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Establishment and Persistence of *Sedum* spp. and Native Taxa for Green Roof Applications

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Abstract. **Although the economic, environmental, and aesthetic benefits of green roofs have been recognized for decades, research quantifying these benefits has been limited—particularly in the U.S. Green roof usage and research is most prevalent in Germany, but can also be seen in several other European countries and Canada. If green roof installations are to be successful in Michigan and the rest of the U.S., then a better understanding of what specific taxa will survive and thrive under harsh rooftop conditions in this geographic area is required. Nine simulated rooftop platforms containing three commercially available drainage systems were installed at Michigan State University. Eighteen Michigan native plants planted as plugs and nine *Sedum* spp. planted as either seed or plugs were evaluated over three years for growth, survival during both establishment and overwintering, and visual appearance. All *Sedum* spp. tested were found to be suitable for use on Midwestern green roofs. Of the eighteen native plant taxa tested, *Allium cernuum* L., *Coreopsis lanceolata* L., *Opuntia humifosa* Raf., and *Tradescantia ohiensis* L. are suitable for use on unirrigated extensive green roofs in Michigan. If irrigation is available, then other native species are potential selections.**

Installations of vegetated rooftop systems, commonly referred to as green roofs, have been documented since the Hanging Gardens of Babylon (Farrar, 1996). In parts of the world where wood was not available, clay and sod were used as building materials. This construction practice can be considered to be the foundation on which modern green roof systems are patterned. Several benefits can be realized from the use of green roofs. First, they reduce the quantity of runoff entering municipal stormwater management systems (Kolb, 2004; Liesecke, 1998, 1999; Rowe et al., 2003; Schade, 2000; U.S. EPA, 2003). Second, they provide insulation for buildings, thus reducing energy consumption (Eumorfopoulou and Aravantinos, 1998; Lükenga and Wessels, 2001; Theodosiou, 2003). Third, they increase the life span of a typical roof by protecting the various roof components from damaging UV rays, extreme temperatures, and rapid temperature fluctuations (Lükenga and Wessels, 2001; Stein, 1990). Fourth, they have the potential to reduce the Urban Heat Island Effect (Dimoudi and Nikolopoulou, 2003; Wong et al., 2003). In addition, green roofs can reduce air and water pollution (U.S. EPA, 2003), enable city residents to produce their own food (Shariful Islam, 2004), increase biodiversity (Brenneisen, 2004), and the aesthetic value of plants reduces stress and provides a positive influence on human well-being (Relf and Lohr, 2003).

Although these benefits have long been identified, research quantifying these benefits and suitability of various plant taxa for use on green roofs has been limited—particularly in the U.S. Green roof usage and research have been most prevalent in Germany, but can also be seen in several other European countries and Canada. Studies have been conducted utilizing simulated rooftop platforms or other methods to evaluate the success of a variety of taxa, both herbaceous and woody, under various conditions (Durhman et al., 2004; Emilsson, T. 2003; Heinz, 1985; Koehler, 2003). The physical properties, suitability for plant growth, and cost of various substrates has also been examined (Dunnett and Nolan, 2004; Kolb and Schwarz, 1984). Heinz (1985) compared combinations of various *Sedum* spp., grasses, and herbaceous perennials, planted at two substrate depths in simulated roof platforms to determine which taxa were best suited for a rooftop environment. *Sedum* spp. outperformed the other taxa except when planted in combination with grass taxa in substrate deeper than 10 cm that was kept moist. Decreased plant performance in shallower substrate is probably due to rapid, frequent changes in substrate temperature that causes plants to constantly shift in and out of dormancy (Boivin et.al., 2001). Other studies support the suitability of low-growing *Sedum* spp. for use in green roofs due to superior survival in substrate layers as thin as 2 to 3 cm (Gómez-Campo, 1994; Gómez-Campo and Gómez-Tortosa, 1996).

Native taxa have potential for use on green roofs due to their adaption to the existing climate. *Coreopsis lanceolata* and *Rudbeckia hirta* are two Midwest native taxa that have been shown to be more successful than traditional grass taxa in establishing cover in landfills (Sabre et al., 1987). These two taxa are also a viable alternative to grass in the production of sod due to their lack of a deep taproot and ability to withstand transplanting (Johnson and Whitwell, 1997). One concern in regards to native taxa, particularly grasses, is the potential fire hazard resulting from accumulation of dry matter associated with their natural life cycle.

If green roof installations are to be successful in the wide range of climatic conditions present in the U.S., then a better understanding of what specific taxa will survive and thrive in those geographic locations is needed. Taxa suitable for Germany are not necessarily ideal for the midwestern U.S. because of our greater extremes in winter and summer temperatures. Therefore, the objectives of this study were to compare propagation method, rate of establishment, growth, and persistence of various plant taxa grown on roof platforms with three commercially available drainage systems in Michigan.

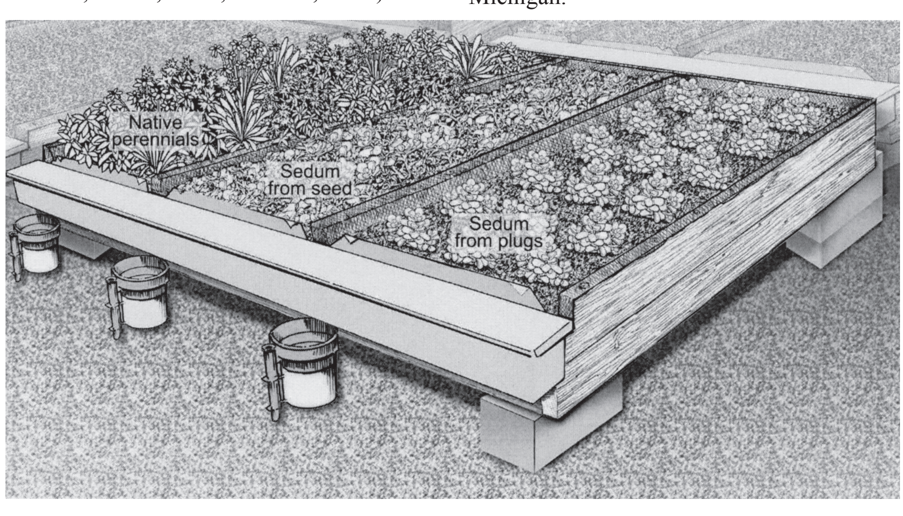

Fig. 1. Graphic representation of an individual model scale roof platform used to evaluate plant taxa. Illustration by Marlene Cameron.

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Materials and Methods

Platforms. Nine roof platforms (ChristenDETROIT Roofing Contractors, Detroit, Mich.) measuring 2.4 × 2.4 m were installed at Michigan State University (East Lansing, Mich.). Platforms were divided into three self-contained sections measuring 0.8 × 2.4 m (Fig. 1). Each platform duplicated a typical green roof construction with respect to insulation, protective layers, and waterproofing membranes. A wood frame housed each system with sides extending 20 cm above the platform floor. Lining the floor of each platform was 3.8 cm of "E'NRG'Y 2" insulation board (Johns Manville, Denver, Colo.) composed of a closed cell polyisocyanurate foam core bonded in the foaming process to universal fiberglass reinforced facers. Over this layer was a 1.9 cm Fesco Board (Johns Manville, Denver, Colo.) roof insulation layer. Fesco Board is a homogeneous insulation board composed of expanded perlite, blended with selected binders and fibers. The "E'NRG'Y 2" and Fesco insulation boards meet the physical property requirements of the American Society for Testing of Materials (ASTM) C1289 and ASTM C728, respectively. The next layer consisted of a Siplast Paradiene 20 protective layer (Siplast Inc., Irving, Texas) overlaid with a Siplast Teranap waterproof membrane.

Three commercially available drainage systems (American Hydrotech Extensive Garden Roof (American Hydrotech, Inc., Chicago, Ill.), Sarnafil (Sarnafil, Inc., Canton, Mass.), and Siplast (Siplast, Inc.) were installed on top of the base platforms to evaluate their effect on propagation method, rate of plant establishment, growth, and persistence of various plant taxa. Both the American Hydrotech and Siplast systems use a drainage layer about 3.5 cm thick and consists of small, interconnected cups designed to provide additional water retention capability to the system. Sarnafil uses a cross hatch drainage system about 1 cm in thickness that allows water that leaches through the substrate to exit the roof with no retention. Platforms were set at a 2% grade with the top edge of each platform elevated about 1.4 m from ground level and were oriented with the low end of the slope toward the south to maximize sun exposure.

Substrate. Each platform received 10 cm of growing substrate. The substrate was composed of 60% heat-expanded slate (PermaTill; Carolina Stalite; Salisbury, N.C.) with a particle size ranging from 7.9 to 9.5 mm, 25% USGA (U.S. Golf Association) grade sand, 5% aged compost, and 10% Michigan peat. Compost consisted of aged poultry manure (Herbruck's Poultry Ranch; Saranac, Mich.) and composted yard waste (Charter Township of Ypsilanti; Ypsilanti, Mich.) mixed in a 2:1 ratio (v:v). Substrate bulk density, capillary pore space, noncapillary pore space, infiltration rate, and water holding capacity at 0.1 MPa were 1.3 $g{\cdot}cm^{-3}$, 19.9%, 21.4%, 51.6 $cm{\cdot}h^{-1}$, and17.1 %, respectively (A & L Laboratories, Fort Wayne, Ind.). Saturated weight was equal to 1.5 $g{\cdot}cm^{-3}$.

Plant material. Within the platform partitions, three groups of plants were cultivated to evaluate the effect of drainage system on plant establishment, growth, and survival (Fig. 1). One group consisted of seven *Sedum* spp. propagated from seed. Taxa included *S. acre* L., *S. album* L., *S. kamtschaticum* Fis. & Mey., *S. ellacombeanum* Praeger, *S. pulchellum* Asnav., *S. reflexum* L., and *S. spurium* Bieb. 'Coccineum'. Seed was applied at a rate of 1.0 $g{\cdot}m^{-2}$ and was mixed with 250 $mL{\cdot}m^{-2}$ of dry sand to ensure even distribution. All seed was obtained from Jelitto Staudensamen, GmbH (Schwarmstedt, Germany). A second group consisted of two *Sedum* spp. planted from plugs (116.3 cm^3, 38/flat): *S. middendorffianum '*Diffusum' L. and *S. spurium* L. 'Royal Pink*'*. These plugs were supplied by Hortech, Inc. (Spring Lake, Mich.) and the study contained 108 plugs of each taxa. The third group consisted exclusively of 18 taxa of Michigan native plants: *Agastache foeniculum* J. Clayton ex Gron. (lavender hyssop), *Allium cernuum* L. (nodding wild onion), *Aster laevis* L. (smooth aster), *Coreopsis lanceolata* L. (lanceleaf coreopsis), *Fragaria virginiana* Duchesne (wild strawberry), *Juncus effusus* L. (spikerush), *Koeleria macrantha* Regel (junegrass), *Liatris aspera* Gaertn. ex Schreb. (rough blazingstar), *Monarda fistulosa* L. (bergamot), *Monarda punctata* L. (horsemint), *Opuntia humifosa* Raf. (prickly pear), *Petalostemon purpureum* Rydb. (purple prairie clover), *Potentilla anserina.* L. (silver feather), *Rudbeckia hirta* L. (black-eyed Susan), *Schizachyrium scoparium* Nash (little bluestem), *Solidago rigida* L. (stiff goldenrod), *Sporobolus heterolepis* A. Gray (prairie dropseed), and *Tradescantia ohiensis* L. (spiderwort). All native plants were planted from plugs (150.8 cm^3, 38/flat) obtained from Wildtype Nursery Inc. (Mason, Mich.) except for *Potentilla anserina,* which was planted from stolons supplied by Hortech, Inc. There were 27 plugs of each native taxa included in the study. All plugs and seed were planted or sewn on the platforms 15 June 2001.

Each of the three plant groups (*Sedum* spp. plugs, native plugs, and *Sedum* spp. seed) were randomly assigned to one of three platform sections (Fig. 1). Each native plant section contained three plugs of 18 taxa randomly planted in three rows of 18 plants on 17.5 cm centers for a total of 54 plants per section. In addition, two spaces at random locations were left unplanted. The *Sedum* plug sections contained 12 plugs each of two taxa randomly planted in three rows of eight on 30 cm centers for a total of 24 plants per section. The experiment was a split-plot design with platform drainage system as the main plot factor and plant group as the subplot factor.

Fertilizer. Nutricote 13–13–13 Type 180 controlled-release fertilizer (Agrivert Inc., Webster, Tex.) was applied to each platform at a rate of 100 $g{\cdot}m^{-2}$ at the time of planting. Additional 12–12–12 fertilizer (Chisso-Asahi Inc.; Tokyo, Japan) was applied to all seeded sections at a rate of 30 $g{\cdot}m^{-2}$ 66 d after initiation of the experiment to promote growth.

Irrigation. An automated overhead irrigation system (Rainbird; Azusa, Calif.) was used to support seed germination, plant establishment, and plant coverage. The system was programmed to run for three 15-min cycles per day (9:00 AM, 12:00 PM, and 3:00 PM) from day 1 through day 36, two cycles per day (10:00 AM and 3:00 PM) from day 37 through day 51, and once per day (12:00 PM) until irrigation was terminated for the first growing season on day 91 (13 Sept. 2001). Irrigation was resumed during the second season on day 362 (11 June 2002) and operated for one 15-min cycle per day as needed until it was terminated on day 390 (10 July 2002). Each cycle applied about 0.38 cm of water to each platform. No supplemental irrigation was supplied during the remainder of the second growing season and for the entire third year, so plants had to rely solely on natural rainfall.

Data collection. Data on plant height and two-dimensional width as well as seedling coverage were recorded monthly during establishment and during the growing season over the course of 3 years. Establishment was defined as the period after planting, but prior to the first year dormancy. A growth index was calculated for each plant by averaging the three individual growth measurements. Percent coverage was determined visually. The relative appearance of each plant was also evaluated at the time of measurement on a 0 to 5 scale: 0 = dead, 1 = stressed plant showing visible wilting or browning, 2 = a plant that showed little change since planting, 3 = slow growth, 4 = healthy plant exhibiting a large amount of growth, and 5 = exceptional growth and fullness. Final growth measurements and survival data were recorded during October 2003 and May 2004, respectively.

A snapshot of volumetric substrate moisture ($m^3{\cdot}m^{-3}$) was measured at depths of 1.0 cm and 9.0 cm at the center of each subsection (low end of slope, middle of slope, high end of slope) within each platform on day 104 (Sept. 27) using a soil moisture sensor (Theta Probe model ML2X; Delta-T Devices Ltd., Cambridge, U.K.). The probe was calibrated to measure mineral soil moisture within a working range of $0 – 0.54 \pm 0.006$ $m^3{\cdot}m^{-3}$. Values reported are the means of three measurements. Substrate temperatures (locations the same as for soil moisture) were recorded on day 106 using a thermocouple (Barnant Company, Barrington, Ill). Ambient air temperature and precipitation data were compiled from the Michigan Automated Weather Network's (MAWN) East Lansing weather station. Air temperatures were recorded at 1.5 m from the ground.

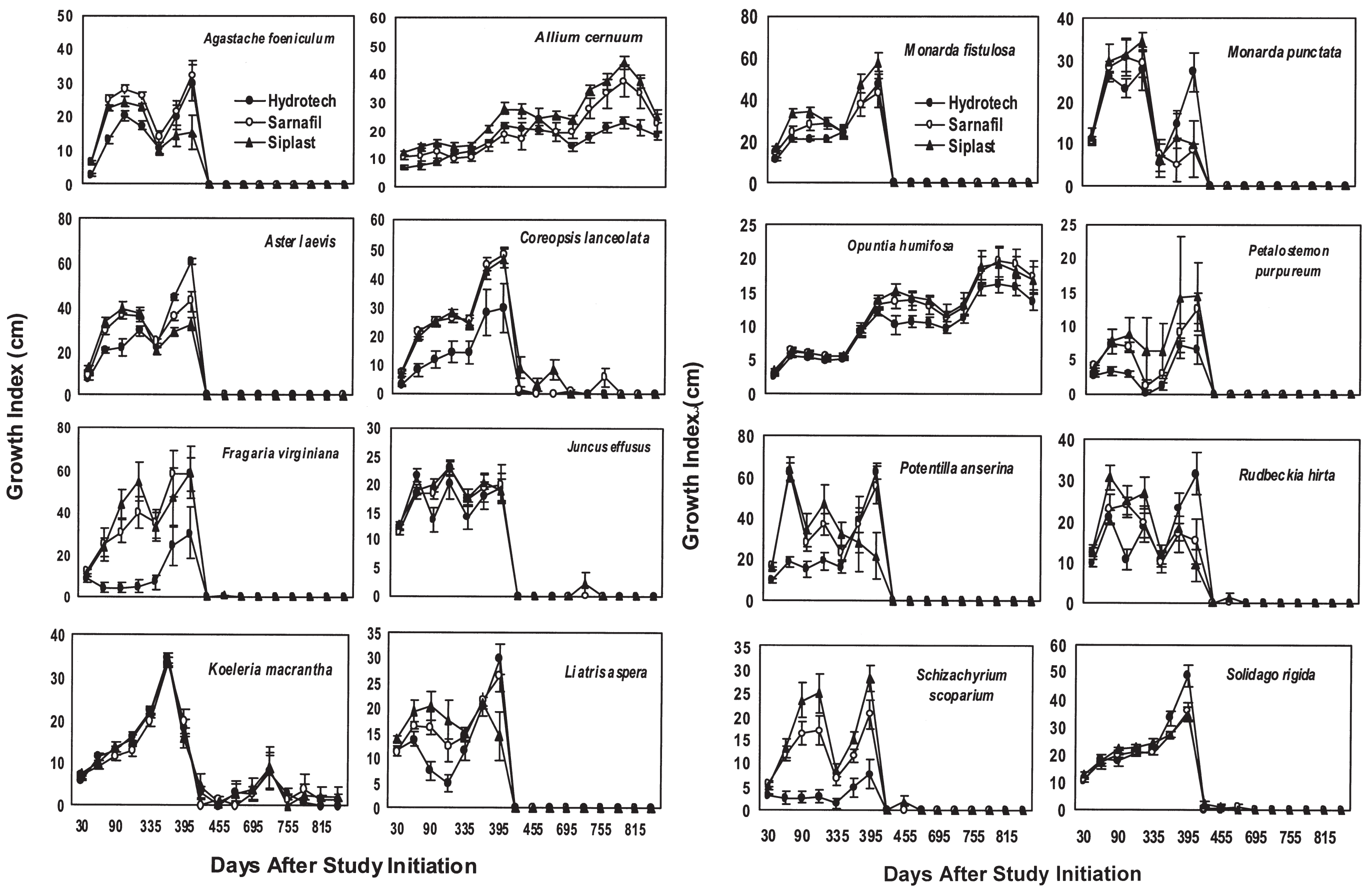
Data analysis. To compare plant growth indices, a mixed model was fit with repeated measures and fixed effects of system design, time, and platform section (PROC GLM SAS version 8.02, SAS Institute, Cary, N.C.). An autoregressive covariance structure was used and platform was treated as a random effect. To compare visual ratings, a generalized linear model with a multinomial error structure was fit with system design as a fixed effect (PROC GENMOD). Differences between system designs were tested within each taxa using chi-squared tests. Seedling coverage was fit to a mixed model with fixed effects of location, system design, and time using repeated measures with an unstructured covariance matrix. Seedling coverage values were transformed before analysis using an arcsine square root transformation to ensure homogeneity of variance and normality. In all analyses, Tukey-Kramer adjustments were made to test for pairwise differences.

Results and Discussion

Plant establishment from seed. During establishment, seed germination and subsequent plant coverage was affected by position on the platform and varied by drainage type. In general, faster seedling coverage for *Sedum* was found at the low end of the slope probably due to higher substrate moisture levels. After spring growth the following year, 100% *Sedum* coverage was observed in all seeded sections of all platforms. At this time, the two dominant species were *S. acre* and *S. album*. This implies that these two species are relatively aggressive spreaders relative to the others tested, a phenomenon that was also observed by Durhman et al. (2004).

Plant growth and appearance. During the first season, growth of most native plants peaked in September, and then declined with the onset of dormancy (Fig. 2). Optimum growth and appearance during the entire first season was possible because irrigation was provided during the plant establishment phase. Supplemental irrigation was much reduced during the second season and was terminated completely by 10 July of the second season. Therefore, after this date plants had to rely on natural rainfall, the likely scenario on most extensive green roofs.

After irrigation was terminated in 2002, plants from many of the native taxa died or went into dormancy. In the second season, most taxa were at their peak growth and appearance in July. These drastic effects might have been reduced if no supplemental irrigation had been supplied during the entire season and the plants were allowed to grow in response to natural rainfall. However, when no irrigation was applied during 2003, none of the native plants exhibited the growth they experienced in the previous two years, except for *A. cernuum* and *O. humifosa*, which continued to increase in size. Growth of *C. lanceolata, J. effusus, K. macrantha, S. heterolepis*, and *T. ohiensis* was marginal. Removing irrigation had little or no effect on all of the species of *Sedum*. Both the seed propagated and plug planted Sedum had reached 100% coverage by June 2002.



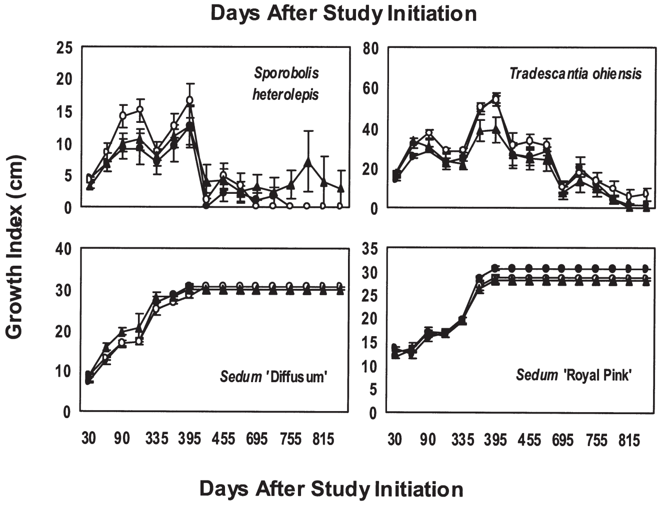


Fig. 2. Growth index of 20 taxa cultivated on three commercial green roof systems. Growth index is calculated as the average of plant height plus two-way width at the widest point along the vertical axis of the plant: (H+W1+W2)/3. Initial planting date was 15 June 2001. Error bars represent standard error.

Drainage system did not consistently affect plant growth across all taxa (Fig. 2). During 2001, *A. foeniculum, C. lanceolata, F. virginiana, L. aspera, P. anserina*, and *S. scoparium*, grew significantly less in the Hydrotech system compared to Sarnafil and Siplast. This trend continued into 2002 for *F. virginiana, O. humifosa*, and *S. scoparium*. However, in July 2002, the Hydrotech system resulted in the greatest growth for *A. laevis, M. punctata, R. hirta*, and *S. rigida*. By 2003, there was very little difference among the green roof systems except that *A. cernuum* exhibited the least amount of growth in Hydrotech and *S. heterolepis* did best in Siplast. Growing system had little or no effect on *Sedum*.

Few differences were observed within taxa in each drainage system and no system produced consistently higher visual ratings (Table 1). In a previous study, Kessler (1987) reported that *Sedum* spp. grew very well in three of four drainage systems tested with the exception being a system used by Hydrotech. Our tests showed no consistent problems with the Hydrotech system when compared to the others.

Throughout the study, *S.* 'Diffusum' and *S.* 'Royal Pink' showed the highest visual results rating of all taxa tested, as well as displaying the greatest drought tolerance after the termination of irrigation in the 2002 season. Visual ratings were not recorded on the seed propagated *Sedum*, but they maintained their 100% coverage even after irrigation ended. This finding supports the concept that *Sedum* spp. can be used in a wide variety of conditions and will grow successfully, particularly in dry areas (Gravatt and Martin, 1992; Heinz, 1985). Sedum can survive severe drought because of their method of photosynthetic carbon metabolism (Crassulacean acid metabolism) and their ability to store water (Gurevitch et al., 1986; Lee and Kim, 1994; Teeri et al., 1986; Ting, 1985). Teeri et al. (1986) showed that apical portions of *S. rubronticum* R.T. Clausen could survive at least two years without water in a greenhouse due it its ability to reallocate water to viable plant parts.

Of the native taxa tested, *A. laevis, M. fistulosa, S. rigida,* and *T. ohiensis* were the only taxa with a visual rating above 3.0 across all three growing systems when recorded in July 2002 (Table 1). Among the four native grass taxa, only *K. macrantha* showed much increase in growth from year 1 to year 2 (Fig. 2). The other three grass taxa, *J. effusus, S. scoparium, and S. heterolepis*, grew very little or not at all during the second or third season. Many grass taxa require deeper substrates than what is typically utilized in extensive green roof systems.

Both *P. anserina* and *F. virginiana* had a very high growth index due to their stoloniferous growth habit, but this growth habit also provides poor substrate coverage as top growth only appears at the nodes. *Potentilla anserina* exhibited less mortality, but also less consistent growth. These two taxa may be useful in green roofs utilizing entirely low-growing taxa. In green roofs containing taxa that grow taller than 10 cm, these taxa may not receive enough sunlight to survive. They would also require irrigation when grown in <10 cm of substrate, at least in Michigan.

Fast establishment, substrate coverage, and low mortality 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. These criteria describe all *Sedum* spp. used in this study, whether established by planting plugs or from sowing seed.

Soil moisture and temperature. Drainage system design did not influence substrate moisture at any of the measured locations. However, greater moisture contents were present at the lower portions of the platforms relative to the middle or higher portions along the slope. Mean volumetric soil moisture fractions for low, middle, and high slopes were 0.11, 0.09, and 0.08 $m^3 \cdot m^{-3}$, respectively. No precipitation was recorded the day measurements were obtained and the ambient air temperature reached a high of 14.5 °C that afternoon. Minimal precipitation occurred the previous day (2.03 mm) when the maximum temperature was 10.5 °C. Vegetation type alone had no impact on soil moisture levels.

Platform position also had an effect on soil temperature at all three locations along the slope. When measured at an ambient air temperature of 11.0 °C, substrate temperatures for low, middle, and high slopes were 8.5, 8.6, and 8.8 °C. Reduced substrate temperatures are probably related to the higher soil moisture at the lower regions in platform slope.

Plant survival. Over half of the taxa tested showed no mortality during establishment and by October 2001 only *F. virginiana, P.*

Table 1. Visual rating for each taxa planted from plugs by system design during July 2002 and October 2003).

	July 2002			October 2003		
Taxa	Hydrotech	Sarnafil	Siplast	Hydrotech	Sarnafil	Siplast
Agastache foeniculum	2.8 ab[z]	3.3 a	1.7 b	0	0	0
Allium cernuum	2.7 ab	2.3 b	3.2 a	2.8 a	3.2 a	3.2 a
Aster laevis	5.0 a	3.9 a	3.4 a	0	0	0
Coreopsis lanceolata	2.8 a	4.6 a	4.4 a	0 b	0.7 a	0 b
Fragaria virginiana	1.7 b	3.1 a	3.1 a	0	0	0
Juncus effusus	2.6 a	2.1 a	2.4 a	0	0	0
Koeleria macrantha	2.4 a	2.4 a	2.3 a	0 b	0.2 a	0.2 a
Liatris aspera	2.8 a	2.3 a	2.8 a	0	0	0
Monarda fistulosa	4.0 ab	4.2 a	3.1 b	0	0	0
Monarda punctata	2.9 a	0.9 b	1.0 b	0	0	0
Opuntia humifosa	2.0 a	2.3 a	2.4 a	3.7 a	3.7 a	2.8 b
Petalostemon purpureum	1.1 a	1.8 a	1.9 a	0	0	0
Potentilla anserina	3.0 a	1.1 b	3.0 a	0	0	0
Rudbeckia hirta	2.8 a	1.7 ab	1.1 b	0	0	0
Schizachyrium scoparium	1.1 b	2.4 a	3.0 a	0	0	0
Sedum Diffusum	4.5 a	4.5 a	4.5 a	4.5 a	4.5 a	4.5 a
Sedum Royal Pink	4.4 a	4.4 a	4.4 a	4.4 a	4.4 a	4.4 a
Solidago rigida	4.6 a	3.4 b	3.2 b	0	0	0
Sporobolus heterolepis	1.4 a	2.3 a	1.8 a	0 b	0 b	0.2 a
Tradescantia ohiensis	4.8 a	4.4 a	3.4 a	0.2 b	0.8 a	0 b

[z]Mean separation in rows between system design within each taxa were tested using chi-squared tests. $P \leq 0.05$; n = 9. Tests were done individually for 2002 and 2003.

Table 2. Percent survival of taxa over three seasons (2001–04). Values indicate survival of original plugs planted 15 June 2001.

	Survival (%)					
Taxa	October 2001	May 2002	October 2002	May 2003	October 2003	May 2004
Agastache foeniculum	100 a[z]	100 a	0 c	0 d	0 c	0 c
Allium cernuum	96 a	96 a	96 a	96 a	96 a	96 a
Aster laevis	100 a	100 a	0 c	0 d	0 c	0 c
Coreopsis lanceolata	89 b	89 ab	15 bc	4 d	4 c	4 c
Fragaria virginiana	70 d	70 c	0 c	0 d	0 c	0 c
Juncus effusus	96 a	96 a	4 c	4 d	0 c	0 c
Koeleria macrantha	100 a	100 a	22 b	22 c	7 c	7 c
Liatris aspera	100 a	100 a	0 c	0 d	0 c	0 c
Monarda fistulosa	96 a	96 a	0 c	0 d	0 c	0 c
Monarda punctata	100 a	56 d	0 c	0 d	0 c	0 c
Opuntia humifosa	100 a	100 a	100 a	100 a	100 a	100 a
Petalostemon purpureum	78 c	78 bc	0 c	0 d	0 c	0 c
Potentilla anserina	100 a	100 a	0 c	0 d	0 c	0 c
Rudbeckia hirta	89 b	85 b	0 c	0 d	0 c	0 c
Schizachyrium scoparium	74 cd	67 c	0 c	0 d	0 c	0 c
Sedum Diffusum	100 a	100 a	100 a	100 a	100 a	100 a
Sedum Royal Pink	100 a	100 a	100 a	100 a	100 a	100 a
Solidago rigida	100 a	4 e	0 c	0 d	0 c	0 c
Sporobolus heterolepis	85 bc	81 b	26 b	11cd	4 c	4 c
Tradescantia ohiensis	100 a	100 a	96 a	56 b	18 b	18 b

[z]Pairwise differences within columns were made by Tukey-Kramer adjustments. $P \leq 0.05$; n = 27 for native taxa, n = 108 for *Sedum* spp.

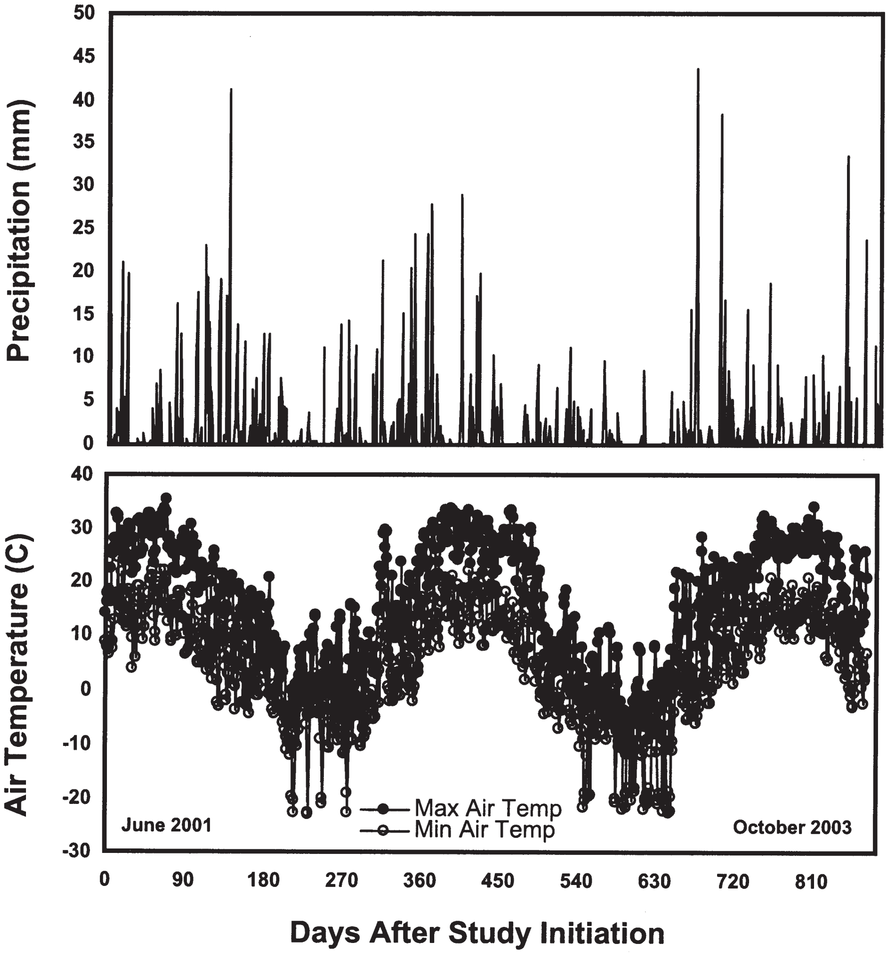


Fig. 3. Daily temperature and precipitation during the experimental study. Measurements were taken using the Michigan Automated Weather Network's weather station located at the research site in East Lansing.

purpureum, and *S. scoparium,* experienced losses greater than 15% (Table 2). The hot weather that prevailed during much of the first growing season could have effected plant mortality during the establishment phase. During the summer growing season from 1 June 2001 through 1 Sept. 2001, the mean daily high air temperature was 27.0 °C. The high temperature was 35.4 °C and nine days had a high temperature greater than 32.2 °C (Fig. 3). Total natural precipitation during this time period was 149.6 mm, however, plants were irrigated the entire summer so drought was not a factor.

The termination of supplemental irrigation during the second growing season combined with another unusually warm summer was fatal to many of the native taxa (Table 2). During the same timeframe in 2002, the mean daily high temperature was 27.8 °C. The high temperature was 33.6 °C and 12 d had a high temperature greater than 32.2 °C. Total natural precipitation amounted to 184.4 mm. At the end of the 2002 growing season, there were no surviving plants of *A. foeniculum, A. laevis, F. virginiana, L. spicata, M. fistulosa, M. punctata, P. purpureum, P. anserina, R. hirta, S, scoparium*, and *S. rigida* (Table 2). Likewise, there were high mortality rates for *C. lanceolata, J. effusus, K. macrantha*, and *S. heterolepis*. *Allium cernuum, O. humifosa, T. ohiensis*, and all of the *Sedum* proved to be drought tolerant. However, there were major losses of *T. ohiensis* during the summer of 2003. This is somewhat surprising, because 2003 growing season was relatively cooler with a mean daily high temperature of 26.3 °C. The high was 34.2 °C and a high temperature greater than 32.2 °C was reached on only two days. Even though temperatures were not as warm, total precipitation during this time period was only 125.5 mm.

Cold tolerance is also an important attribute of plants for green roofs in cold climates such as Michigan. During the first winter, major losses occurred for *M. punctata* and *S. rigida* where only 56% and 4% of the plants survived. Thus, because of cold hardiness problems, it appears these two species are not suitable for use on Michigan green roofs or other regions with a similar climate. *Rudbeckia hirta, S. scoparium*, and *S. heterolepis* also exhibited overwintering mortality, but losses were <7%. Additional mortality occurred during the second winter to plants of *C. lanceolata, S. heterolepis*, and *T. ohiensis*, but no further losses occurred during the third winter. Plants that survived the relatively mild winter of 2002 likely succumbed the following winter because of the much colder temperatures during the second winter. Minimum temperatures experienced during the winters of 2002, 2003, and 2004, were –15.9, –24.6, and –25.7 °C, respectively. Only *A. cernuum, O. humifosa,* and all species of *Sedum* experienced no overwintering losses.

Mortality during winter could be due to death of the root systems, which are generally not as cold tolerant as the tops of plants (Wu et al., 2000). Boivin et al. (2001) suggests using a minimum of 10 cm of substrate in northern latitudes (43 to 60°N). It is possible that the 10 cm substrate depth used in this research allowed for less winter mortality than would have occurred if a shallower substrate layer was used. The shallower substrate would make root systems more susceptible to cold damage. However, on an actual roof the rooting substrate would be warmed somewhat from heat transfer from the building roof structure.

Nearly any plant taxa could be used for green roof applications assuming that it was suited to the climatic region, was grown in an appropriate substrate at an adequate depth, and irrigation was available. Native plants are generally considered ideal choices for landscapes due to their natural adaptations to local climates. Unfortunately, many native plants are not suitable for extensive green roof systems because of the harsh environmental conditions and shallow substrate depths. Of the native plants tested in 10 cm of substrate, all plants of *O. humifosa* survived and increased in size during the study. However, *O. humifosa* is not an ideal green roof selection because of its slow growth and lack of quick surface coverage. Although, only one of the original 27 plants of *C. lanceolata* survived for three years, 30 plants were present in May 2004 due to reseeding in alternate locations on the platforms. Likewise, there were 17 separate clumps of *T. ohiensis* in May 2004, even though only five of the original plants had survived. *A. cernuum* also proved to be an excellent choice as 96% of the original clumps of plants were still present after three years. In addition, *A. cernuum* spread from 27 to 34 locations and the average number of plants per clump increased from one to 21.4. The ability of *C. lanceolata, T. ohiensis,* and *A. cernuum* to seed freely and naturalize make them potential choices for extensive green roofs. Of the nine *Sedum* spp. tested, all proved to be suitable for shallow substrate green roof systems.

Conclusion

Drainage system design had minimal effect on the initial growth, appearance during establishment, or mortality of the taxa tested. Ideal plant selections for extensive green roofs in northern climates such as Michigan that lack irrigation must be heat and cold tolerant, drought resistant, have a high growth index in order to provide quick coverage, and must be self-generating by seed, root systems, or some other means. Of the species tested, all nine species of *Sedum* along with *A. cernuum, C. lanceolata,* and *T. ohiensis* were the most suitable for unirrigated roofs. *O. humifosa* survived, but lacked the ability to provide quick surface coverage. Further experiments are necessary to determine the soil moisture requirement to sustain native perennials and to determine whether these taxa can tolerate the low winter temperatures that are typical of the Midwest climate.

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