improved aesthetics. Although rapid coverage is important, the ability of plant species to be self-sustaining reduces the need for future replanting and maintenance. Species that are long-lived, that reseed themselves, or spread vegetatively should continue to provide ample coverage [60% or greater, as defined by FLL guidelines (FLL, 1995)] as long as environmental conditions are favorable.

The genus *Sedum* is a popular choice among extensive green roofing projects as a result of its tolerance for drought (Durhman et al., 2006; Wolf and Lundholm, 2008), shallow substrate adaptability (Durhman et al., 2007; Emilsson, 2008), persistence (Köhler, 2006; Monterusso et al., 2005; Rowe et al., 2006), and ability to limit

transpiration (Kluge, 1977; Lee and Kim, 1994), and store water (Gravatt, 2003; Teeri et al., 1986). However, even for such a well-suited genus, substrate depth can influence the rate of substrate coverage and subsequent plant growth (Durhman et al., 2007; Getter and Rowe, 2008; Rowe et al., 2006). Deeper substrates are beneficial for both increased waterholding capacity (VanWoert et al., 2005a, 2005b) and as a buffer in fluctuating winter temperatures (Boivin et al., 2001). Despite the cultural limitations of shallow substrate depths, they are often desirable because of lighter roof loads.

Plant stress resulting from shallow substrate and other conditions on a roof can be recorded by measuring chlorophyll fluorescence. This technique is used to quantify the efficiency of the photosynthetic apparatus (Maxwell and Johnson, 2000). Photon energy absorbed by a chlorophyll molecule can be used to fuel photosynthesis, dissipated as heat, or re-emitted as fluorescence. Measurement of the latter is used to indicate how efficient the former two processes are proceeding. Fluorometers are used to measure this value, usually reporting the ratio (F_v/F_m) of variable fluorescence (F_v) to maximum fluorescence (F_m) that typically ranges from 0.70 to 0.83 with values less than 0.60 indicating photosynthetic stress (Ritchie, 2006).

Many studies for plant survival on green roofs collect data for 1 to 2 years (Durhman et al., 2007; Emilsson and Rolf, 2005; Kircher, 2004; MacDonagh et al., 2006; Nagase and Dunnett, 2008). Because the waterproofing membrane beneath green roofs is estimated to last 45 years or longer (Kosareo and Ries, 2007), long-term plant performance beyond the first few years' growth is important. Plants that survive initially on a green roof may not exist there in the long term because of variability in climate and other factors. Therefore, the objective of this study was to evaluate the effect of substrate depth on substrate moisture, plant stress as measured by chlorophyll fluorescence, and plant community development and survival of 12 *Sedum* species over a period of 4 years.

Materials and Methods

Green roof platforms. Three roof platforms with dimensions of 2.44 m × 2.44 m (8.0 ft × 8.0 ft) were used at the Michigan State University Horticulture Teaching and Research Center (East Lansing, MI). Each platform was situated at ground level and replicated a commercial extensive green roof, including insulation, protective and waterproofing membrane layers. Construction details are outlined in VanWoert et al. (2005a).

The wood-framed platforms included sides that extend 20.3 cm (8.0 in) above the platform deck. Each platform was divided into three equal sections measuring 0.77 m × 2.40 m (2.53 ft × 7.87 ft) using wood dividers. The platform sides and dividers were also covered with waterproofing membrane. Each platform was set at a 2% slope and was placed

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with the low end of the slope facing south to maximize sun exposure.

Drainage system and vegetation carrier. Each platform was constructed with a Xero Flor XF108 drainage mat (Wolfgang Behrens Systementwicklung, GmbH, Groß Ippener, Germany) installed over the waterproofing system, which allows excess water to flow off the roof. For additional waterholding capacity, a 0.75-cm (0.26-in) thick moisture retention fabric (Xero Flor XF159) capable of retaining 5.92 kg·m⁻² of water was placed over the drainage layer followed by the vegetation carrier (Xero Flor XF301). Growing substrate was placed on the vegetation carrier at three different depths [4.0 cm, 7.0 cm, or 10.0 cm (1.6, 2.8, and 3.9 in)]. Initially, the substrate

consisted of 86% sand, 10% silt, and 4% clay and had a bulk density of 1.37 g·cm⁻³ and a waterholding capacity at 0.01 MPa of 16.05%. Further details of the initial physical and chemical properties of the substrate are detailed in Getter and Rowe (2008).

Plant species. The 12 species tested included *Sedum* 'Angelina' (crooked stonecrop), *Sedum cauticola* 'Lidakense' (stonecrop), *Sedum ewersii* (stonecrop), *Sedum floriferum* (kamtschatka stonecrop), *Sedum hispanicum* (Spanish stonecrop), *Sedum ochroleucum* (European stonecrop), *Sedum reflexum* 'Blue Spruce' (crooked stonecrop), *Sedum sarmentosum* (stringy stonecrop), *Sedum sediforme* (pale stonecrop), *Sedum sexangulare* (tasteless stonecrop), *Sedum spurium* 'John

Creech' (creeping sedum), and *Sedum stefco* (stonecrop). Plants were obtained from Emory Knoll Farms (Street, MD) as plugs (120 cm³; 72/flat) that were established in a standard propagation mix of peat, perlite, and vermiculite (Super-Fine Germination Media; Farfard, Inc., Agawam, MA). Plugs were planted on 8 June 2005 with four plants in 12 rows. Each species was planted four times randomly in each section resulting in plugs spaced 17.0 cm (6.7 in) apart from each other and platform walls. All plots were fertilized [Nutricote controlled-release fertilizer 18N-6P-8K type 120 (Agrivert, Webster, TX) at 100.0 g·m⁻²] and watered to field capacity by hand on the day of planting. No further irrigation was provided.

Table 1. Mean absolute cover $\pm$ SDs of 12 *Sedum* species cultivated at three substrate depths (4.0, 7.0, and 10.0 cm) at the end of four growing seasons (2005 to 2008).

Species	Absolute cover (depth = 4.0 cm) ^z			
	Week 15	Week 67	Week 120	Week 172
<i>S. Angelina</i>	0.0052 $\pm$ 0.0045 a ABC	0.0182 $\pm$ 0.0045 b BC	0.0104 $\pm$ 0.0119 ab AB	0.0052 $\pm$ 0.0045 a AB
<i>S. cauticola</i> Lidakense	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A
<i>S. ewersii</i>	0.0000 $\pm$ 0.0000 a A	0.0130 $\pm$ 0.0226 a AB	0.0104 $\pm$ 0.0180 a AB	0.0182 $\pm$ 0.0316 a AB
<i>S. floriferum</i>	0.0130 $\pm$ 0.0163 a BC	0.1016 $\pm$ 0.0135 b DE	0.1979 $\pm$ 0.0726 b C	0.2891 $\pm$ 0.0639 b C
<i>S. hispanicum</i>	0.0000 $\pm$ 0.0000 a A	0.0469 $\pm$ 0.0282 b CD	0.0234 $\pm$ 0.0207 b B	0.0391 $\pm$ 0.0435 b B
<i>S. ochroleucum</i>	0.0026 $\pm$ 0.0045 ab AB	0.0078 $\pm$ 0.0078 b AB	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A
<i>S. reflexum</i> Blue Spruce	0.0000 $\pm$ 0.0000 a A	0.0208 $\pm$ 0.0180 b BC	0.0234 $\pm$ 0.0207 b B	0.0104 $\pm$ 0.0045 b AB
<i>S. sarmentosum</i>	0.0729 $\pm$ 0.0163 c D	0.0130 $\pm$ 0.0119 b AB	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A
<i>S. sediforme</i>	0.0052 $\pm$ 0.0045 b ABC	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A
<i>S. sexangulare</i>	0.0104 $\pm$ 0.0119 a BC	0.1120 $\pm$ 0.0296 b DE	0.2214 $\pm$ 0.0813 b C	0.2031 $\pm$ 0.0979 b C
<i>S. spurium</i> John Creech	0.0182 $\pm$ 0.0119 a CD	0.1172 $\pm$ 0.0413 b DE	0.1719 $\pm$ 0.0668 b C	0.2318 $\pm$ 0.0592 b C
<i>S. stefco</i>	0.0130 $\pm$ 0.0045 a C	0.2292 $\pm$ 0.0627 b E	0.3698 $\pm$ 0.0325 b C	0.3984 $\pm$ 0.0547 b C

Species	Absolute cover (depth = 7.0 cm) ^y			
	Week 15	Week 67	Week 120	Week 172
<i>S. Angelina</i>	0.0078 $\pm$ 0.0078 a AB	0.0599 $\pm$ 0.0239 b DE	0.0339 $\pm$ 0.0197 b B	0.0104 $\pm$ 0.0119 a B
<i>S. cauticola</i> Lidakense	0.0052 $\pm$ 0.0045 b AB	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A
<i>S. ewersii</i>	0.0156 $\pm$ 0.0156 ab BC	0.0312 $\pm$ 0.0207 b CD	0.0286 $\pm$ 0.0369 ab B	0.0130 $\pm$ 0.0119 a B
<i>S. floriferum</i>	0.0443 $\pm$ 0.0090 a DE	0.1536 $\pm$ 0.0180 b EF	0.2760 $\pm$ 0.0502 b C	0.3880 $\pm$ 0.0296 b D
<i>S. hispanicum</i>	0.0156 $\pm$ 0.0156 b BC	0.0156 $\pm$ 0.0078 b BC	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A
<i>S. ochroleucum</i>	0.0026 $\pm$ 0.0045 a A	0.0182 $\pm$ 0.0045 b BCD	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A
<i>S. reflexum</i> Blue Spruce	0.0026 $\pm$ 0.0045 a A	0.0391 $\pm$ 0.0135 b CD	0.0234 $\pm$ 0.0000 b B	0.0000 $\pm$ 0.0000 a A
<i>S. sarmentosum</i>	0.1641 $\pm$ 0.0156 b E	0.5286 $\pm$ 0.1329 b F	0.2031 $\pm$ 0.0812 b C	0.0443 $\pm$ 0.0325 a C
<i>S. sediforme</i>	0.0026 $\pm$ 0.0045 ab A	0.0104 $\pm$ 0.0090 b B	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A
<i>S. sexangulare</i>	0.0208 $\pm$ 0.0045 a CD	0.1745 $\pm$ 0.0430 b EF	0.2891 $\pm$ 0.0207 b C	0.2839 $\pm$ 0.0163 b D
<i>S. spurium</i> John Creech	0.0260 $\pm$ 0.0119 a CD	0.1458 $\pm$ 0.0197 b EF	0.3385 $\pm$ 0.0180 b C	0.3802 $\pm$ 0.0251 b D
<i>S. stefco</i>	0.0260 $\pm$ 0.0197 a CD	0.2161 $\pm$ 0.0722 b EF	0.2552 $\pm$ 0.0705 b C	0.2396 $\pm$ 0.0759 b D

Species	Absolute cover (depth = 10.0 cm) ^x			
	Week 15	Week 67	Week 120	Week 172
<i>S. Angelina</i>	0.0052 $\pm$ 0.0090 a AB	0.0469 $\pm$ 0.0207 b BCD	0.0078 $\pm$ 0.0135 a AB	0.0104 $\pm$ 0.0119 a B
<i>S. cauticola</i> Lidakense	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A
<i>S. ewersii</i>	0.0104 $\pm$ 0.0119 a BC	0.0339 $\pm$ 0.0119 b BC	0.0130 $\pm$ 0.0119 a B	0.0078 $\pm$ 0.0135 a A
<i>S. floriferum</i>	0.0677 $\pm$ 0.0119 a DE	0.1979 $\pm$ 0.0709 ab DE	0.4219 $\pm$ 0.0870 b C	0.5599 $\pm$ 0.0502 b C
<i>S. hispanicum</i>	0.0182 $\pm$ 0.0045 c CD	0.0052 $\pm$ 0.0045 b A	0.0339 $\pm$ 0.0401 bc B	0.0000 $\pm$ 0.0000 a A
<i>S. ochroleucum</i>	0.0026 $\pm$ 0.0045 a AB	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A
<i>S. reflexum</i> Blue Spruce	0.0026 $\pm$ 0.0045 ab AB	0.0286 $\pm$ 0.0226 c B	0.0104 $\pm$ 0.0090 b B	0.0000 $\pm$ 0.0000 a A
<i>S. sarmentosum</i>	0.1745 $\pm$ 0.0369 b E	0.6641 $\pm$ 0.1369 c E	0.1693 $\pm$ 0.1466 b C	0.0521 $\pm$ 0.0709 a B
<i>S. sediforme</i>	0.0026 $\pm$ 0.0045 ab AB	0.0052 $\pm$ 0.0045 b A	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A
<i>S. sexangulare</i>	0.0365 $\pm$ 0.0119 a D	0.1406 $\pm$ 0.0078 b CD	0.2292 $\pm$ 0.0759 b C	0.1901 $\pm$ 0.0554 b C
<i>S. spurium</i> John Creech	0.0286 $\pm$ 0.0090 a D	0.1484 $\pm$ 0.0078 b DE	0.3333 $\pm$ 0.0576 b C	0.3333 $\pm$ 0.0726 b C
<i>S. stefco</i>	0.0547 $\pm$ 0.0135 a DE	0.1849 $\pm$ 0.1331 ab DE	0.2474 $\pm$ 0.1641 b C	0.1875 $\pm$ 0.1447 ab C

^zCover reported in weeks, in which Week 15 = 23 Sept. 2005; Week 67 = 19 Sept. 2006; Week 120 = 24 Sept. 2007; Week 172 = 25 Sept. 2008. Absolute cover was calculated for each species at each substrate depth as the total number of point frame contacts divided by the number of data collection points. Mean separation in rows and columns for each species by least significant difference ($P \leq 0.05$). Lowercase letters in rows denote comparisons over time within individual substrate depths and species ($n = 12$). Uppercase letters in columns denote differences among species ($n = 12$). SE was ± 0.0975 and ± 0.1757 for rows and columns, respectively.

^yMean separation in rows and columns for each species by least significant difference ($P \leq 0.05$). Lowercase letters in rows denote comparisons over time within individual substrate depths and species ($n = 12$). Uppercase letters in columns denote differences among species ($n = 12$). SE was ± 0.0763 and ± 0.1376 for rows and columns, respectively.

^xMean separation in rows and columns for each species by least significant difference ($P \leq 0.05$). Lowercase letters in rows denote comparisons over time within individual substrate depths and species ($n = 12$). Uppercase letters in columns denote differences among species ($n = 12$). SE was ± 0.0856 and ± 0.1543 for rows and columns, respectively.

This planting arrangement resulted in a split-plot design that was arranged in randomized complete blocks with two factors replicated three times. The main plot was substrate depth [4.0, 7.0, and 10.0 cm (1.6, 2.8, and 3.9 in)] and the subplot factor was plant species, which had 12 treatments, each replicated four times within a subplot for a total of 48 plants per substrate depth per plot.

Data collection and analysis. A transect (a stainless steel point frame) was used every 2 weeks during the first three growing seasons and monthly in the fourth growing season to measure community composition and change (Waite, 2000). The point frame had internal measurements of 0.77 m × 1.2 m (2.5 ft × 3.9 ft) and had eight strings (50 pound Berkley Gorilla Super Braid Fishing Line; Berkley, Spirit Lake, IA) vertically and eight strings horizontally to create 64 measurement points. The point frame sat directly on top of the platform sides secured by finishing nails that allowed the frame to be positioned in the exact same spot every time. A stainless steel skewer was placed vertically at each measuring point and each species the skewer contacted was recorded up to three canopy layers.

Substrate moisture and chlorophyll fluorescence data were collected throughout the last two growing seasons. Substrate moisture measurements were monitored by inserting a theta probe (ML2x; Delta-T Devices, Ltd., Cambridge, U.K.) with 6.0-cm (2.4-in) rods into the media until they were completely buried. Measurements were collected at random times each week in triplicate in each subplot. Chlorophyll fluorescence measurements were collected at six different times (21 May 2007, 18 June 2007, 2 Aug. 2007, 17 Sept. 2007, 29 May 2008, and 20 Aug. 2008) using a Hansatech plant efficiency analyzer (PEA; Hansatech Instruments, Ltd., Norfolk, U.K.). These measurement dates were selected to cover a wide range of environmental conditions, including active growth and drought stress during the growing season. Leaves from each plant were dark-adapted for 20 min before measurement. Maximum quantum efficiency of photosystem II was recorded (F_v/F_m). Three single leaf blades of each surviving species were randomly selected in each subplot and excised from the plant to be dark-adapted and measured. This was necessary because the PEA clips were not secure on the leaf of most species while still attached to the whole plant.

Data analysis. Absolute cover (AC) was calculated for each species at each substrate depth as the total number of contacts recorded divided by the number of data collection points. Data were then analyzed as mean AC using repeated measures. Although original means are presented, all AC values were transformed before analysis using a log transformation to stabilize the variance and normalize the data set (Underwood, 1998). Significant differences between treatments were determined using multiple comparisons (PROC MIXED, SAS Version 8.02; SAS Institute, Cary, NC). In addition, mean substrate volumetric moisture content and mean

chlorophyll fluorescence data were analyzed by PROC MIXED, least significant differences (SAS Version 8.02; SAS Institute).

Results and Discussion

Four points in time (Weeks 15, 67, 120, and 172) were chosen for comparing growth that represent the end of each growing season (before first frost). At a substrate depth of 4.0 cm, four species exhibited no significant growth between the end of the first and fourth growing seasons (*S. 'Angelina'*, *S. caudicola* 'Lidakense', *S. ewersii*, and *S. ochroleucum*), whereas at 7.0 cm, five species (*S. 'Angel-*

ina', *S. ewersii*, *S. ochroleucum*, *S. reflexum* 'Blue Spruce', and *S. sediforme*) fit this category (Table 1; Fig. 1). At the 10.0-cm substrate depth, there were six such species (*S. 'Angelina'*, *S. caudicola* 'Lidakense', *S. ewersii*, *S. ochroleucum*, *S. reflexum* 'Blue Spruce', and *S. sediforme*). As a result, at their respective substrate depths, all of these species have zero or near zero AC by Week 172.

At each substrate depth, there were also species that decreased in AC across the four growing seasons, also resulting in zero AC by Week 172 (Table 1; Fig. 1). At substrate depths of 4.0 cm (*S. sarmentosum* and *S. sediforme*) and 10.0 cm (*S. hispanicum* and *S.*

Fig. 1. Absolute cover ± SDs of 12 *Sedum* spp. cultivated at three substrate depths (4.0, 7.0, and 10.0 cm) over the 2005 to 2008 growing seasons. Symbols represent absolute cover means with SDs ($n = 3$). For clarity of graphing, Weeks 0 through 120 were plotted at every other data point.

Fig. 2. Monthly average maximum air temperatures ($^{\circ}\text{C}$), monthly average minimum air temperatures ($^{\circ}\text{C}$), and monthly total precipitation (mm) throughout the study (1 June 2005 to 30 Sept. 2008). Data are from the Michigan Automated Weather Network's East Lansing weather station (located adjacent to the research site).

Table 2. Mean absolute cover $\pm$ SDs of 12 *Sedum* species cultivated at three substrate depths (4.0, 7.0, and 10.0 cm) reported on Week 172 (25 Sept. 2008).^z

Species	Absolute cover (Week 172)		
	4.0 cm	7.0 cm	10.0 cm
<i>S. Angelina</i>	0.0052 $\pm$ 0.0045 a	0.0104 $\pm$ 0.0119 a	0.0104 $\pm$ 0.0119 a
<i>S. cauticola</i> Lidakense	0.0000 $\pm$ 0.0000 a	0.0000 $\pm$ 0.0000 a	0.0000 $\pm$ 0.0000 a
<i>S. ewersii</i>	0.0182 $\pm$ 0.0316 a	0.0130 $\pm$ 0.0119 a	0.0078 $\pm$ 0.0135 a
<i>S. floriferum</i>	0.2891 $\pm$ 0.0639 a	0.3880 $\pm$ 0.0296 b	0.5599 $\pm$ 0.0502 c
<i>S. hispanicum</i>	0.0391 $\pm$ 0.0435 a	0.0000 $\pm$ 0.0000 a	0.0000 $\pm$ 0.0000 a
<i>S. ochroleucum</i>	0.0000 $\pm$ 0.0000 a	0.0000 $\pm$ 0.0000 a	0.0000 $\pm$ 0.0000 a
<i>S. reflexum</i> Blue Spruce	0.0104 $\pm$ 0.0045 a	0.0000 $\pm$ 0.0000 a	0.0000 $\pm$ 0.0000 a
<i>S. sarmentosum</i>	0.0000 $\pm$ 0.0000 a	0.0443 $\pm$ 0.0325 a	0.0521 $\pm$ 0.0709 a
<i>S. sediforme</i>	0.0000 $\pm$ 0.0000 a	0.0000 $\pm$ 0.0000 a	0.0000 $\pm$ 0.0000 a
<i>S. sexangulare</i>	0.2031 $\pm$ 0.0979 a	0.2839 $\pm$ 0.0163 b	0.1901 $\pm$ 0.0554 a
<i>S. spurium</i> John Creech	0.2318 $\pm$ 0.0592 a	0.3802 $\pm$ 0.0251 b	0.3333 $\pm$ 0.0726 b
<i>S. stefco</i>	0.3984 $\pm$ 0.0547 b	0.2396 $\pm$ 0.0759 a	0.1875 $\pm$ 0.1447 a

^zAbsolute cover was calculated for each species at each substrate depth as the total number of point frame contacts divided by the number of data collection points. Mean separation in rows for each species by least significant difference ($P \leq 0.05$). Lowercase letters denote comparisons within the same row ($n = 12$) with $\text{SE} \pm 0.0146$.

sarmentosum), there were two such species. The 7.0-cm substrate depth had three species (*S. cauticola* 'Lidakense', *S. hispanicum*, and *S. sarmentosum*).

The remaining species at each substrate depth increased in AC across the four growing seasons (Table 1; Fig. 1). All substrate depths had the same four species (*S. florife-*

rum, *S. sexangulare*, *S. spurium* 'John Creech', and *S. stefco*) with the 4.0-cm substrate depth having an additional two species (*S. hispanicum* and *S. reflexum* 'Blue Spruce'). For all species, the increase in AC was only significant between the first and second growing seasons. This perhaps indicates that by the end of the second growing season, the plant community had reached a mature or stable state.

Results for the first growing season, as previously published, demonstrated that by the end of the first growing season (Week 19) at all three substrate depths, *S. sarmentosum* exhibited a much higher AC than all other species (Getter and Rowe, 2008; Fig. 1). However, subsequent growing seasons produced very different results, highlighting the importance of long-term studies. For the 4.0-cm substrate depth, this species remained at near zero AC for the remaining growing seasons. At the 7.0-cm and 10.0-cm substrate depths, however, this species represents more than half of the coverage by the end of the second growing season, has a slow recovery in the third growing season to represent nearly 20% of coverage, but then falls to near zero AC at the end of the fourth growing season.

It is possible that the reason for *S. sarmentosum*'s eventual failure at all three substrate depths is the result of incorrect hardiness zone classification for this species. Minimum air temperatures were lower during the second winter (-22.0°C) and had a longer duration of extreme cold (33 d less than -10°C) as compared with the first winter (-19.9°C ; 20 d less than -10°C) in which this species successfully recovered (Fig. 2). East Lansing, MI, is classified as Zone 5 on the USDA plant-hardiness map, a value corresponding to an average minimum temperature between -26 and -29°C (-20 to -10°F) (Cathey, 1990). Plants that are classified with hardiness zones less than or equal to a geographical area should in theory survive in that climate (assuming all other plant requirements are met). *Sedum sarmentosum* is categorized as a Zone 5 species (Snodgrass and Snodgrass, 2006), but typically species are assigned a hardiness zone based on observation only or based on how related species have performed in the past. Hardiness zones are also meant for plants growing at ground level. Although initial work with this species indicated that it was able to overwinter successfully when given enough establishment time before first frost (Getter and Rowe, 2007), this current study shows that *S. sarmentosum* is likely unsuitable for this climate. In climates with warmer winters, it is possible that this species may cover a majority of the roof, as suggested by first-year data here. However, this situation poses a threat in that an unusual cold spell may completely wipe out *S. sarmentosum* resulting in many bare spots on the roof.

Differences in growth as measured by AC across the sampled substrate depths and time may be partially explained by the habit of the species themselves. Some species such as *S. 'Angelina'*, *S. cauticola* 'Lidakense', *S.*

Table 3. Mean absolute cover $\pm$ SDs averaged over species cultivated at three substrate depths (4.0, 7.0, and 10.0 cm) over the 2005 to 2008 growing seasons.^z

Depth	Absolute cover			
	Week 15	Week 67	Week 120	Week 172
4.0 cm	0.1406 $\pm$ 0.0282 a A	0.6797 $\pm$ 0.2115 a A	1.0286 $\pm$ 0.1864 b A	1.1953 $\pm$ 0.1151 c A
7.0 cm	0.3333 $\pm$ 0.0119 a A	1.3932 $\pm$ 0.0722 bc B	1.4479 $\pm$ 0.0798 b B	1.3594 $\pm$ 0.0078 c B
10.0 cm	0.4036 $\pm$ 0.0508 a A	1.4557 $\pm$ 0.0607 b B	1.4661 $\pm$ 0.0369 b B	1.3411 $\pm$ 0.0430 c B

^zCover reported in weeks, in which Week 15 = 23 Sept. 2005; Week 67 = 19 Sept. 2006; Week 120 = 24 Sept. 2007; Week 172 = 25 Sept. 2008. Absolute cover was calculated for each species at each substrate depth as the total number of point frame contacts divided by the number of data collection points. Mean separation in rows for each depth by least significant difference ($P \leq 0.05$). Lowercase letters denote comparisons over time within individual substrate depths ($n = 12$). Uppercase letters in columns denote differences among depths ($n = 12$). SE was ± 0.0251 and ± 0.0904 for rows and columns, respectively.

Fig. 3. Substrate volumetric moisture content (m^3/m^3) $\pm$ SEs for three substrate depths (4.0, 7.0, and 10.0 cm) averaged over two growing seasons (2007 and 2008). Uppercase letters represent mean separation by least significant difference ($P \leq 0.05$).

ochroleucom, *S. reflexum* 'Blue Spruce', and *S. sediforme* are more erect in nature and therefore may be underrepresented in point frame sampling techniques (Wilson, 1960). Furthermore, some species vegetatively reproduce easier than others, allowing them to cover more area than simple growth would allow. Within this genus, Stephenson (2002) reports that increasing degrees of succulence are correlated with improved ability of a species to reproduce asexually (such as *S. stefco*, *S. sexangulare*, and to some extent *S. sarmentosum*). Some species also seem to allocate more energy to sexual reproduction (such as *S. hispanicum*), whereas others allocate more energy to creeping growth (such as *S. sarmentosum*, which has sterile flowers).

At all substrate depths, by the end of the fourth growing season (Week 172), the same four species (*S. floriferum*, *S. sexangulare*, *S. spurium* 'John Creech', and *S. stefco*) consistently exhibited the greatest AC (Table 2). However, relative abundance differed between substrate depths. For example, *S. stefco* was most abundant at the 4.0-cm substrate depth followed by *S. floriferum*, *S. spurium* 'John Creech', and *S. sexangulare*. By contrast, at 7.0 cm and 10.0 cm, *S. floriferum* was most abundant followed by *S. spurium* 'John Creech', *S. sexangulare*, and *S. stefco*.

These same four species are also the only four species that were influenced by substrate depth at the end of four growing seasons (Week 172; Table 2). *Sedum floriferum* is the only species exhibiting significant differences in AC at all three substrate depths. The remaining three species primarily see the difference between 4.0 cm and 7.0 cm, but not between 7.0 cm and 10.0 cm.

When AC is averaged over species, all depths demonstrated a statistically significant increase in AC across time (Table 3). AC for the 4.0-cm substrate depth increased from 0.1406 at Week 15 to 1.1953 at Week 172, whereas AC for the 10.0-cm substrate depth increased from 0.4036 to 1.3411. With the exception of Week 15, the other times all showed significant substrate depth effects within sampled times, but only between 4.0 cm and 7.0 cm, not between 7.0 cm and 10.0 cm. This indicates that for the surviving and most abundant species, substrate depths greater than 7.0 cm gain no benefit in terms of abundance as measured with a point frame. However, at deeper substrate depths, these plants would likely be healthier, contain greater biomass, and be less susceptible to adverse environmental conditions.

Mean volumetric moisture content of the three substrate depths follows the same pat-

tern as AC (Fig. 3). Although extremely variable, when averaged over time, the 4.0-cm substrate depth held less moisture than the 7.0- or 10.0-cm depths. The 7.0- and 10.0-cm substrate depths were statistically the same. The observation that deeper extensive green roof substrates consistently had higher moisture content than shallower substrates is consistent with similar studies (Liesecke, 1998; VanWoert et al., 2005a, 2005b). In addition, it appears that initially after a rain event, the 4.0-cm substrate depth dries out faster than either the 7.0- or the 10.0-cm depths (Fig. 4).

This greater water availability at the deeper substrate depths may explain why the 7.0-cm and 10-cm substrate depths had higher AC than the 4.0-cm depth. Another factor may be the result of substrate temperature differences. Boivin et al. (2001) found that shallower extensive green roof substrates experienced much more severe temperature fluctuations than deeper substrates. During the growing season, shallower substrates will likely experience higher soil temperatures, which in turn will influence plant growth (Bouma et al., 1997; Prasad et al., 2000). This is exacerbated by the fact that lower AC of the 4.0-cm substrate depth exposes more substrate to direct sun resulting in higher substrate temperatures. In addition, some species are more suited for these temperature or water fluctuations than others. Durhman et al. (2007) found that *S. album* was the only species of 25 that exceeded 1.5 cm^2 of growth per day at a substrate depth of 2.5 cm (1.0 in). At a substrate depth of 5.0 cm (2.0 in) and 7.5 cm (3.0 in), this increased to three species and eight species, respectively.

Chlorophyll fluorescence data did not follow the same pattern as AC and substrate moisture content. Mean F_v/F_m values were not significantly different at 0.795, 0.779, and 0.781 for substrate depths of 4.0 cm, 7.0 cm, and 10 cm, respectively. There were also very few differences between species within the same depth (data not shown). This may be because measurements for chlorophyll fluorescence occurred during the third and fourth growing seasons only, whereby three (*Sedum caudicola* 'Lidakense', *Sedum ochroleucom*, and *Sedum sediforme*) of the 12 initial species had zero AC (i.e., no plants to take measurements on). Had chlorophyll fluorescence data been taken during the first growing season, perhaps noticeable differences would have been detected between species that ultimately survived the 4-year study and those that did not. In addition, at individual measuring

Fig. 4. Substrate volumetric moisture content (m^3/m^3) $\pm$ SEs for a selected 3-d period after a 22.1-mm rain event at three substrate depths (4.0, 7.0, and 10.0 cm).

times, which represent the driest portions of the growing season (18 June 2007, 2 Aug. 2007, and 20 Aug. 2008), mean chlorophyll fluorescence values of individual species never fell below 0.60, indicating very little, if any, stress to the photosynthetic system (Ritchie, 2006). Other research has established the same trend for many species in this genus. In a controlled greenhouse watering study, Durhman et al. (2006) found that three *Sedum* species maintained active photosynthetic capacity for at least 88 d without water. This may at least partially explain why *Sedum* species are such good candidates for extensive green roofs.

These results show the importance of substrate depth on plant performance as well as long-term evaluation of species. Of the substrate depths and species evaluated in this article, substrate depths of at least 7.0 cm are highly recommended. AC was significantly greater at this substrate depth relative to the shallower depth of 4.0 cm. Species exhibiting the greatest AC at all substrate depths were *S. floriferum*, *S. sexangulare*, *S. spurium* 'John Creech', and *S. stefco*. In general, species that are less suitable are *S. 'Angelina'*, *S. cauticola* 'Lidakense', *S. ewersii*, *S. ochroleucum*, and *S. reflexum* 'Blue Spruce'.

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