Green Roof Plant Responses to Different Substrate Types and Depths under Various Drought Conditions

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SUMMARY. **Plants suitable for extensive green roofs must tolerate extreme rooftop conditions, and the substrates in which they grow must fulfill horticultural and structural requirements. Deeper substrates may retain more water for plants during dry periods, but will also weigh more, especially when near saturation. A study in central Pennsylvania was conducted to evaluate the influence of substrate type and depth on establishment of five green roof plants. Two stonecrops [white stonecrop (*Sedum album*) and tasteless stonecrop (*Sedum sexangulare*)], one ice plant (*Delosperma nubigenum*), and two herbaceous perennials [maiden pink (*Dianthus deltoides*) and saxifrage pink (*Petrorhagia saxifraga*)] were planted in three depths (30, 60, and 120 mm) of two commercially available green roof substrates (expanded shale and expanded clay). Study flats inside a plasticulture tunnel received three drought treatments (no drought, 2 weeks early drought, and 2 weeks late drought). The two stonecrops performed well under most conditions, although tasteless stonecrop was stunted by early drought. Ice plant only grew well when provided with water. When subjected to any drought, the herbaceous perennials had the fewest survivors in the expanded shale. Saxifrage pink flowered profusely wherever it survived. The study plants were most affected by substrate depth, except for maiden pink, which responded solely to drought. When subjected to early drought conditions, the herbaceous perennials did not survive in 30 mm of either substrate, or in 60 mm of expanded shale. Although the stonecrops performed well in 60 mm of substrate when subjected to drought, their performance was superior in the expanded clay compared with shale.**

Growing plants on rooftops is an old concept that has evolved from sod roofing to roof gardens and today's lightweight extensive green roofs. Green roofs serve as partial solutions for many problems created by the built environment, and have become an important factor for urban planning in modern Europe (Brenneisen, 2004). A relatively new concept in North America, the known benefits provided by green roofs have initiated research to promote the integration of green roofs into current and future building developments.

Despite their shallow substrates, extensive green roofs have numerous benefits such as reducing the volume of runoff entering stormwater infrastructure (DeNardo et al., 2005; Liesecke, 1998; VanWoert et al., 2005a). Indeed, stormwater management is the main reason green roofs are so widely implemented in Germany (Keeley, 2004). Green roofs also improve air quality by trapping dust and airborne particles, and can mitigate the urban heat island effect by moderating ambient temperatures (Dimoudi and Nikolopoulou, 2003). Through direct shade, evapotranspiration, and insulation by plants and substrate, green roofs can reduce the demand for air conditioning and hence also greenhouse gas emissions (Liu and Baskaran, 2003). Finally, green roofs can offer ecological compensation for the building footprint by providing habitat and refuge for birds and invertebrate life (Brenneisen, 2004).

Extensive green roofs are low-maintenance, low-input systems containing between 50 and 200 mm of substrate, and are typically planted with drought-tolerant perennials (Kolb and Schwarz, 1999). Suitable plants for extensive green roofs are shallow-rooted, low-growing perennials that are tolerant of heat, sun, wind, drought, salt, insects, and disease. The factors that influence green roof plant selection, such as substrate depth and local climate, can likewise determine the lifespan of perennials (White and Snodgrass, 2003).

Green roofs with less than 100 mm of substrate and lacking irrigation systems support mainly stonecrops and few other perennials (Liesecke, 1998), especially in regions with summer droughts. Many stonecrops avoid desiccation in drought by switching to crassulacean acid metabolism (CAM) and/or by C3-CAM shifting (Ting, 1985). CAM plants take up carbon dioxide (CO_2) at night and then, with closed stomata, fix carbon via the CAM photosynthetic pathway by day. Some CAM plants, such as white stonecrop, are facultative and can switch from the C3 to the CAM pathway in response to drought, salt stress, or changes in the duration of photosynthesis (Sayed et al., 1994).

With increasing substrate depths and/or supplemental irrigation, green roof plant selection broadens. In temperate climates with hot summers and cold winters, stonecrops are perfect for substrate depths of less than 100 mm. However, in deeper substrates, 200 mm for example, stonecrops do not benefit from additional water as do

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This paper is dedicated to Dr. David J. Beattie (RIP Feb. 9, 2008), pioneer of the green roof movement and industry in North America.

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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
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
6.4516	$inch^2$	cm^2	0.1550
28.3495	oz	g	0.0353
(°F – 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

other species (Dunnett and Nolan, 2004). By contrast, many herbaceous perennials perform well only when irrigation is provided, even at greater substrate depths (Dunnett and Nolan, 2004; Durhman et al., 2007; Monterusso et al., 2005; Rowe et al., 2006). While 80 to 100 mm of substrate will support stonecrops and grasses, 100 to 120 mm can support a stonecrop-grass-herbaceous community, and 120 to 150 mm can support a grass-herbaceous community with stonecrops interspersed (Liesecke, 1998).

Plant lists from European green roofs are often used in eastern North America, but evaluation of these species in the Americas is limited. In some cases, these selections are based purely on their success on European green roofs (E. Snodgrass, personal communication). In a German study of substrate type, depth, and drought, white stonecrop was found to remain photosynthetically active after 100 d without water (38 d of which had temperatures higher than 18 °C) (Lassalle, 1998). Studies in Michigan and Maryland have observed similar responses for white stonecrop, while also testing native perennials in various green roof scenarios (Durhman et al., 2007; Monterusso et al., 2005; Murphy and Snodgrass, 2006). Using native plants can add bioregional value to green roof projects, with potential benefits for local ecosystems and food webs.

This study was designed to evaluate the effects of substrate type and three depths on the establishment and early growth of five plants that are frequently found on green roof plant lists in North America. Two main hypotheses anticipated that 1) early drought is more harmful for plants grown in shallow (30 mm) rather than deeper (120 mm) substrate depths, and 2) plants that survived early drought conditions would produce less shoot biomass than those subjected to late drought. By observing survival and quantifying shoot biomass, the objective of this study was to determine the conditions and combination of factors in which these popular green roof plants perform the best.

Materials and methods

EXPERIMENTAL DESIGN. The experiment was conducted in a 4- × 30-m polyethylene greenhouse (Tuff-lite IV; U.S. Global Resources, Seattle) in Potter's Mills, PA. The floor of the tunnel was overlaid with shale to facilitate rapid drainage through the groundcover fabric. The sides of the walls were rolled up around 30 cm on either side to provide maximum air movement, but also to ensure that plants received no natural precipitation, whether from direct, dripping, or splashed rain.

Each treatment (substrate type, depth, and drought condition) was represented by 10 plants for each species (n = 10). Overall, the study was comprised of 1800 plants, or 360 of each species. The experiment began on 16 June 2004 and ended on 4 Sept. 2004; this time frame was considered representative of a reasonable establishment period for a new green roof. In the climate of eastern North America, green roofs are ideally planted at the start of the growing season, when daylight hours promote the most growth and precipitation is frequent.

The experiment was designed in a split-block arrangement, with drought conditions separated as blocks of irrigation treatments (Fig. 1). The treatments of substrate type and depth were placed randomly within the blocks at factorial levels, and the blocks were also placed randomly within two replications, each with five subsamples.

Irradiance measurements (model BQM quantum meter; Spectrum Technologies, Plainfield, IL) were recorded at 17 positions along the length and width of the tunnel on 23 Aug. 2004 to verify that all plants received the same level of solar radiation (data not shown). Air temperatures at the substrate surface were recorded by placing temperature sensors (optic stowaway; Onset Computer, Bourne, MA) at alternating points in each block. The mean air temperatures calculated for substrate surface at the west, middle, and east ends were similar throughout the tunnel and experimental period (data not shown). The diurnal ranges measured at this time of the year (6 to 53 °C) were very similar to the air temperatures that occur at the surface of green roofs (Connelly et al., 2006).

SUBSTRATE TYPE AND DEPTH. The two green roof substrates used here, an expanded clay (HydRocks™; Garrick, Cleveland) and an expanded shale (Solite®; Northeast Solite, Saugerties, NY), were compared for their influences on plant performance in combination with treatments of depth and drought. The mineral aggregates were mixed with pelletized spent mushroom compost (Laurel Valley Soils, Avondale, PA) to obtain a ratio of 85% mineral to 15% organic matter (v/v).

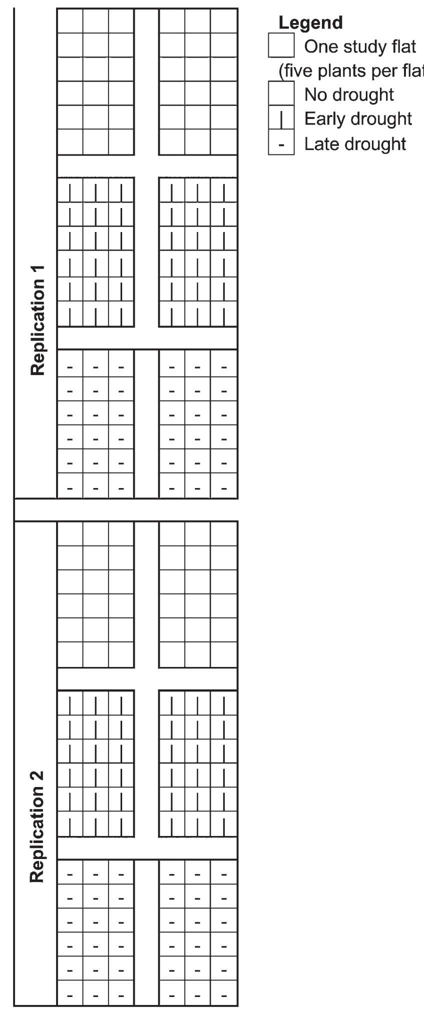

Fig. 1. A split-plot, randomized complete block design separated the three drought treatments into blocks: early drought (no irrigation in first 2 weeks of the study period), late drought (no irrigation in last 2 weeks of the study period), and no drought (regular irrigation throughout the study period). Each study species (white stonecrop, tasteless stonecrop, ice plant, maiden pink, and saxifrage pink) was represented by 120 plants per block, and each square in the figure represents a study flat containing five plants.

Propagation flats (1044 cm^2; Anderson Dye and Manufacturing, Portland, OR) were used as experimental green roof modules. The flats suited the deepest depth tested, 120 mm, without modification. The shallower depths (30 and 60 mm) were achieved by cutting the sides with a table saw. The bottom of each flat was fitted with a piece of a geotextile drainage layer frequently used in the green roof industry (Enkadrain®; Colbond, Enka, NC). Because the herbaceous plugs were deeper than the two shallower flats, the root masses were cut vertically into four sections and spread out along the bottom of the container. Care was taken to minimize root damage and to treat all plugs from all species equally.

Plant material. In late Apr. 2004, cuttings from the three succulent plants (white stonecrop, tasteless stonecrop, and ice plant) were taken from greenhouse stock plants and propagated in modular plug trays (2 cm^2, 273 cells/ tray) in a peat-based propagation mix. The two herbaceous species (maiden pink and saxifrage pink) were provided as plugs (8 × 4.5 cm, 72 cells/ tray) by Green Roof Plants (Emory Knoll Farms, Street, MD). This article compares individual plants within each species and does not compare different species to each other.

The green roof flats were planted on 13 June 2004 with five individual plants per flat for each treatment. To prevent splashing, shading, and edge effects, the flats were placed 80 mm apart. Before planting, the flats were irrigated twice to container capacity, or the point at which water drained freely from below. All flats were irrigated again 3 d after planting, and the experiment officially commenced on 16 June 2004.

Watering treatments. Because drought is often the main environmental limitation to plant growth on extensive green roofs, three different watering regimes were applied for further plant performance evaluation. For the 11-week study, no-drought flats (control) were watered evenly to container capacity (72 mm) twice weekly. Irrigation was hand applied and the quantity was measured by timing. Plants subjected to early drought received no water for the first 2 weeks after planting, while those subjected to late drought received no water in the last 2 weeks of the study period. When drought was not in effect, plants received the same irrigation as the control flats.

Data collection. Species performance was evaluated at the end of the study period. Shoot biomass (aboveground plant material, including stems, foliage, and flowers) was harvested and dried at 50 °C for at least 36 h and then weighed. The mean shoot dry weight for each treatment represents total shoot biomass produced after the respective conditions of the evaluation period (initial biomass, plus growth, as influenced by the various treatments).

Data analysis. Shoot dry weight for the means of two replications was analyzed with the SAS Mixed Procedure and the General Linear Model (GLM) (version 8.2, SAS Institute, Cary, NC) at the 0.05 level of significance. The Mixed Procedure suited this study because the model contained fixed- and random-effects parameters, and because the data set was unbalanced due to plant mortality. Dead plants did not contribute to mean shoot dry weight. The Mixed Procedure served to determine the overall analysis effects, and GLM was used for the analysis of variance, in which the variability within the dependent variable (shoot biomass) was assigned to different sources.

Results and discussion

Drought. As hypothesized, most plants that survived early drought developed less shoot biomass than plants from equal substrate depths subjected to late drought (Fig. 2). The herbaceous species were significantly affected by drought, while the succulents were not. Shoot growth varied within species depending on the timing of drought or the type of substrate.

By the close of the experiment, most species grown in 120 mm had produced less shoot biomass after early, rather than late, drought. Tasteless stonecrop performed this way in both substrates, as did ice plant, maiden pink, and saxifrage pink in the expanded shale. White stonecrop was the only species that actually had more shoot biomass after early rather than late drought in 120 mm of both substrates. This may be a tribute to this species' high water use efficiency, and its rapid response to water availability.

When grown in 120 mm of substrate, after early drought, white stonecrop produced 5% more shoot biomass (clay) and 47% less shoot biomass (shale) compared with control plants (substrate $P = 0.05$). When subjected to late drought conditions, this species produced 70% and 49% less shoot biomass (clay and shale substrates, respectively) compared with control plants. This species' immediate response to drought, as well as its full recovery in the clay substrate, may be explained by the phenomenon of CAM-idling, which occurs when CAM plants become severely water stressed. Under drought, such species close their stomata day and night and reduce their metabolism to a low rate, maintaining biochemical activities until water becomes available again and the plant recovers (Sayed et al., 1994).

Unlike white stonecrop, early drought significantly stunted shoot growth by the other species. When grown in 120 mm of either substrate, tasteless stonecrop had the fewest surviving plants and the least shoot growth following early drought compared with plants grown under control or late-drought conditions. Mean shoot dry weight differed significantly between control and early-drought plants, and early drought plants did not match the shoot growth of plants subjected to late drought by the end of the study period.

Although the statistics indicate that ice plant was significantly influenced by substrate depth ($P = 0.01$) and type ($P = 0.03$) but not by drought ($P = 0.1$), the single consistency by this species was positive growth under control conditions. Ice plant produced the most dramatic results when grown under early drought, and in the shale substrate. Under early drought in 30 mm, eight of 10 plants survived in the expanded clay, but none survived in the shale (Table 1). Of plants subjected to early drought and grown in 120 mm, those grown in shale had 86% less mean shoot dry weight than control plants, while plants in 120 mm of clay had only 36% less growth. Of all the species evaluated, ice plant appeared to be most sensitive to drought in the establishment period, early and late.

Compared with late-drought plants, ice plant, maiden pink, and saxifrage pink produced less shoot dry weight after early drought when grown in the expanded shale. When grown in 120 mm of shale and subjected to early drought, these species produced less shoot biomass and experienced the most mortality. For example, saxifrage pink in 120 mm of shale had 83% less mean shoot dry weight after early drought compared with control plants. In contrast, plants grown in clay had only 24% less biomass than control plants and suffered less mortality.

Under control conditions, this species produced similar shoot growth in both substrates and, next to white stonecrop, performed the most consistently with regard to survival and growth.

Insufficient water during establishment can result in stunted roots and a permanent decrease in leaf size, which inhibits the uptake of water and nutrients and reduces surface area for photosynthesis. Even after water is reinstated, a stunted plant's growth capacity may be restricted (Boodley, 1998). Rapid establishment can be promoted by preventing transplant stress, i.e., providing water before the symptoms of water stress appear (Nelson, 1998). For non-CAM plants, irrigation in the first weeks after planting was highly beneficial. Other studies have also observed that supplemental irrigation during the establishment period (i.e., the first year) can benefit plant performance significantly (Dunnett and Nolan, 2004; Monterusso et al., 2005; White and Snodgrass, 2003).

SUBSTRATE DEPTH. As discussed above, early-drought conditions caused reduced growth in most of the evaluated species. This was particularly true when early drought was combined with shallow substrate depths. Provided they survived the shallowest depth tested, the five species always developed the least shoot biomass therein. Depth influenced shoot growth for the overall experiment significantly ($P < 0.0001$), and all species studied, except for maiden pink, showed significant responses to

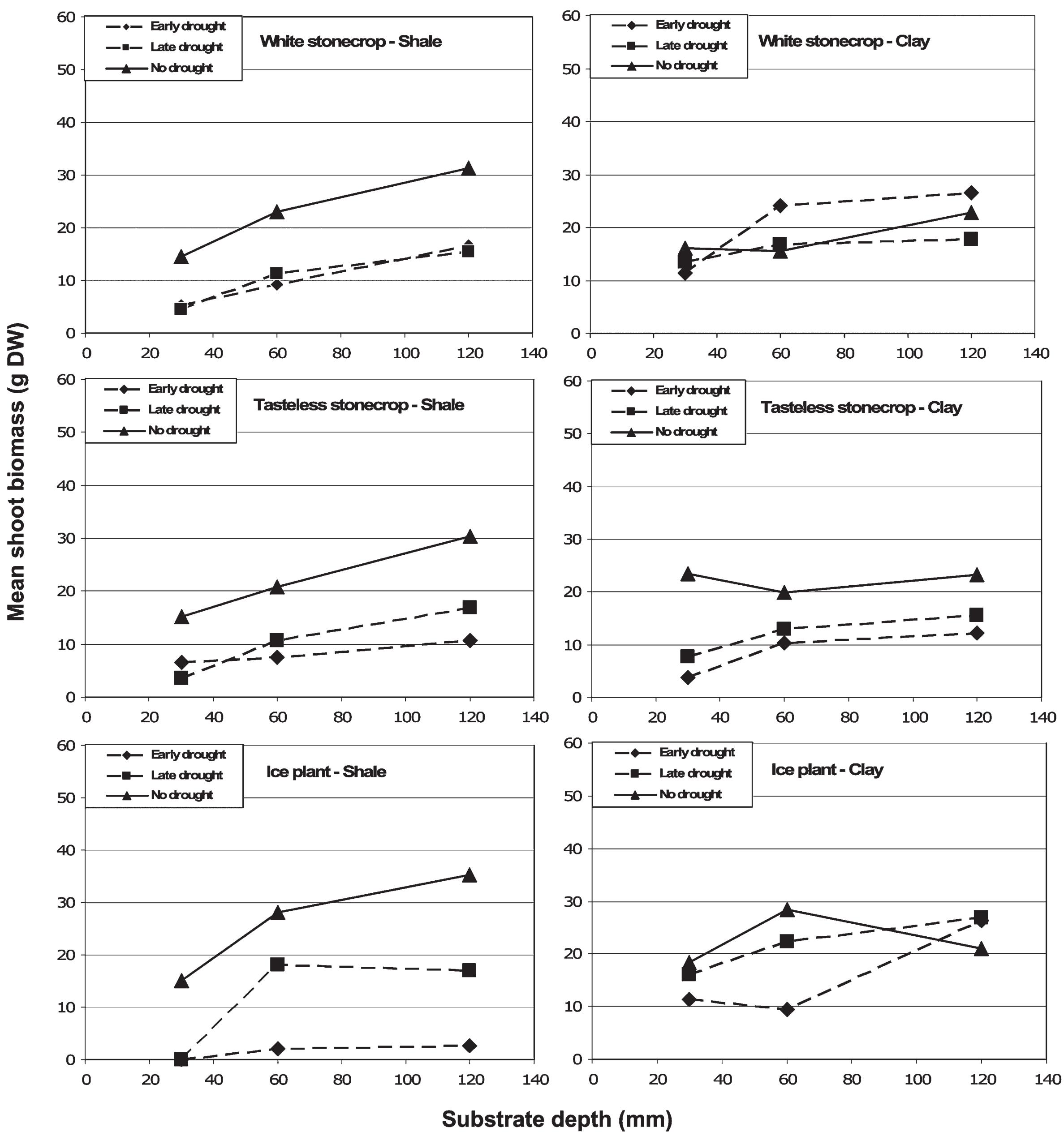

Fig. 2. Mean shoot biomass (dry weight) of five species (n = 10) grown in three depths (30, 60, and 120 mm) of expanded shale- and expanded clay-based substrates when subjected to three drought treatments: early drought [no irrigation in first 2 weeks of the study period (dashed lines)], late drought [no irrigation in last 2 weeks of the study period (dashed lines)], and no drought [regular irrigation throughout the study period (solid lines)]. Mean shoot biomass was calculated only for surviving plants; dead plants did not contribute to this value; 1 mm = 0.0394 inch, 1 g = 0.0353 oz.

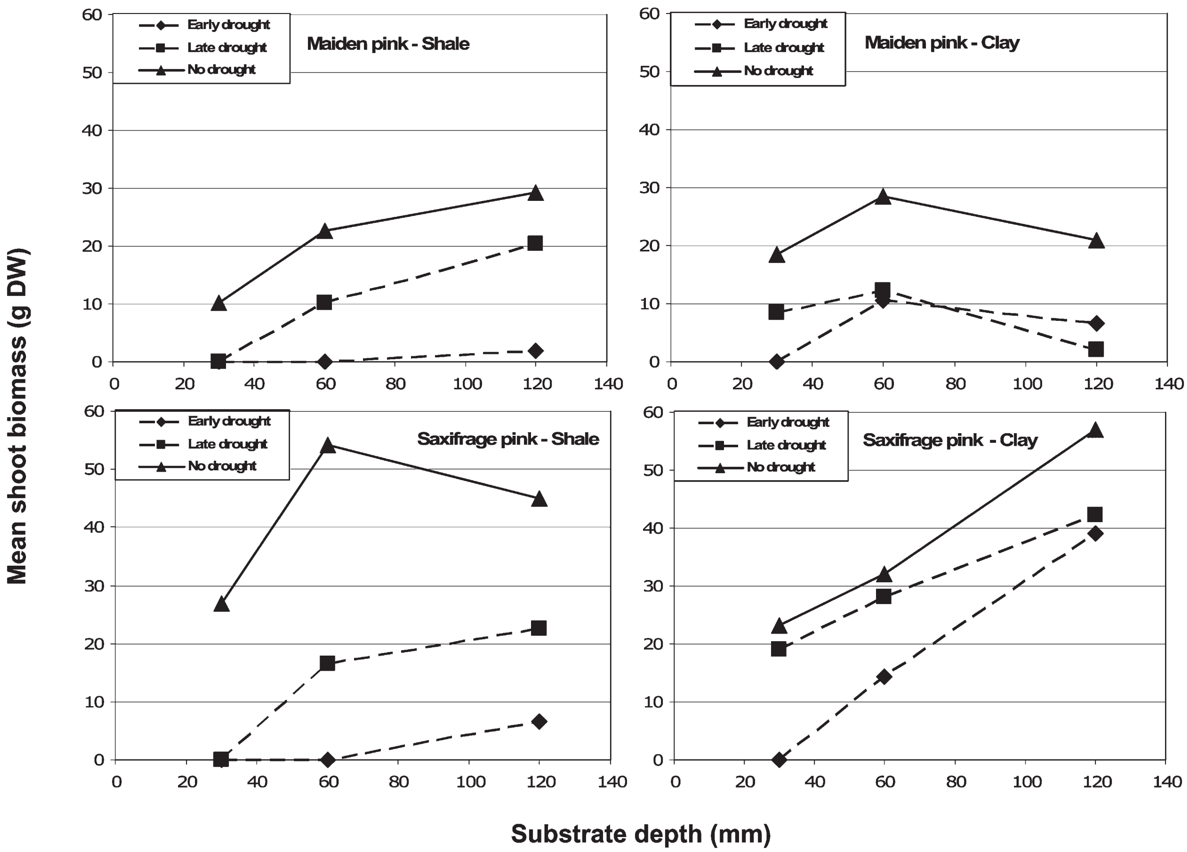

Fig. 2. (continued)

depth. Of the three factors studied (substrate type, depth, and drought), the succulents responded most strongly to depth, while the herbaceous species responded to depth and to drought.

Under early drought, neither maiden pink nor saxifrage pink survived in 30 mm of either substrate, nor did they survive in 60 mm of shale. However, in 60 mm of expanded clay, these species performed contrarily such that maiden pink had more shoot biomass after early drought while saxifrage pink had more after late drought. It would seem that when provided with 60 mm rooting volume, maiden pink could recover from early drought with the reinstatement of irrigation. A related study found maiden pink uninfluenced by substrate depth, exhibiting good growth and survival only with the provision of regular and sufficient water (Dunnett and Nolan, 2004). Saxifrage pink flowered vigorously wherever it survived. Although this study period was insufficient for observing seed viability, Kolb et al. (1982) praised this species for its ability to fill in gaps on green roofs by self-seeding.

The two stonecrops always produced more shoot biomass with increasing substrate depths, regardless of water availability. Unlike the other species studied, the two stonecrops performed adequately in 30 mm of rooting depth, although plants grown in 60 and 120 mm produced significantly more shoot biomass. If performance by these species, as measured by survival, establishment, and biomass production, defines green roof success, then results of this study suggest that unirrigated extensive green roofs in the climate of central Pennsylvania should be at least 60 mm deep.

Lassalle (1998) showed that shallower substrate depths (50 mm) had lower container capacities compared with deeper depths (100 and 150 mm), and had proportionally higher water losses. These findings agree with those of Durhman et al. (2007), Getter and Rowe (2007), Liesecke (1998), and VanWoert et al. (2005b). Beyond water availability, substrate depth is also an important factor to winter survival, and Boivin et al. (2001) recommend using a minimum of 100 mm for green roofs in northern latitudes (i.e., north of lat. 40°N) to prevent freezing injury to plants.

Substrate type. Currently, the largest components of green roof substrates in eastern North America are lightweight aggregates, often expanded shale, clay, or slate [ESCS (Friedrich, 2005)]. The availability, consistency, and physical properties of ESCS meet the requirements of the green roof substrate criteria defined by the German Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) in its extensive green roof standard (Beattie and Berghage, 2004). The expanded clay was expected to support plants better than the expanded shale because clay has the ability to retain water and possesses good cation exchange capacity (Nelson, 1998).

The capacity of the two substrates to support plant growth differed significantly (P = 0.002), but the five species showed individual responses to substrate type. Shoot biomass of the two herbaceous species was not significantly affected by substrate type, for instance, but during any drought, the expanded clay always supported plants better than the shale. Furthermore, the herbaceous species performed just as well as white stonecrop under early

Table 1. Survival (n = 10) by five species at the close of an 11-week study period (16 June until 4 Sept. 2004) when grown in three depths [30, 60, and 120 mm (1.18, 2.36, and 4.72 inches)] of two substrates (expanded shale and expanded clay) under three drought treatments (no drought = regular irrigation, early drought = no irrigation in first 2 weeks of study period, and late drought = no irrigation in last 2 weeks of study period).

	Survival when subjected to no drought (%)					
	Shale-based substrate			Clay-based substrate		
Species	30 mm	60 mm	120 mm	30 mm	60 mm	120 mm
White stonecrop	100	100	100	90	90	90
Tasteless stonecrop	100	100	100	100	100	100
Ice plant	90	70	90	90	100	90
Maiden pink	50	100	100	90	100	90
Saxifrage pink	60	100	80	80	100	100
	Survival when subjected to early drought (%)					
	Shale-based substrate			Clay-based substrate		
Species	30 mm	60 mm	120 mm	30 mm	60 mm	120 mm
White stonecrop	80	80	100	90	90	100
Tasteless stonecrop	100	100	90	40	100	100
Ice plant	0	20	50	80	30	70
Maiden pink	0	0	50	0	80	50
Saxifrage pink	0	0	70	0	70	90
	Survival when subjected to late drought (%)					
	Shale-based substrate			Clay-based substrate		
Species	30 mm	60 mm	120 mm	30 mm	60 mm	120 mm
White stonecrop	80	80	100	90	100	100
Tasteless stonecrop	40	100	100	90	90	100
Ice plant	50	50	100	100	90	90
Maiden pink	0	90	90	100	100	50
Saxifrage pink	0	100	100	100	100	100

drought when grown in the expanded clay (while plants grown in the shale died or grew poorly). This suggests that the clay substrate in this study held more moisture than the shale.

It is important to note, however, that the substrate used in this study was a blend of large aggregates with compost, while most commercial blends contain more fines, which can contribute to significant water holding capacity. Similar studies that used expanded slate found that herbaceous perennials only performed well when irrigation was provided as needed (Monterusso et al., 2005; Rowe et al., 2006). Slate and shale are geologically related and because the expanded forms of these aggregates have similar physical and chemical characteristics (Friedrich, 2005), those findings may substantiate these observations.

The differences in plant performance in these substrates were likely due to variations in plant-available moisture. According to five replicated tests of each substrate (4-inch columns, data not shown) at field capacity, the clay substrate had a mean moisture holding capacity of 31.7% (SD = 2.01) and the shale had 27.5% (SD = 0.76). In addition to knowing the substrate's water holding capacity, amending particle size distribution with more fines or increasing the organic content can support plants during drought. The FLL guidelines recommend that extensive green roof substrates should contain between 10% and 30% organic content by volume (FLL, 2002); the substrates for this study were blended to 15% organic content by volume.

Conclusions

The results from this study illustrate how appropriate species selection in the design of unirrigated extensive green roofs may be directed by factors such as substrate type and depth, as well as anticipated drought conditions. This experiment revealed the variability among drought-tolerant species to various treatments, as well as the different plant responses to substrate type during drought. It is valuable to know the needs and tendencies of a selected species when planning for unirrigated extensive green roofs.

Proper establishment is critical to the long-term viability of green roof plant cover. Early drought appeared to be more harmful to plant survival and performance than late drought. Depending on local microclimate and species mix, White and Snodgrass (2003) recommend irrigating for the first 3 weeks after planting, unless at least 25 mm of rain falls each week. Other studies have also found that herbaceous perennials perform significantly better when provided with additional water during the establishment period (Dunnett and Nolan, 2004; Durhman et al., 2007; Monterusso et al., 2005).

The three most resilient species studied here, saxifrage pink, white stonecrop, and tasteless stonecrop, always produced more shoot biomass with increasing substrate depth, regardless of water availability. Ice plant performed erratically and, along with maiden pink, poorly in face of drought during establishment. The attractive appearance and persistent flowering by saxifrage pink recall Kolb's (1982) affirmation that this self-seeding species is an excellent green roof plant. Before introducing exotic species onto plant lists for North American green roofs, however, especially those that produce prolific seeds, their phenologies, growth strategies, and intraspecific behavior should verify that they will not behave invasively.

Specifying plants according to popular selections from other parts of the world will not necessarily guarantee good performance in different regions or climate zones. Aside from white stonecrop, the species evaluated did not perform so well as to dismiss consideration for other plant species for green roofs in eastern North America. In this age of cosmopolitan plant communities and declining biodiversity overall, the use of regionally native species expands the potential of green roofs to support specific ecosystem functions. Just as the early pioneers of German rooftop greening explored their local nutrient-poor, drought-prone habitats, so should emerging green roof markets investigate their regional biotopes for potential plant communities and suited flora.

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