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Assessment of Physical Properties and Stonecrop Growth in Green Roof Substrates Amended with Compost and Hydrogel

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SUMMARY. There is a lack of quantifiable data concerning physical analyses specific to shallow-depth green roof substrates and their effects on initial plant growth. Physical properties were determined for green roof substrates containing (by volume) 50%, 60%, or 70% heat-expanded coarse slate and 30% heat-expanded fine slate amended with 20%, 10%, or 0% landscape and greenhouse waste compost. Each substrate also was amended with hydrogel at 0, 0.75, 1.50, or 3.75 lb/yd³. There were no differences in total porosity among substrates containing 0%, 10%, or 20% compost, although total porosity increased for all substrates amended with hydrogel at 3.75 lb/yd³. Container capacity increased in substrates containing 3.75 lb/yd³ hydrogel, except for substrates containing 10% compost where hydrogel had no effect. Aeration porosity decreased when 10% or 20% compost was added to substrates. Determination of aeration porosity at an applied suction pressure of 6.3 kPa (AP_{-6.3 kPa}), indicated that AP_{-6.3 kPa} was higher in substrates containing 0% compost than substrates containing 20% compost. Shoot dry weight and coverage area measurements of 'Weihenstephaner Gold' stonecrop (*Sedum floriferum*) and 'Summer Glory' stonecrop (*Sedum spurium*) were determined 9 weeks after plug transplantation into substrates. Both stonecrop species responded similarly to substrate amendments. Initial plant growth was greater in substrate containing 20% compost and 3.75 lb/yd³ hydrogel than nonamended substrate resulting in 198% and 161% higher shoot dry weight and coverage area, respectively. Alkaline heat-expanded slate and acidic compost components affected initial pH of substrates, but there was less variation among final substrate pH values. We conclude that compost and/or hydrogel amendments affected physiochemical properties following incorporation into slate-based green roof substrates, resulting in greater initial plant growth, and that these amendments may have practical applications for improving growing conditions on green roofs.

Vegetated roofs, or green roofs, are multilayered systems containing plant and substrate materials. Green roof substrates are not similar to field soils, but have characteristics in common with shallow-drained

soils and/or greenhouse container substrates (Beattie and Berghage, 2004; Spomer, 1990). There is no single ideal substrate for green roofs in all locations throughout the United States due to regional climatic differences; however,

a blend of characteristics provides optimal container capacity, nutrient-holding capacity, pH, aeration, and bulk density. Typically, green roof substrates are 80% to 100% mineral and 0% to 20% organic matter, which contribute to water- and nutrient-holding capacities (Beattie and Berghage, 2004). Organic matter also can act as an adhesive between soil particles, resulting in improved moisture-holding capabilities (Alexander, 1996). Compost is the preferred source of organic matter incorporated into green roof substrates primarily due to nutrient, microbial, and social benefits (Friedrich, 2005). A maximum of 15% (Rowe et al., 2006) or 0% to 25% (Friedrich, 2005) organic matter content (by volume) is recommended for green roof substrates, although there are few research reports of compost effects on green roof substrate performance. Compost components reported in green roof substrates include green waste compost (Dunnett and Nolan, 2004), composted yard waste, and composted turkey waste (Durhman et al., 2007; Rowe et al., 2006; VanWoert et al., 2005). Non-succulent native plant growth is more dependent on organic matter content than succulent stonecrop species, although visual ratings of 'Diffusum' stonecrop (*Sedum middendorffianum*) and 'Royal Pink' stonecrop (*Sedum spurium*) increased 9.4% and 15.8%, respectively, with the substitution of 15% (by volume) organic matter consisting of peatmoss, aged poultry manure, and composted yard waste (Rowe et al., 2006).

Substrate depth determines the vegetation forms and species planted on green roofs [Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL), 2002]. A 1-inch-deep substrate often can be used without supplemental irrigation or major structural modifications, resulting in lower installation and maintenance costs (Friedrich, 2005). However, plants grown in 1-inch-deep substrates have reduced survival over those grown in 2-inch-deep substrates (Durhman et al., 2007). Winter plant damage is less in 4- or 6-inch-deep than in 2-inch-deep substrates, possibly due to lower minimum temperature and higher temperature variation (Boivin et al., 2001). Shallow-depth substrates (1.6–3.1 inches deep) support moss-sedum vegetation types (FLL,

2002). Green roofs with 1.6-inch-deep substrate hold less water and likely dry out more rapidly than 2.8- or 3.9-inch-deep substrates (Getter and Rowe, 2009). Lower survival rates of native herbaceous plants on a 4-inch-deep substrate was probably due to low container capacity (Rowe et al., 2006) and water availability was hypothesized to be the limiting factor for coverage of 'Weihenstephaner Gold' stonecrop (Getter and Rowe, 2009). 'Summer Glory' stonecrop is a good choice for shallow-depth green roof substrates and is capable of 75% survival within a 1-inch-deep substrate after 482 d or 100% survival on a 2-inch-deep substrate after 482 d (Durhman et al., 2007). 'Weihenstephaner Gold' stonecrop, 'Tasteless' stonecrop (*Sedum sexangulare*), stonecrop (*Sedum stefco*), and 'John Creech' stonecrop (*S. spurium*) are suitable for 1.6- or 2.8-inch-deep substrates (Getter and Rowe, 2009).

Water-absorbent crystals, or hydrogels, expand into pliable gels when hydrated and are added to horticultural substrates to reduce plant stress and act as a water reservoir supply during periods of drought (Johnson and Leah, 1990). Potassium propenat propenamide copolymer-based hydrogel amendments delayed wilting during drought conditions for marigold (*Tagetes erecta*) and zinnia (*Zinnia elegans*) following incorporation into a peat-lite mix at a rate of 4 to 16 kg·m⁻³ (Gehring and Lewis, 1980). Polyacrylamide-based hydrogels incorporated into a sandy soil (4 g·kg⁻¹) increased survival of but-tonwood (*Conocarpus erectus*) under drought stress (Al-Humaid and Moftah, 2007). In addition, coarse sand amended with hydrogel at 0.5 to 5 g·kg⁻¹ increased mean shoot fresh weight and reduced evapotranspiration for lettuce (*Lactuca sativa*), rad-ish (*Raphanus sativus*), and common

wheat (*Triticum aestivum*) when sub-jected to temporary drought (Johnson and Leah, 1990). After incorpora-tion with a polyacrylamide hydrogel (SuperSorb-C; Aquatrols Corp. of America, Paulsboro, NJ) at 1.8 kg·m⁻³, there was a 6.9% increase of container capacity (and a concomitant 22.8% decrease of aeration porosity) in pine bark substrate and a 6.0% increase of container capacity (and a concomitant 33.0% decrease of aeration porosity) in a mix containing (by volume) 80% pine bark and 20% sand (Fonteno and Bilderback, 1993). SuperSorb-C also increased water retention in a mix containing (by volume) 50% peatmoss and 50% pine bark (Wang and Gregg, 1990). It has been suggested that hydrogels also may be used during land restoration to address water lim-itations during seed germination and seedling establishment (Mangold and Sheley, 2007).

Two reviews summarized known green roof substrate information (Beattie and Berghage, 2004; Frie-drich, 2005). Nonetheless, there are few research reports that evaluate physical and chemical properties of shallow-depth substrates and their relationship to initial plant growth. Greenhouse and laboratory trials were conducted to determine the physical properties of substrates with increasing concentrations of compost and hydrogel, and to evaluate initial growth of two stonecrop species in 12 substrates by measuring shoot dry weight and coverage area.

Materials and methods

Landscape and greenhouse waste was collected from The Landscape Arboretum of Temple University

(Ambler, PA) and was composted by a process described previously (Olszewski et al., 2009). Materials were composted in windrows for 9 weeks followed by sieving through a 1-cm screen. Final processing consisted of heating in an electric soil sterilizer (SS60R; Pro-Grow Supply, Brookfield, WI) at 82 °C for 40 min. The chemical properties of compost used in the experiments are shown in Table 1. Green roof substrates (a total of 12) were prepared in 7.5-L batches consisting of 50%, 60%, or 70% (by volume) coarse-grade, heat-expanded slate (average particle size = 9.3 mm), 30% (by volume) fine-grade, heat-expanded slate (average particle size = 2.5 mm; Carolina Stalite, Salisbury, NC), and 0%, 10%, or 20% compost. Substrate components were blended for 3 min in a cement mixer with 6 lb/yard³ controlled-release fertilizer (15N-3.9P-10K, Osmocote Plus; Scotts-Sierra, Marysville, OH) and 0, 0.75, 1.50 (1×-rate), or 3.75 lb/yard³ hydrogel (SuperSorb-C). The fertilizer incorporation rate was selected based on manufacturer recommendations for a 3- to 4-month release in nursery sub-strates. The hydrogel 1×-rate was se-lected based on recommendations for nursery, greenhouse, landscape, and interiorscape mix amendments.

Physical properties of green roof substrates were determined in four replications at 0 and -6.3 kPa pres-sure. These values were selected based on FLL (2002) recommendations for testing physical properties of green roof substrates. Because container ca-pacity and aeration porosity may be affected by substrate depth, it is ap-propriate to use a cylinder of a height equivalent to the depth of the test

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Units			
To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
100	bar	kPa	0.01
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
645.1600	inch ²	mm ²	0.0016
16.3871	inch ³	cm ³	0.0610
0.5933	lb/yard ³	kg·m ⁻³	1.6856
1	mmho/cm	mS·cm ⁻¹	1
28.3495	oz	g	0.0353
28,350	oz	mg	3.5274 × 10 ⁻⁵
1.7300	oz/inch ³	g·cm ⁻³	0.5780
1	ppm	mg·kg ⁻¹	1
1	ppm	mg·L ⁻¹	1
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

Table 1. Compost analyses including pH, electrical conductivity, nitrate ($\text{NO}_3\text{-N}$), ammonium ($\text{NH}_4\text{-N}$), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), boron (B), copper (Cu), zinc (Zn), molybdenum (Mo), sodium (Na), aluminum (Al), sulfur (S), carbon (C), nitrogen (N), and C:N ratio.

	pH	EC	NO ₃ -N	NH ₄ -N	P	K	Ca	Mg	Fe	Mn	B	Cu	Zn	Mo	Na	Al	S	C	N	C:N
Substrate	(mean $\pm$ sd) ^z																			
	(mS·cm ⁻¹) ^y										(ppm) ^y									
Compost ^a	6.62 $\pm$ 0.04	1.60 $\pm$ 0.04	112 $\pm$ 2	48 $\pm$ 8	6 $\pm$ 0.3	120 $\pm$ 3	125 $\pm$ 4	44 $\pm$ 1	1.88 $\pm$ 0.3	0.04 $\pm$ 0.006	0.5 $\pm$ 0.1	0.09 $\pm$ 0.01	0.03 $\pm$ 0.006	0.02 $\pm$ 0.006	21 $\pm$ 1	4 $\pm$ 0.5	0.05 $\pm$ 0.007	10.7 $\pm$ 0.03	0.7 $\pm$ 0.02	15 $\pm$ 0.6
Normal range ^w	5.3–6.2	0.76–2.50	40–200	0–30	5–30	40–200	40–200	28–80	0.3–3.0	0.1–3.0	0.05–0.5	0.01–0.3	0.1–0.3	0.01–0.1	— ^v	—	—	—	—	—

^zThree replicates.

^y1 mS·cm⁻¹ = 1 mmho/cm, 1 ppm = 1 mg·kg⁻¹.

^a— = unknown or unspecified normal ranges.

^wValues and normal ranges were determined by Micro-Macro International (Athens, GA) for horticultural substrates.

site to determine substrate physical properties (Spomer, 1990). Thus, 2-inch-tall $\times$ 9.3-cm-diameter Buchner funnel removable cylinders were filled with 358 cm³ substrate and subjected to procedures described by Wang and Gregg (1990) and Spomer (1990). Bulk density of substrates (6.9% water content, w/w) was determined by using a 358-cm³-capacity cylinder. Maximum water-holding capacity was achieved through subirrigation with distilled water added until water surface was at the cylinder rim. When the substrate surface glistened, the cylinder and substrate then were lifted quickly, removed to a pan, and weighed. Total porosity was determined from the amount of water needed to saturate substrate. Substrate was allowed to drain for 24 h (20 °C; 98% relative humidity) before being weighed and water retention determined gravimetrically. Container capacity equaled the amount of water retained after drainage divided by 358 cm³ followed by multiplication by 100. Aeration porosity equaled total porosity minus container capacity. A vacuum pressure apparatus described by Spomer (1990) was constructed with a water reservoir to allow a 63-cm rise in water column within a 100-cm buret for aeration porosity determination at applied pressure (AP_{-6.3kPa}).

Substrate particle size distribution was determined by screening, using four replications of 100 g of air-dried samples placed into the top of a sieve series with mesh diameters of 4.00, 3.35, 2.00, 1.00, 0.50, and 0.25 mm. Each sample was shaken for 3 min with a shaker (Ro-Tap; W.S. Tyler, Mentor, OH) and particles in each sieve and receiver pan were weighed and percentages were determined.

Seeds of 'Weihenstephaner Gold' stoncrop and 'Summer Glory' stoncrop (Jelitto Perennial Seeds, Schwarmstedt, Germany) were sowed onto double thickness blotters (No. 385; Seedburow, Chicago) contained in 125 $\times$ 80 $\times$ 20-mm transparent polystyrene boxes moistened with 20 mL of distilled water and incubated as per requirements for 'Goldmoss' stoncrop (*Sedum acre*) (Association of Official Seed Analysts, 2007). 'Summer Glory' stoncrop seeds were sowed on 26 Nov. 2008 and 'Weihenstephaner Gold' stoncrop seeds were sowed on 19 Dec. 2008. One

week after sowing, seedlings were removed to Redi-Earth Plug and Seedling Mix (SunGro Horticulture, Bellevue, WA) contained in 288 plug sizes (one seedling per plug). Seedlings initially were fertilized once weekly with 200 ppm nitrogen (N) alternating with 20N–3.2P–16.6K and 13N–0.6P–10.8K, but subsequently was reduced to once every 2 weeks with 100 ppm N. Plugs (10-week 'Weihenstephaner Gold' stoncrop plugs and 13-week 'Summer Glory' stoncrop plugs) were transplanted into substrates contained within constructed 1- $\times$ 4-ft wooden platforms tilted at a 5° angle. Plugs were spaced 10 cm apart from one another and there were four replications (wooden platforms) for each of the two plant species and 12 substrates. Irrigation occurred once every 10 d (about 5 gal/irrigation per platform) in a greenhouse with natural and artificial light (February, March, and April). Midday photosynthetically active radiation (PAR) ranged from 235 to 825 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and temperatures ranged from 17 to 31 °C. Nine weeks after transplanting, a photograph of each plant was taken using a 55-mm EOS Rebel XT digital camera (Canon, Tokyo). Each photograph was taken directly overhead and included a 400-mm² standard; photographs and standards were printed, cut, weighed, and coverage area was determined relative to the standard. Shoots were cut at the surface of the substrate, dried at 70 °C for 48 h, and weighed. Pre- and postharvest substrate samples were obtained from each treatment for a 1:2 dilution test [1 substrate:2 distilled water (by volume)] for pH and electrical conductivity (EC) determination using a pH Testr30 and EC Testr11 plus (Oakton Instruments, Vernon Hills, IL).

The plant growth experiment was arranged using a randomized complete block randomization procedure for a split-plot design (Gomez and Gomez, 1984) with 12 substrates (main plot treatments) and two species of stoncrop (subplot treatments). Data were subjected to analysis of variance using PROC GLM where appropriate (SAS version 9.1; SAS Institute, Cary, NC). Data were transformed according to Gomez and Gomez (1984) and means were separated by Fisher's protected least

significance difference (LSD) at $P \leq 0.05$ or single df contrasts.

Results and discussion

Compost nutrient concentrations, pH, EC, and carbon (C):N ratio were within normal ranges for green roof substrates as stated by FLL (2002). However, there are no comprehensive standards for compost amendments for green roof substrates. Chemical analyses indicated that there were supraoptimal ammonium (48 ppm), and suboptimal manganese (0.04 ppm) and zinc (0.03 ppm) concentrations (Table 1). Because blended substrates used in this study were amended with slow-release fertilizer and with compost that did not exceed 20% (by volume) of the total substrate composition, the effects of nutrient imbalance due to compost were thought to be minimal. The C:N ratio for compost used in this study was low (15), and this value is indicative of composting process effectiveness (Day and Shaw, 2001). Kayhanian and Tchobanoglous

(1992) determined a C:N ratio of 22.8 for composted yard waste. By contrast, sphagnum peatmoss has a C:N ratio of 54 (Handreck and Black, 1994), making it susceptible to rapid decomposition and subsequent shrinkage. Excessive organic matter decomposition in green roof substrates may result in drainage and plant health issues (Friedrich, 2005).

Green roof substrates must be heavy enough to resist water and wind erosion (Beattie and Berghage, 2004). In the current study, bulk density measurements of blended substrates ranged from 0.87 to 0.88 $\text{g}\cdot\text{cm}^{-3}$. Bulk densities of 0.67 $\text{g}\cdot\text{cm}^{-3}$ (Friedrich, 2005) or 0.96 $\text{g}\cdot\text{cm}^{-3}$ (Beattie and Berghage, 2004) were suggested as desirable values for green roof substrates. Guidelines (FLL, 2002) for green roof substrates include container capacity $\geq 35\%$ (by volume) and aeration porosity $>10\%$ (by volume) or $\text{AP}_{-6.3 \text{ kPa}} \geq 25\%$ (by volume); however, these values are determined using 6.5-inch-deep cylinders rather than the 2-inch-deep

cylinders used in this study. Hydrogel at 3.75 lb/yard^3 increased total porosity percentage in all substrates (Table 2). Aeration porosity for substrate with 10% compost and no hydrogel or substrate with 20% compost and hydrogel at 3.75 lb/yard^3 were 9% and 7%, respectively [$\text{AP}_{-6.3 \text{ kPa}} = 24\%$ (both substrates)]. All other substrates met FLL (2002) guidelines for aeration porosity. The sole substrate that met recommended guidelines for container capacity contained 20% compost and hydrogel at 3.75 lb/yard^3 (container capacity = 37%). Because plant health is dependent on local environmental conditions, regional standards for physical properties may need to be adjusted to allow for varying substrate depths, areas with minimal rainfall, or green roofs with no irrigation.

Particle size distribution of substrates containing 0%, 10%, or 20% compost is shown (Fig. 1). Substrate containing 0% compost had 4% and 15%, respectively, more large ($\geq 4.00 \text{ mm}$) particles than substrates

Table 2. Total porosity, container capacity, aeration porosity, and aeration porosity at applied suction pressure of 6.3 kPa (0.063 bar) of heat-expanded, slate-based substrates amended with compost and hydrogel.

Substrate components				Total porosity (%) ^y	Container capacity [% (deg)] ^x	Aeration porosity [% (√)] ^w	Aeration porosity at applied suction pressure of 6.3 kPa [% (deg)]
Coarse slate (% by vol)	Fine slate (% by vol)	Compost (% by vol)	Hydrogel (lb/yard ³)				
70	30	0	0.00	36	23 (28)	14 (3.7)	31 (34)
			0.75	38	22 (28)	16 (3.9)	31 (33)
			1.50	38	26 (30)	12 (3.4)	24 (29)
			3.75	40	28 (32)	12 (3.4)	26 (30)
60	30	10	0.00	34	25 (30)	9 (3.0)	24 (29)
			0.75	34	25 (30)	11 (3.3)	24 (32)
			1.50	39	24 (30)	14 (3.8)	29 (33)
			3.75	42	27 (31)	14 (3.8)	27 (31)
50	30	20	0.00	36	26 (30)	10 (3.1)	23 (29)
			0.75	37	26 (31)	11 (3.2)	24 (29)
			1.50	39	29 (32)	10 (3.2)	25 (30)
			3.75	44	37 (37)	7 (2.7)	24 (29)
LSD _{0.05} ^v				2	(2)	(0.5)	(3)
Significance ^u							
3.75 vs. 0.00 lb/yard ³				**	***	NS	NS
3.75 vs. 0.75 lb/yard ³				**	NS	NS	NS
3.75 vs. 1.50 lb/yard ³				NS	NS	NS	NS
0% vs. 10% compost				NS	***	***	NS
0% vs. 20% compost				NS	***	***	***
10% vs. 20% compost				*	NS	NS	NS

^z1 $\text{lb}/\text{yard}^3 = 0.5933 \text{ kg}\cdot\text{m}^{-3}$.

^yTotal porosity, container capacity, aeration porosity, and aeration porosity at applied suction pressure of 6.3 kPa were determined for 358- cm^3 (21.85 inch^3), 2-inch-tall $\times$ 9.3-cm-diameter (5.1 $\text{cm} \times$ 3.66 inches) cylinder.

^xdeg = angular transformation of percentage data ($\arcsin \sqrt{\%}$).

^w√ = square root transformation of percentage data.

^uMeans separation within columns by substrate by Fisher's protected least significant difference at $P \leq 0.05$.

****, **, * $P \leq 0.001$, 0.01, 0.05, respectively; NS = not significant.

containing 10% and 20% compost. However, substrate with 0% compost had 31% and 55%, respectively, less small (<0.5 mm) particles than

substrates containing 10% and 20% compost. The particle size distribution provides an explanation for the higher aeration porosity and $AP_{-6.3 \text{ kPa}}$ in

nonamended slate substrate (Table 2). Drainage must be extremely rapid for green roof substrates, necessitating large particle sizes and high aeration porosity. Spomer (1990) reviewed the practical importance of soil depth on physical characteristics of shallow-drained soils. In shallow-depth substrates with a high proportion of large particle sizes, there will be reduced capillary water due to large pore spaces and, conversely, increased capillary water is predicted within substrate containing smaller particles and smaller pore sizes.

Shoot dry weight and coverage area generally increased when substrates were amended with compost and hydrogel but there were no differences between 'Weihenstephaner Gold' stonecrop and 'Summer Glory' stonecrop (Table 3). These results are in agreement with Al-Humaid and Mofiah (2007), Gehring and Lewis (1980), Johnson and Leah (1990), and Pill and Jacono (1984), who determined growth benefits by incorporating hydrogel into mineral soil or horticultural substrate. Initial plant growth was affected by hydrogel when incorporated at 3.75 lb/yard³ into

Fig. 1. Particle size distribution of heat-expanded, slate-based green roof substrates containing 0%, 10%, or 20% compost (by volume). Each substrate had 30% (by volume) heat-expanded fine slate and 50%, 60%, or 70% (by volume) heat-expanded coarse slate. Vertical bars indicate SE; 1 mm = 0.0394 inch.

Table 3. Initial growth of 'Weihenstephaner Gold' stonecrop (*Sedum floriferum*) and 'Summer Glory' stonecrop (*S. spurium*) 9 weeks after transplanting into 1 × 4-ft (30.5 × 121.9 cm) wooden platforms containing heat-expanded, slate-based substrates amended with compost and hydrogel. All plants were irrigated once every 10 d.

Substrate components ^z				‘Weihenstephaner Gold’ stonecrop		‘Summer Glory’ stonecrop	
Coarse slate (% by vol)	Fine slate (% by vol)	Compost (% by vol)	Hydrogel (lb/yard ³) ^y	Shoot dry wt [mg/shoot (ln)] ^{y,x}	Coverage area [mm ² (ln)] ^y	Shoot [mg/shoot (ln)]	Coverage area [mm ² (ln)]
70	30	0	0.00	201.0 (5.288) ^w	2533 (7.810)	273.5 (5.587)	2304 (7.735)
			0.75	223.0 (5.354)	2309 (7.701)	221.5 (5.334)	1852 (7.467)
			1.50	272.0 (5.590)	3038 (7.963)	371.3 (5.898)	2691 (7.895)
			3.75	356.5 (5.856)	3301 (8.098)	502.0 (6.194)	4223 (8.339)
60	30	10	0.00	431.8 (6.033)	4908 (8.422)	382.0 (5.906)	3233 (8.058)
			0.75	469.5 (6.126)	4967 (8.477)	437.3 (5.999)	3852 (8.155)
			1.50	485.8 (6.177)	4497 (8.388)	317.3 (5.736)	2944 (7.946)
			3.75	460.8 (6.036)	4583 (8.389)	537.0 (6.245)	4366 (8.332)
50	30	20	0.00	544.3 (6.220)	5679 (8.580)	671.0 (6.367)	4837 (8.369)
			0.75	448.5 (6.040)	4481 (8.275)	527.5 (6.250)	4550 (8.402)
			1.50	419.3 (6.003)	3496 (8.121)	720.5 (6.559)	5654 (8.583)
			3.75	696.3 (6.518)	6301 (8.715)	683.0 (6.521)	6279 (8.724)
LSD _{0.05} (two-way) ^v				(0.348)	(0.363)		
Significance ^u							
Substrate components (SC)				***	***		
Stonecrop species (SS)				NS	NS		
ST × SS				NS	NS		

^zSubstrates initially contained controlled-release fertilizer (Osmocote Plus; Scotts-Sierra, Marysville, OH), and plants received no subsequent fertilizer throughout the experiment.

^y1 lb/yard³ = 0.5933 kg·m⁻³, 1 mg = 3.5274 × 10⁻⁵ oz, 1 mm² = 0.0016 inch².

^xShoot dry weight was determined by drying plant shoots at 70 °C (158.0 °F) for 48 h.

^wValues in parentheses are the natural logarithm (ln) transformations of the mean.

^vMeans separation within columns by substrate by two-way Fisher's protected least significant difference (LSD) at $P \leq 0.05$.

^u*** $P \leq 0.001$. NS: not significant.

substrates without compost, resulting in an 81% and 57% respective increase of shoot dry weight and coverage area (pooled means). To the best of our knowledge, this is the first research report of a hydrogel used in green roof substrates. Water relations are an important limiting factor of stonecrop growth in green roof substrates (VanWoert et al., 2005). The ability of hydrogel to absorb water decreases with an increase in the number of irrigation cycles (Wang and Gregg, 1990) so hydrogel must be reapplied if optimal container capacity is desired beyond the initial treatment. Also, large quantities of hydrogel will result in expansion of substrate (Pill and Jacono, 1984); thus, there are limitations with this component. During greenhouse studies, there was some expansion within substrates treated with hydrogel at 3.75 lb/yard³ (data not shown), but it is unknown as to whether this would be commercially acceptable. When amendments of 20% compost and hydrogel at 3.75 lb/yard³ were combined into a slate-based substrate, shoot dry weight and coverage area increased by 198% and 161%, respectively, over plants grown in nonamended substrates. A high amount of slate can be used (70%–80%) without negative visual effects of ‘Royal Pink’ stonecrop, but growth is related to organic material content within green roof

substrate (Rowe et al., 2006). However, decomposition and subsequent volume shrinkage limit organic material proportions within green roof substrates (Beattie and Berghage, 2004).

Green roof substrate components contribute to pH and EC changes (Nektarios and Chronopoulos, 2004). In the current study, there were no substantial initial EC differences among substrates (Table 4). There were no EC differences among substrates at the end of the experiment, but it is clear that much of the initial nutrient charge had dissipated after 9 weeks. Storm water runoff results in higher nutrient leaching from green roofs than asphalt roofs (United States Environmental Protection Agency, 2009), and nutrients must be periodically reapplied to green roof substrates for adequate plant growth (Beattie and Berghage, 2004). Determinations of pH before experiments indicated that substrate with 20% compost initially had more desirable pH (less alkaline) ranges than substrates without compost, although no or little difference was noted after 9 weeks. Initial pH was influenced by heat-expanded slate (an alkaline material) and compost (an acidic material), and higher alkalinity may partially explain some reductions in initial plant growth (Table 3).

The hydrogel used in this study was polyacrylamide-based and it is

unknown if other hydrogels would behave similarly within green roof substrates. Water retention capabilities of hydrogel decrease with repeated fertilization, and water absorption by hydrogel is affected by chemical category, including polyacrylamide, starch, and propenoate-propenamide copolymer types (Wang and Gregg, 1990). Compost additions decreased initial pH and aeration porosity or AP_{6.3kPa} and increased the percentage of small (<0.50 mm) particles. Although aeration porosity of some substrates tested in this study were below FLL guidelines (2002), this seems less important than attaining adequate container capacity and related hydrological properties. Supplemental watering decreased height of ‘Blue Queen’ stonecrop (*S. acre*) in 10-cm-deep substrates (Dunnett and Nolan, 2004), suggesting that increased water retention could potentially cause root anoxia or other physiological problems. However, we observed increased shoot dry weight and coverage area for ‘Weihenstephaner Gold’ stonecrop and ‘Summer Glory’ stonecrop when amendments of 20% compost and hydrogel at 3.75 lb/yard³ were incorporated into slate-based substrates. Increased initial growth of stonecrop is hypothesized to have been caused by several factors including container capacity, aeration porosity and AP_{6.3kPa}, initial pH, particle size distribution, and improved soil structure accompanied by reduced evapotranspiration. Because hydrogel and compost amendments affected physiochemical properties of green roof substrates, they may have applications as shallow-depth substrate components in areas that are prone to excessive evaporative water loss, including new green roof installations or wind-eroded areas. Future research should analyze physical properties of other major components of green roof substrates at specific depths, including components such as shale or clay plus other recycled compost or organic components with an emphasis on cost-effective roofing strategies and shallow-depth green roofs.

Table 4. Initial and final pH and electrical conductivity (EC) of heat-expanded, slate-based substrates amended with compost and hydrogel and subjected to a plant growth study. Final pH and EC were determined 9 weeks after transplanting ‘Weihenstephaner Gold’ stonecrop and ‘Summer Glory’ stonecrop plugs into substrates.

Substrate components ^z				pH		EC (mS·cm ⁻¹) ^y	
Coarse slate (% by vol)	Fine slate (% by vol)	Compost (% by vol)	Hydrogel (lb/yard ³) ^y	Initial	Final	Initial	Final
70	30	0	0.00	7.91	7.15	2.23	0.60
			0.75	7.93	7.12	1.94	0.53
			1.50	8.08	6.99	2.18	0.67
			3.75	8.04	6.98	2.06	0.64
60	30	10	0.00	7.59	6.97	1.71	0.60
			0.75	7.60	6.90	2.09	0.65
			1.50	7.83	6.86	2.09	0.69
			3.75	7.80	6.82	2.04	0.63
50	30	20	0.00	7.51	6.82	1.95	0.59
			0.75	7.45	6.92	2.08	0.56
			1.50	7.12	6.92	2.23	0.53
			3.75	7.11	6.78	2.18	0.63
LSD _{0.05} ^x				0.41	0.24	0.50	0.30

^aSubstrates initially contained controlled-release fertilizer (Osmocote Plus; Scotts-Sierra, Marysville, OH), and plants received no subsequent fertilizer throughout the experiment.

^y1 lb/yard³ = 0.5933 kg·m⁻³, 1 mS·cm⁻¹ = 1 mmho/cm.

^xMeans separation within columns by substrate by Fisher’s protected least significant difference at $P \leq 0.05$.

Literature cited

Alexander, R. 1996. Field guide to compost use. Composting Council, Alexandria, VA.

- Al-Humaid, A. and A.E. Moftah. 2007. Effects of hydrophilic polymer on the survival of buttonwood seedlings grown under drought stress. *J. Plant Nutr.* 30: 53–66.
- Association of Official Seed Analysts. 2007. Rules for testing seeds. Association of Official Seed Analysts, Stillwater, OK.
- Beattie, D.J. and R. Berghage. 2004. Green roof media characteristics: The basics. *Proc. 2nd North Amer. Green Roof Conf.: Greening rooftops for sustainable communities.* Portland, OR. 2–4 June 2004. Cardinal Group, Toronto. p. 411–416.
- Boivin, M.-A., M.-P. Lamy, A. Gosselin, and B. Dansereau. 2001. Effect of artificial substrate depth on freezing injury of six herbaceous perennials grown in a green roof system. *HortTechnology* 11:409–412.
- Day, M. and K. Shaw. 2001. Biological, chemical and physical processes of composting, p. 17–50. In: P.J. Stoffella and B.A. Kahn (eds.). *Compost utilization in horticultural cropping systems.* CRC Press, Boca Raton, FL.
- Dunnett, N. and A. Nolan. 2004. The effect of substrate depth and supplementary watering on the growth of nine herbaceous perennials in a semi-extensive green roof. *Acta Hort.* 643:305–309.
- Durham, A.K., D.B. Rowe, and C.L. Rugh. 2007. Effect of substrate depth on initial growth, coverage, and survival of 25 succulent green roof taxa. *HortScience* 42:588–595.
- Fonteno, W.C. and T.E. Bilderback. 1993. Impact of hydrogel on physical properties of coarse-structured horticultural substrates. *J. Amer. Soc. Hort. Sci.* 118:217–222.
- Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau. 2002. Guidelines for the planning, execution and upkeep of green-roof sites. *Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau*, Bonn, Germany.
- Friedrich, C.R. 2005. Principles for selecting the proper components for a green roof growing media. *Proc. 3rd North Amer. Green Roof Conf.: Greening rooftops for sustainable communities.* Washington, DC. 4–6 May 2005. Cardinal Group, Toronto. p. 262–273.
- Gehring, J.M. and A.J. Lewis. 1980. Effect of hydrogel on wilting and moisture stress of bedding plants. *J. Amer. Soc. Hort. Sci.* 105:511–513.
- Getter, K.L. and D.B. Rowe. 2009. Substrate depth influences *Sedum* plant communities on a green roof. *HortScience* 44: 401–407.
- Gomez, K.A. and A.A. Gomez. 1984. *Statistical procedures for agricultural research.* 2nd ed. Wiley, New York.
- Handreck, K.A. and N.D. Black. 1994. *Growing media for ornamental plants and turf.* University of New South Wales Press, Randwick, Australia.
- Johnson, M.S. and R.T. Leah. 1990. Effects of superabsorbent polyacrylamides on efficiency of water use by crop seedlings. *J. Sci. Food Agr.* 52:431–434.
- Kayhanian, M. and G. Tchobanoglous. 1992. Computations of C/N ratio for various organic fractions. *Biocycle* 33: 58–60.
- Mangold, J. and R.L. Sheley. 2007. Effects of soil texture, watering frequency, and a hydrogel on the emergence and survival of coated and uncoated crested wheatgrass seeds. *Ecol. Res.* 25:6–11.
- Nektarios, P.P.T. and I. Chronopoulos. 2004. Comparison of different roof garden substrates and their impact on plant growth. *Acta Hort.* 643:311–313.
- Olszewski, M.W., T.A. Trego, and R. Kuper. 2009. Effects of peat moss substitution with arboretum and greenhouse waste compost for use in container media. *Compost Sci. Util.* 17:151–157.
- Pill, W.G. and C.C. Jacono. 1984. Effects of hydrogel incorporation in peat-lite on tomato growth and water relations. *Commun. Soil Sci. Plant Anal.* 15:799–810.
- Rowe, D.B., M.A. Monterusso, and C.L. Rugh. 2006. Assessment of heat-expanded slate and fertility requirements in green roof substrates. *HortTechnology* 16:471–477.
- Spomer, L.A. 1990. Evaluating ‘drainage’ in container and other shallow-drained horticultural soils. *Commun. Soil Sci. Plant Anal.* 21:221–235.
- U.S. Environmental Protection Agency. 2009. Green roofs for stormwater runoff control. EPA-600-R-09-026.
- VanWoert, N.D., D.B. Rowe, J.A. Andresen, C.L. Rugh, and L. Xiao. 2005. Watering regime and green roof substrate design affect *Sedum* plant growth. *HortScience* 40:659–664.
- Wang, Y.-T. and L.L. Gregg. 1990. Hydrophilic polymers-their response to soil amendments and effect on properties of a soilless potting mix. *J. Amer. Soc. Hort. Sci.* 115:943–948.