Shallow Substrates Support the Growth of Contrasting Plant Types Installed in Irrigated, Arid-Climate Green Roofs[1]

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Abstract

Extreme evaporative demand makes substrate depth a critical design factor in arid-climate green roofs. The objective of this study was to determine whether a shallow irrigated substrate could support the growth of hens and chicks (*Sempervivum calcareum* L.) and iceplant [*Delosperma nubigenum* (Hook.f.) L.Bolus] in an arid environment. First, an experiment was conducted in the greenhouse that established that plants survived in 10 cm (3.9 in), 15 cm (5.9 in), and 20 cm (7.9 in) substrate depths, which then lead to a second experiment in an outdoor environment. The substrate was heat-expanded clay:sand:worm castings (6:3:1, by volume) in a greenhouse experiment and heat-expanded clay:zeolite:worm castings (6:3:1, by volume) in an outdoor experiment. In the greenhouse experiment, deep root length density (RLD) was significantly greater in the 10 cm-deep (3.9 in) substrate, while outdoors, deep RLD was highest for plants grown in the 15 cm-deep (5.9 in) substrate. Outdoors, iceplant had significantly greater mean coverage and shoot dry weight than hens and chicks. Lack of significant differences in quality and coverage due to substrate depth, coupled with higher RLD in the 10 cm (3.9 in) and 15 cm (5.9 in) depths in both experiments provides evidence that shallow irrigated substrates support the growth of both taxa.

Index words: iceplant, hens and chicks, plant coverage, root length density, quality, zeolite, heat expanded clay.

Species used in this study: hens and chicks (*Sempervivum calcareum* L.); iceplant [*Delosperma nubigenum* (Hook.f.) L. Bolus].

Significance to the Horticulture Industry

Green roofs make many positive impacts on the environment, including reduced air temperatures, slowing storm water, filtering pollutants from the atmosphere and providing wildlife habitat. Most research done into suitable growing media for green roofs has been done in climates with more precipitation and humidity than the arid environment of the Chihuahuan desert where this experiment was conducted. Substrate depth plays a significant role in green roof design in arid climates, where evaporation is high. This research demonstrates that hens and chicks and iceplant taxa were successful in 10 and 15 cm substrate depths in a simulated green roof setting. Nursery personnel wishing to grow these taxa in arid green roofs could use substrate depths of 10 cm or deeper.

Introduction

Green roofs in arid climates are frequently considered unfeasible for several reasons, among them being that the substrate depth necessary to sustain plant growth in a dry environment is too heavy for existing roofs. There is scant data concerning the depth of the growing substrate that will encourage the success of green roofs in arid environments. Thus, there is a need for information about substrate depths for green roofs that are successful in arid environments.

Historically, green roofs have been found in arid environments. One example is the green roofs in the ancient city of Tenochtitlan, in what is now Mexico City (Osmundson 1999). The green roof of the Conference Center of the Church of Jesus Christ of Latter-day Saints in Salt Lake City, Utah, supports 1,300 trees and 2,700 shrubs, and is a modern example of a green roof in an arid environment (Weiler and Scholz-Barth 2009). In both arid and mesic environments, temporary irrigation is needed after green roof installation (Weiler and Scholz-Barth 2009).

Extensive and intensive are the two most common categories of green roofs (McIntyre and Snodgrass 2010). Extensive green roofs have shallow substrates, generally less than 15 cm (5.9 in), are frequently planted with a monoculture and a generally need little maintenance. In contrast, intensive roofs have substrates deeper than 15 cm (5.9 in), a wider plant palette and require more maintenance (Dunnett and Kingsbury 2008, McIntyre and Snodgrass 2010).

Previous studies have demonstrated that extensive green roofs reduce surrounding air temperatures, manage storm water, create wildlife habitat, and filter pollutants from the atmosphere (Buccola and Spolek 2011, Getter and Rowe 2006). However, these studies have been conducted in humid regions and do not address the complications that arise from the low humidity and scarce precipitation of an arid climate.

Buccola and Spolek (2011) showed that water retention improved by about 30% at a substrate depth of 14 cm (5.5 in) when compared to a 5 cm (2 in) substrate depth. This led to the conclusion that improved moisture retention of deeper substrates would be useful in water-limited environments. During drought conditions, plants grown in substrate depths of 6 cm (2.4 in) and 12 cm (4.7 in) survived better than plants grown at depths of 3 cm (1.2 in) (Thuring et al. 2010). Durhman et al. (2007) showed that greater plant growth occurred in deeper substrates and that

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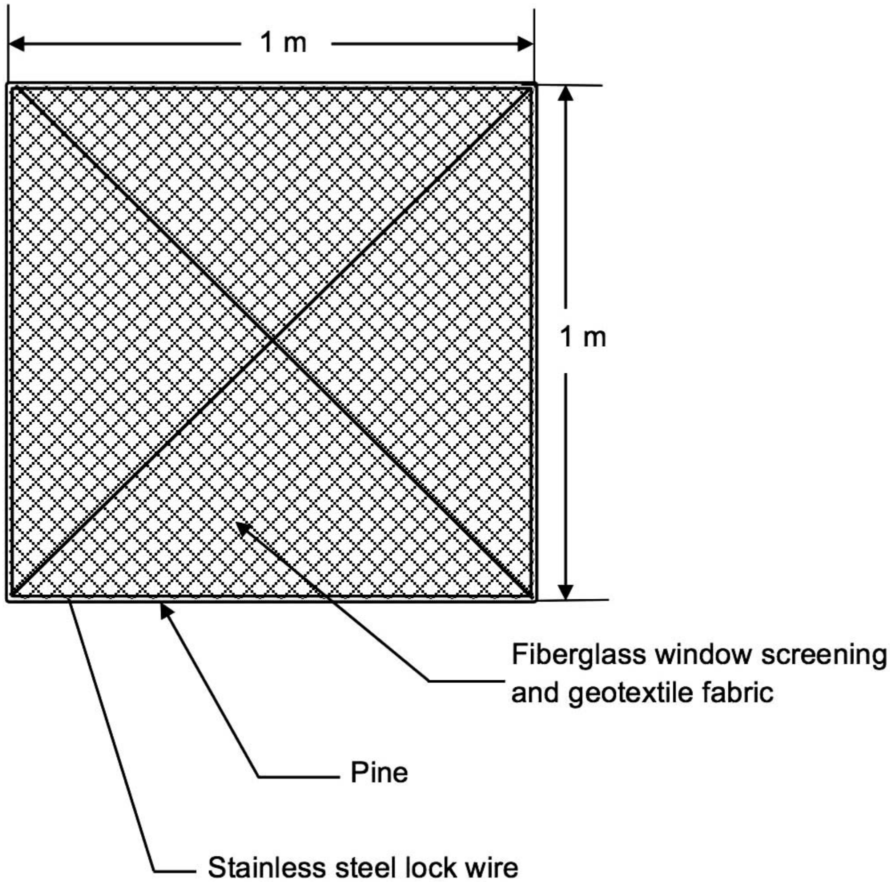


Fig. 1. Diagram of the custom planting tray. The outer envelope was constructed of 2.54 cm (1 in) untreated pine wood.

a limited selection of species persisted in shallower substrates. Plants grown in substrate depths of 7 cm (2.76 in) and 10 cm (3.94 in) showed significantly greater growth and plant coverage than depths of 4 cm (1.6 in) (Getter and Rowe 2009). Interestingly, while substrate depths of 4 cm (1.58 in) had significantly less volumetric moisture content than 7 cm (2.8 in) and 10 cm (3.9 in) depths, all depths exhibited similar levels of plant stress as indicated by chlorophyll fluorescence (Getter and Rowe 2009). Information is virtually nonexistent on the minimum substrate depth required to sustain plant growth in extensive green roofs destined for arid environments.

The objective of this study was to determine whether a shallow, irrigated substrate could support the growth of green roof taxa installed in an arid environment. The plants chosen for this experiment were iceplant, which has a spreading habit, and hens and chicks, which has a rosette-forming habit. Both have been widely used in previous green roof studies. Our approach was to use a custom-made, simulated extensive green roof system to grow plant taxa with contrasting growth habits.

Materials and Methods

Site location. Experiments were conducted at the New Mexico State University (NMSU) Fabian Garcia Science Center located in Las Cruces, NM (elev. 1191 m; lat. 32°16′45.8″N and long. 106°46′24.7″W). Las Cruces is in zone 8a of the USDA Plant Hardiness Zone map, has mean annual minimum temperatures that range from -12 to -9 C (10.4 to 15.8 F), and averages of 120 to 150 d above 30 C (86 F) per year (USDA 2003). Precipitation averages 23.4 cm (9.2 in) per year.

Greenhouse study. Custom built 1 m^2 (3.28 ft^2) plant trays of three different depths were used for the experiment (Fig. 1). The substrate was mixture of 6 heat-expanded clay (Hydroton, Sunlight Supply, Vancouver, WA): 3 washed play sand (0.5 mm): 1 worm castings (v:v:v) (Table 1). Substrate was mixed by hand using a tarp and appropriate volumes of each component (Bowen-O'Connor et al. 2013). Trays were randomly arranged on the greenhouse benches and were filled with substrate to depths of 10 cm (3.9 in), 15 cm (5.9 in), and 20 cm (7.9 in). Each of three depths was replicated four times for a total of 12 trays. A Netafim™ (Netafim Ltd. Corporate Headquarters, Tel Aviv, Israel) drip irrigation system was installed 2.5 cm (1.0 in) below the substrate level to provide supplemental irrigation. While surface drip irrigation is used in many green roof systems (Kotsiris et al. 2012), subsurface drip irrigation reduces evaporative losses in hot, dry, and windy roof sites (Sutton et al. 2012). The substrate was amended with 18N-6P-8 K controlled-release fertilizer (Nutricote Type 180, Florikan, Sarasota, FL) at a rate of 18 $g{\cdot}m^{-2}$ (0.056 $oz{\cdot}sq\ ft^{-2}$) of N before planting. No fertilizer was applied post-planting, which agrees with the recent fertilizer recommendations of Clark and Zheng (2014) for

Table 1. **Water holding capacity (WHC), bulk density, air-filled porosity, and pH of two substrates, Mix A [6 heat-expanded clay:3 washed play sand: 1 worm castings (v:v:v)] and Mix B mix [6 heat-expanded clay:3 zeolite:1 worm castings (v:v:v)] used in greenhouse and outdoor simulated green roof experiments, respectively, conducted at New Mexico State University.**

Substrate	WHC at saturation ($mL \cdot mL^{-1}$)	Bulk density ($g \cdot mL^{-1}$)	Air filled porosity ($mL \cdot mL^{-1}$)	pH
Mix A	0.26 (>0.20)[z]	0.77	0.42 (>0.20)	7.31 (5.5 – 8.0)
Mix B	0.52 (>0.20)	0.64	0.20 (>0.20)	7.03 (5.5 – 8.0)

[z]Value in parentheses is the recommended Forschungsgellschaft Landschaftsentwicklung Landschaftsbau (2008) standard. No specific guidelines for bulk density is recommended.

sedum-vegetated green roof systems. Trays were then planted with hens and chicks and iceplant species.

Air temperature and relative humidity were monitored at ten minute intervals with a temperature sensor (CS 500; Campbell Scientific, Logan, UT). Soil temperature was monitored using a soil probe (Model 107; Campbell Scientific, Logan, UT). A quantum sensor (LI-185; LI-COR, Lincoln, NE) monitored Photosynthetic Photon Flux Density (PPFD), and sensor data was recorded with a CR10X datalogger (Campbell Scientific). For the duration of the experiment, PPFD averaged 223 ± 2.5 $\mu mol \cdot m^{-2} . s^{-1}$. Plugs from a 32-cell tray were planted in the custom trays, with each plug root volume measuring 240 mL (8.5 fl oz). While in the nursery's care (Little Valley Nursery, Brighton, CO) the plants were grown in partial sun conditions in a passive heat hoop house. Once plants arrived at NMSU, they were acclimatized in the greenhouse for seven days before installation. Each plant was selected for uniform size [approximately 2.5 cm by 2.5 cm (1.0 in by 1.0 in) for hens and chicks and 4 cm by 4 cm (1.6 in x 1.6 in) for iceplant] and quality. Roots were washed to remove excess potting mix and re-planted in the experimental substrate.

Species were arranged in a split plot design and included a non-sampled border row. Each tray had 36 plants, 18 of each of the two species, which were spaced 15 cm (5.9 in) apart. Plots were hand watered daily for the first four weeks to limit the possibility of transplant shock. Plants then were watered using a Netafim™ drip irrigation system and a controller set to apply 8.5 mm (0.3 in) of water daily. After eight weeks, the frequency of watering was reduced to three days each week. We did not observe any signs of drought stress during the experiment.

Plant coverage was evaluated every 15 d using a line intercept method. With that method, each plant was evaluated for north-south and east-west width, then these measurements were multiplied to obtain plant coverage. Plants also were evaluated visually on a scale from zero to five. In this scale, zero represents a dead plant, one is a plant showing visible wilting, two is a plant showing slight damage or reduced growth, three represents little change since planting, four represents growth at or slightly above expectation, and five represents a plant exhibiting exceptional growth (Rowe et al. 2006). The greenhouse trial ran from February 18, 2012 to May 18, 2012. Plant growth measurements were taken on February 18, March 4, March 19, April 3, April 18, May 3 and May 18. At the end of the experiment on May 18, plants were evaluated for maximum plant coverage and quality. In addition, two plants of each species were randomly selected from each tray to be used to determine shoot dry weight (SDW) and RLD.

Soil cores were taken to determine RLD using the USDA National Resources Conservation Service (2007) soil core sampling procedure. Four soil cores were taken from each tray by manually inserting a 2.5 cm (1.0 in) wide by 25 cm (9.8 in) deep soil probe (Lamotte Economical Soil Sampler 78240, Chestertown, MD). Data from the four samples was averaged by plant type to represent each tray. Each sample was divided equally into an upper and lower section for analysis. Samples varied in volume depending on which depth they represented. Divided core sections were placed on a 2 mm (0.08 in) mesh screen and washed with tap water. Roots were oven-dried for three days at 65 C (149 F) before being spread on a piece of clear glass [210 mm by 297 mm (8.3 in by 11.7 in)]. Roots were covered with plain paper and scanned (Canon MP210, Melville, NY). Scanned images were saved as 'Grayscale' using photograph-editing software (Photoshop CS2, Adobe Systems, San Jose, CA), and analyzed with ROOTEDGE 2.2c software (Kaspar and Ewing 1997). The software calculated total root length, while upper and lower RLD were calculated by dividing the total root length by the soil sample volume.

Outdoor experiment. After evaluating the results of the greenhouse trial, a lighter-weight substrate composed of 6 heat-expanded clay (Hydroton): 3 zeolite [St. Cloud Mining, Winston, NM) (hydrous sodium aluminosilicate) mix] (16/40): 1 worm castings (v:v:v) was prepared for use in the outdoor trials. The 16/40 classification for zeolite means that 90% of the particles will pass through a number 16 sieve [1.20 mm (0.05 in)] and 10% will pass through a number 40 sieve [0.42 mm (0.02 in)]. Additional custom trays were constructed in an identical manner to those used for the greenhouse experiment. Tray depths were randomized on outdoor benches oriented north to south to eliminate potential variations in solar exposure. There was little potential for differences due to shade patterns. Each tray was filled with 10, 15, or 20 cm (3.9, 5.9 or 7.9 in) of the zeolite substrate mixture, depending on the tray's depth, with a Netafim™ drip irrigation system installed at approximately 2.5 cm (1.0 in) below substrate level. Trays were then planted with hens and chicks and iceplant species in the same manner as in the greenhouse study.

Plants were acclimatized in the greenhouse for 4 d and then hardened off in a lathe house for 7 d before installation. Each plant was selected for uniform size and quality. The plant roots were washed to remove excess potting mix and re-planted within the experiment substrate.

Species were arranged as in the greenhouse study. A Netafim™ drip irrigation watered the trays using a controller set to apply 3.6 mm (0.14 in) of water per day for 6 d a week.

Plant coverage was evaluated every 14 d using the same scale procedure as the greenhouse study. The outdoor trials ran from September 18, 2012 to November 27, 2012. Plant growth measurements were taken on September 18, October 16, October 30, November 12 and November 27. At the end of the experiment on November 27, plants were evaluated for maximum plant coverage and quality. In addition, two plants of each species were randomly selected from each tray to determine SDW and RLD. Soil cores were taken to determine RLD with the same procedure noted in the greenhouse trials. As with the greenhouse experiment, we did not observe signs of drought stress in the outdoor experiment.

Statistical analysis. For both experiments, the experimental design was a split-plot with four replications with the whole plot being substrate depth and the subplot being plant species. For maximum plant coverage, average plant width, and quality, the eight subsamples of each plant type taken per tray at each date were averaged before analysis. These variables were analyzed by date using a mixed model with fixed effects for depth, plant type, and their interaction. Because variances differed for the two plant types, repeated measures (one for each plant type) from trays were accounted for by fitting an unstructured covariance structure. A test for simple effects was used to determine the interaction of depth based on plant type. In addition, plants with a quality value of 0 (dead) were removed to prevent skewing of data due to outliers. Two subsamples were taken at the experiment conclusion to measure RLD and SDW. Because a single observation was missing, rather than analyze sub-plot means, RLD and SDW were analyzed using a mixed model with fixed effects for depth, plant type, and their interaction, and random effects for tray and plant type within tray. For the two plant types, separate variance components for plant type within tray effect were fitted to account for different plant type variances. A log transformation also was applied to the ratio of deep RLD to shallow RLD as a means of coping with the unequal variances. We used SAS statistical software (Version 9.2; SAS institute, Cary, NC) for all statistical analyses. Significance was defined for $P \leq 0.05$.

Results and Discussion

Greenhouse experiment: environmental conditions and substrate properties. On March 25, 2012 [36 days after transplanting (DAT)] of the greenhouse experiment, *Pythium spp*. fungi had affected about 7% of both iceplant and hens and chicks plants with apparently equal severity. The greenhouse was treated with acibenzolar-S-methyl (Quadris flowable fungicide (Syngenta, Basel, Switzerland) at a rate of 0.4 $g \cdot L^{-1}$ (400 ppm) on April 4, 2012. Due to the relatively even spread and short duration of the fungus (roughly two weeks from first appearance to complete eradication) and the rapid plant recovery after treatment, the disease incidence may have had a limited, if any, impact on results. There was no apparent plant damage due to *Pythium spp*.at the end of the experiment.

Greenhouse daily ambient temperatures averaged 26.7 ± 0.1 C (80.1 ± 0.2 F). Substrate weekly daylight (0700 to 1900 HR) temperatures averaged 21.8 ± 0.3 C (71.2 ± 0.5 F). Substrate air-filled porosity, pH, bulk density, and water holding capacities were within FLL (2008) specifications (Table 1).

Greenhouse experiment: plant growth and quality. Iceplant (Fig. 2A) had greater plant coverage than hens and chicks (Fig. 2B) for all sampling dates. Yet, we found no significant differences ($P = 0.0964$) in coverage because of substrate depth for any date for either species. Certain plant types have been shown to adapt to green roof growing conditions better than others (Dunnett et al. 2008, Thuring et al. 2010), and while the reduced coverage of hens and chicks may be attributed partly to its rosette-forming growth habit, the establishment of full coverage is critical to green roof success. Therefore, the spreading habit and resulting increased coverage of iceplant might be advantageous in green roof environments. At 15 DAT, iceplant had a quality determined visually of 4.02 ± 0.12 (Fig. 3A), better ($P = 0.0231$) than the 3.56 ± 0.09 of hens and chicks (Fig. 3B), though by 75 DAT, no differences ($P = 0.2210$) were detected between species. Growing medium depth did not affect quality for either species.

Substrate depth is an important factor to consider in green roofs because depth governs the ability of the substrate to retain water and support plant growth (McIntyre and Snodgrass 2010). Substrate depth impacted plant growth in our greenhouse experiment, as evidenced through SDW. For iceplant, plants grown in the deeper substrates had more SDW ($P = 0.0477$). Surprisingly, hens and chicks at the 15 cm (5.9 in) substrate depth had significantly greater ($P = 0.0477$) SDW than the 20 cm (7.9 in) depth (Fig. 4). We speculate that the higher density of roots in the 15 cm (5.9 in) substrate when compared with that in the 20-cm (7.9 in) deep substrate (Table 2) might have supported more shoot growth. So, in the protected environment of the greenhouse, the SDW data only partially supports the assessment of Thuring et al. (2010) that plants exhibit less growth in shallow substrates.

Greenhouse experiment: root length density. There were no significant differences in shallow RLD due to depth of growing substrate or plant type. The log-transformed ratio of deep RLD to shallow RLD did not show any significant differences for either plant type or substrate depth (Table 2). The lack of differences in RLD might mean there were few soil environmental limitations to uniform root growth.

Plants grown in 10 cm-deep (3.9 in) plots had greater ($P = 0.0082$) deep RLD in comparison to the 15 cm-deep (5.9 in) plots but deep RLD for the 10 cm-deep (3.9 in) plots was not greater ($P = 0.0846$) than that of the 20 cm-deep (7.87 in) plots (Table 2). This result indicates that plants in the 10 cm (3.9 in) substrate depth had roots that more fully occupied the lower half of the substrate profile than those

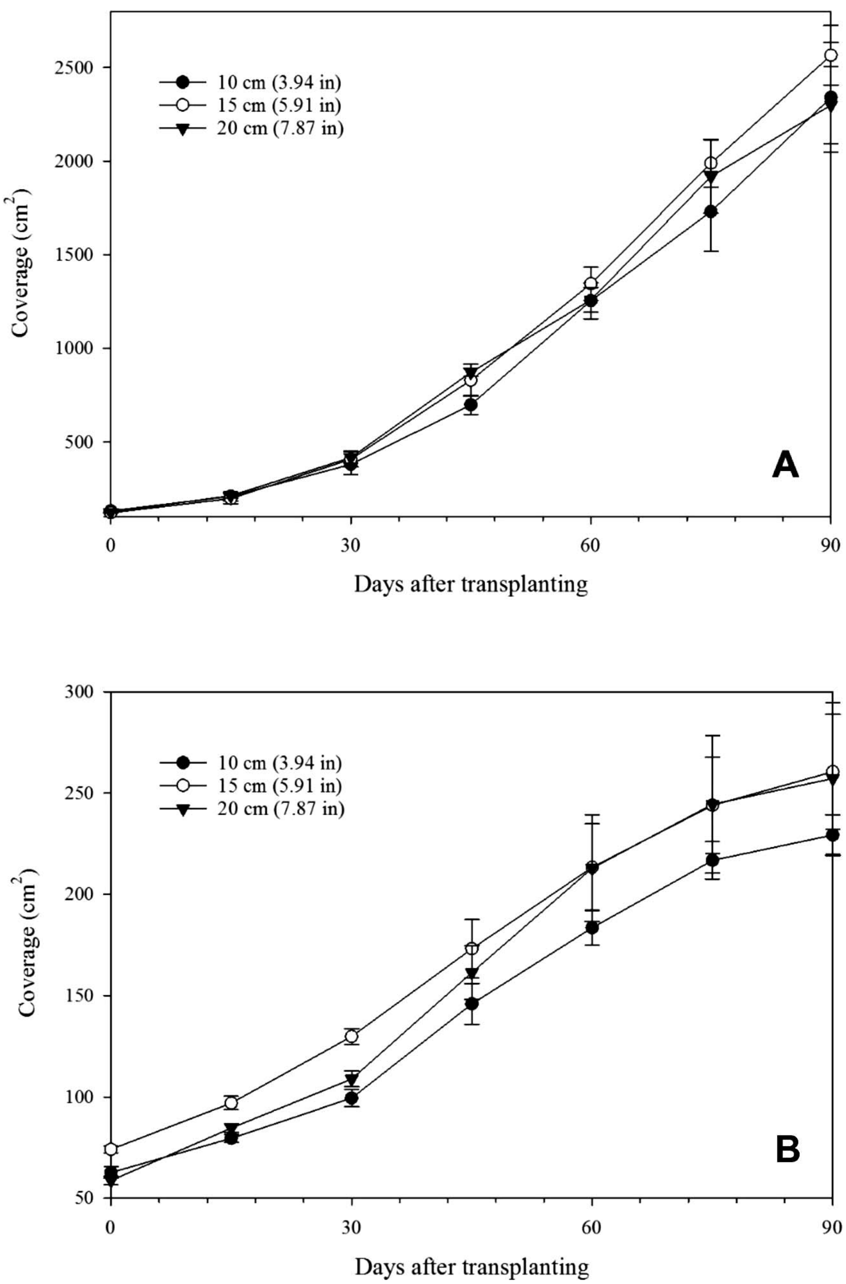


Fig. 2. Mean coverage of (A) iceplant (*D. nubigenum*) and (B) hens and chicks (*S. calcareum*) over time in greenhouse study in 10, 15, and 20 cm (3.9, 5.9 and 7.9 in) substrate depths. Vertical bars represent one standard error in each direction.

in the 15 cm-deep (5.9 in) plots. In a coarse-grained substrate, like those common to green roof substrates, the proliferation of roots in the bottom of the substrate will enable plants to pull water from the drainage layer, a feature common to green roofs. While the potential irrigation effect on deep RLD might warrant further investigation, a deep RLD might favor enhanced growth and survival, which is supported by the research of Carrow (1996) that showed that deep RLD correlated with drought tolerance in tall fescue.

Outdoor experiment: environmental conditions and substrate properties. The bulk density of the zeolite mix substrate was less than that of the substrate used in the greenhouse experiment and pH, air filled porosity, and water holding capacity were within FLL (2008) specifications (Table 1). Ambient temperature in October and November averaged 24.3 and 20.3 C (75.7 and 68.5 °F), respectively and precipitation averaged 36 and 2.5 mm (1.4 and 0.1 in), respectively, for the same months.

Outdoor experiment: plant growth and quality. At all dates, iceplant (Fig. 5A) and hens and chicks (Fig. 5B) had significant differences in mean coverage. At 56 DAT, there was no significant ($P = 0.3154$) difference in quality due to depth (Figs. 6A and B), although the difference in quality between plant types was significant ($P < 0.0001$). At 56 DAT, the quality for iceplant was 3.2 ± 0.1 and that

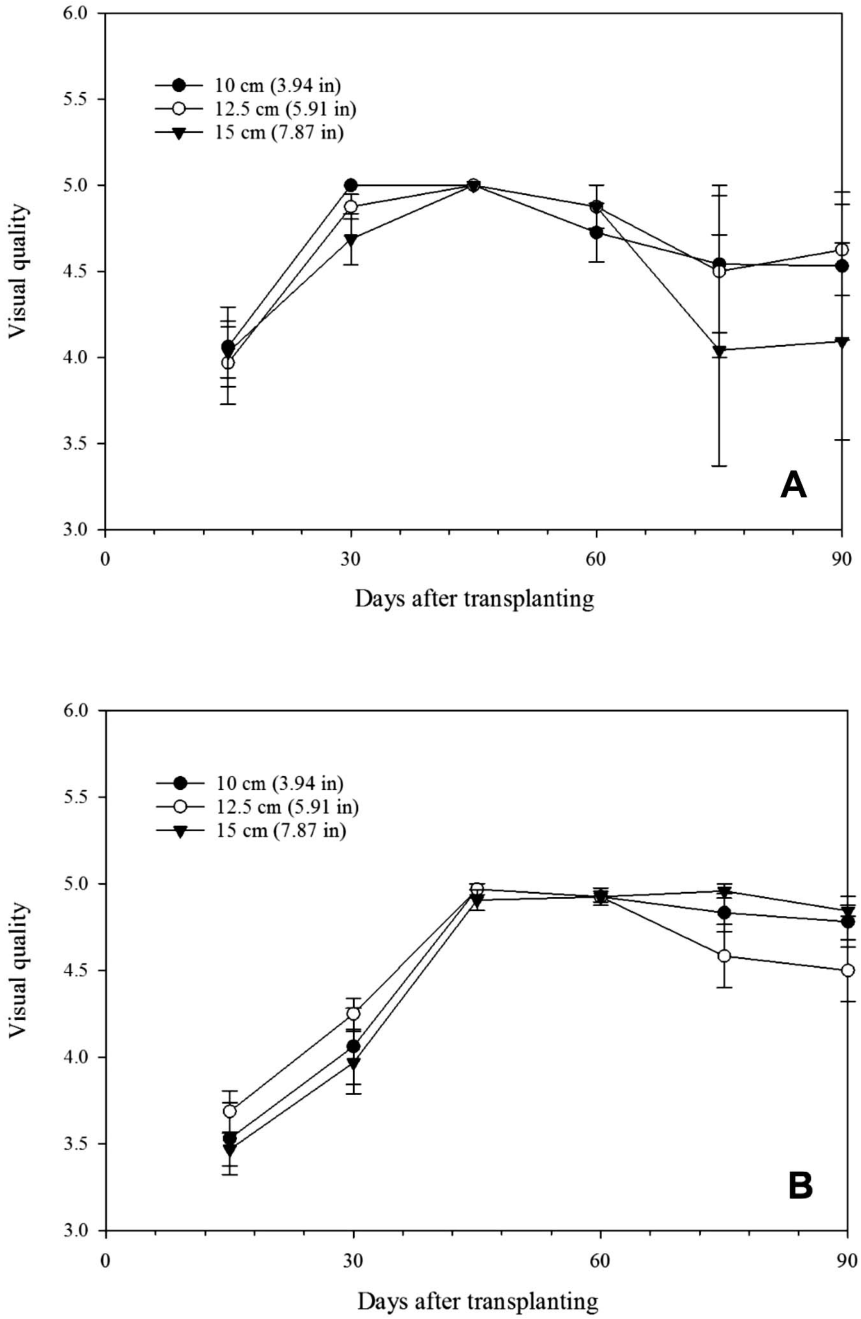


Fig. 3. Mean quality, determined visually, of (A) iceplant (*D. nubigenum*) and (B) hens and chicks *(S. calcareum)* over time in a greenhouse study in 10, 15, and 20 cm (3.9, 5.9 and 7.9 in) substrate depths. Vertical bars represent one standard error in each direction.

of hens and chicks was 1.6 ± 0.2. The decline in the quality of the hens and chicks over time might be due to its relatively low shallow RLD (Table 3). With fewer roots to extract moisture, overall plant quality would be impacted. When examining the data set with outliers removed, at 56 DAT hens and chicks had quality ratings of 2.2 ± 0.2 in the 10 cm (3.9 in) substrate depth, greater than either 1.3 ± 0.2 for the 15 cm (5.9 in) depth or 1.4 ± 0.2 for the 20 cm (7.9 in) depth. While fewer roots could impact plant quality, we cannot rule out the possibility that moisture retained at greater depths could have negatively impacted plant quality. So, the quality data for the hens and chicks favored the 10 cm (3.9 in) substrate depth. Taken together, the coverage and quality data indicate that plant type affects the success of arid green roofs. But, the lack of differences in quality resulting from substrate depth suggests that shallow substrates are acceptable for irrigated green roofs in arid environments.

Thuring et al. (2010) showed that substrate depth was the strongest predictor of green roof success for *Delosperma*, *Dianthus*, and *Petrorhagia* species planted at 3, 6, and 12 cm (1.2, 2.4, and 4.7 in) and exposed to drought. Substrate depth affected all species and the least

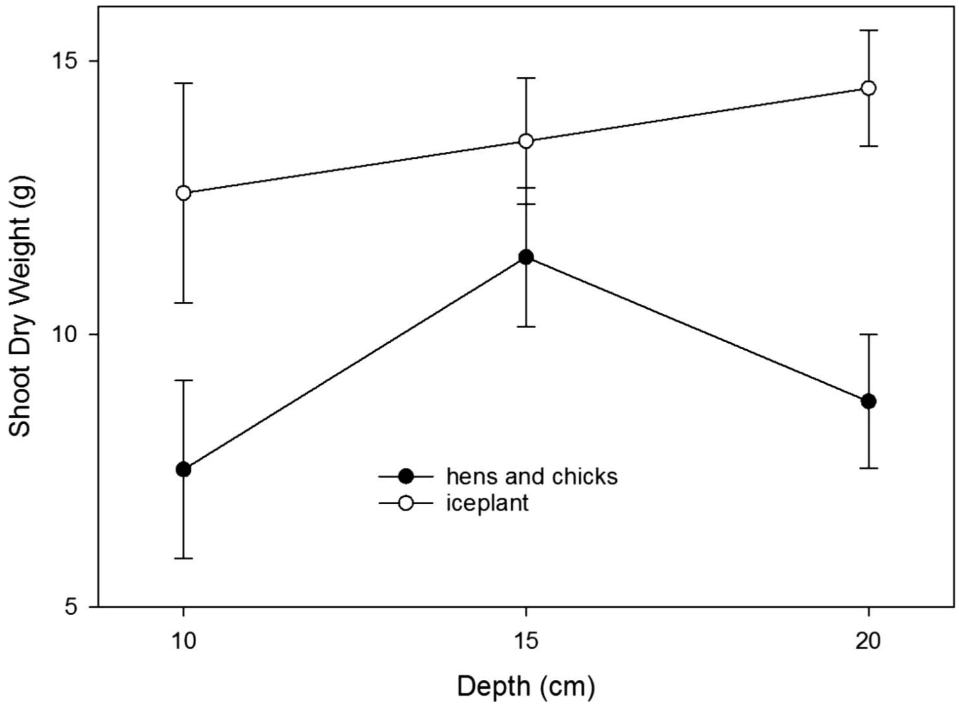


Fig. 4. Shoot dry weight (SDW) of iceplant (*D. nubigenum*) and hens and chicks (*S. calcareum*) at 75 days after planting in a greenhouse study in 10, 15, and 20 cm (3.9, 5.9 and 7.9 in) substrate depths. Vertical bars represent one standard error in each direction.

growth occurred when shallow depth and drought were combined (Thuring et al. 2010). Lavender (*Lavandula angustifolia* Mill.) plants growing in 30 cm-deep (11.8 in) substrates had more shoot and root growth than those growing in 20 cm-deep (7.9 in) substrates (Kotsiris et al. 2012). This led Kotsiris et al. (2012) to conclude that enhanced plant growth was due to better physiological status of plants in the deeper profiles. In our experiment, on November 27, 2012 (56 DAT), the SDW of iceplant was greater ($P < 0.0001$) than that of hens and chicks, but there were no differences in SDW among depths ($P = 0.4308$) (Fig. 7). If SDW is considered as a proxy for growth, then our results differ from those of Thuring et al. (2010) and Kotsiris et al. (2012). Our data demonstrates that shallow irrigated substrates are appropriate for irrigated green roofs grown in arid environments.

Outdoor experiment: root length density. Unlike the results from the greenhouse experiment, shallow RLD exhibited significant differences for plant type ($P < 0.0001$), substrate depth ($P = 0.0189$), and their interaction ($P = 0.0181$) (Table 3). In their research with creeping bentgrass [*Agrostis stolonifera* L. var. *palustris* (Huds.)], Schlossberg et al. (2002) demonstrated that root length density is important to plant growth and is directly linked to overall survival. The higher shallow RLD of the iceplant at the 10- and 15 cm-deep (3.9 and 5.9 in) substrate compared to that of 20 cm-deep (7.9 in) substrate supports the use of the shallower substrates. In contrast, for hens and chicks, the interaction between plant type and substrate depth is evident since the shallow RLD of the 10 cm-deep (3.9 in) substrate was lower than that of either the 15 or 20 cm-deep (5.9 or 7.9 in) substrate.

Table 2. Shallow and deep root length density (RLD) of iceplant (*Delosperma nubigenum*) and hens and chicks (*Sempervivum calcareum*) plants grown in 10, 15, and 20 cm (3.9, 5.9 and 7.9 in) substrate depths in a simulated green roof experiment conducted in a greenhouse at New Mexico State University. Substrate depth data were averaged over species and the species data were averaged over substrate depth.

	Substrate depth			Plant	
Parameter	10 cm	15 cm	20 cm	iceplant	hens and chicks
Shallow RLD ($cm \cdot cm^{-3}$)	11.2 ± 1.5 a[z]	10.3 ± 1.7 a	11.6 ± 1.5 a	11.3 ± 1.1[y]	10.8 ± 2.0
Deep RLD ($cm \cdot cm^{-3}$)	15.9 ± 2.5 a	4.1 ± 2.5 b	9.2 ± 2.5 ab	9.2 ± 2.6	10.3 ± 1.6
Log-transformed RLD ratio[x]	0.2 ± 0.4 a	-0.9 ± 0.4 a	-0.6 ± 0.4 a	-0.7 ± 0.3	-0.2 ± 0.3

[z]Means within a row [for 10, 15, and 20 cm (3.9, 5.9 and 7.9 in) substrate depths] sharing the same letter do not differ significantly at $P < 0.05$.

[y]Means with a row (for iceplant and hens and chicks) lacking a symbol do not differ significantly at $P < 0.05$.

[x]Ratio of deep RLD to shallow RLD

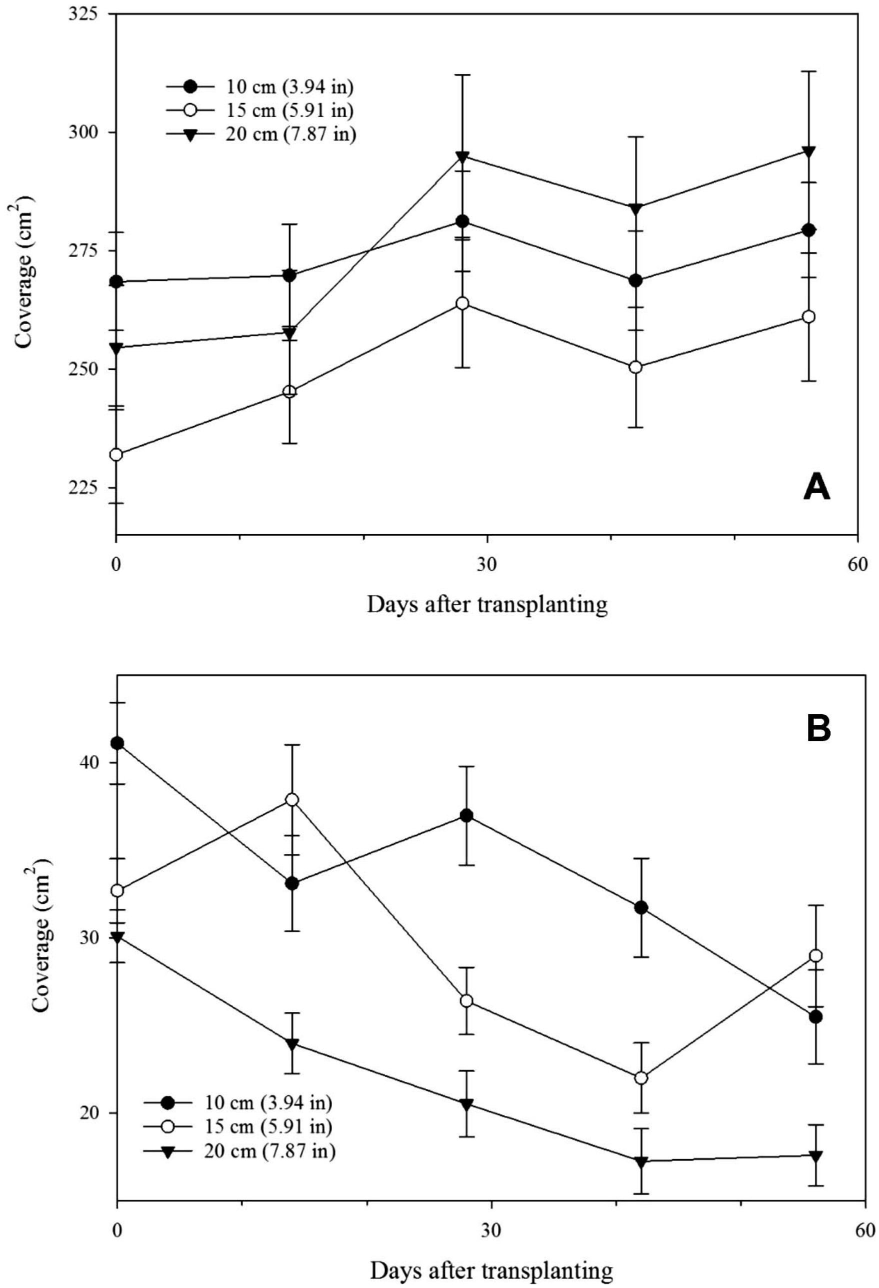
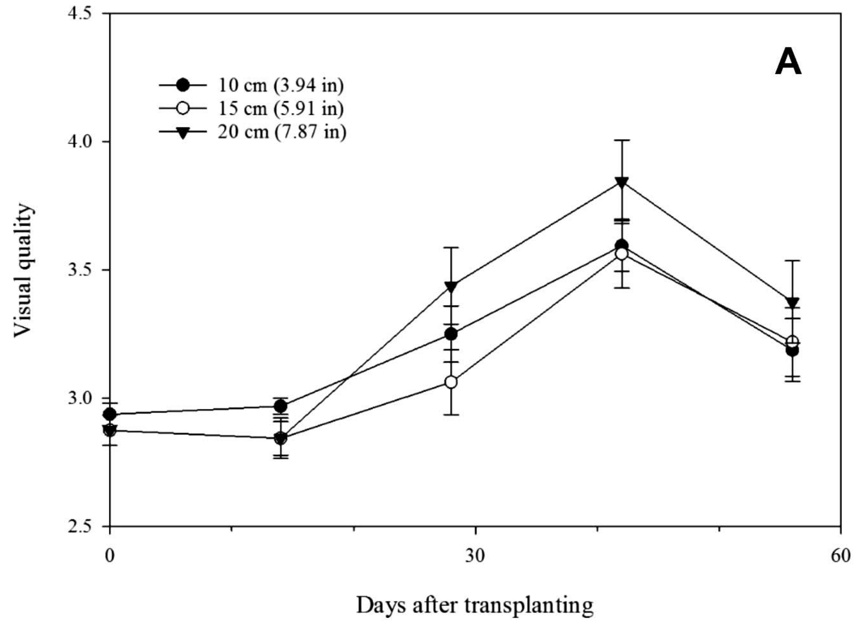


Fig. 5. Mean coverage of (A) iceplant (*D. nubigenum*) and (B) hens and chicks (*S. calcareum*) plants over time when grown in an outdoor arid environment in 10, 15, and 20 cm (3.9, 5.9 and 7.9 in) substrate depths. Vertical bars represent one standard error in each direction.

Deep RLD only exhibited significant differences ($P = 0.0012$) as a result of substrate depth and was highest for plants grown in the 15 cm-deep (5.9 in) substrates (Table 3). That the deep RLD results was only significant for the 15 cm (5.9 in) depth and not the 20 cm (7.9 in) substrate depth holds promise for using shallow irrigated substrates in arid environments.

For the log-transformed ratio of deep RLD to shallow RLD, both depth ($P = 0.0055$) and type ($P = 0.0441$) were significant (Table 3). Differences in the ratio of deep RLD to shallow RLD indicate that in the outdoor environment, the total root length allocated per unit volume of substrate are different in shallow and deep layers of substrate. Furthermore, this result indicates that root distribution differed between the two species.

In summary, we conclude that shallow substrates in irrigated green roofs are acceptable for arid environments, but plants must be selected carefully. This is particularly true for hens and chicks, where the coverage and quality data favored the 10 cm (3.9 in) substrate depth. Research into minimum irrigation requirements, such as that conducted by Ntoulas et al. (2013) and VanWoert et al. (2005), combined with substrate levels that have proven successful for plant survival, should help to make arid climate green roof systems more practical.



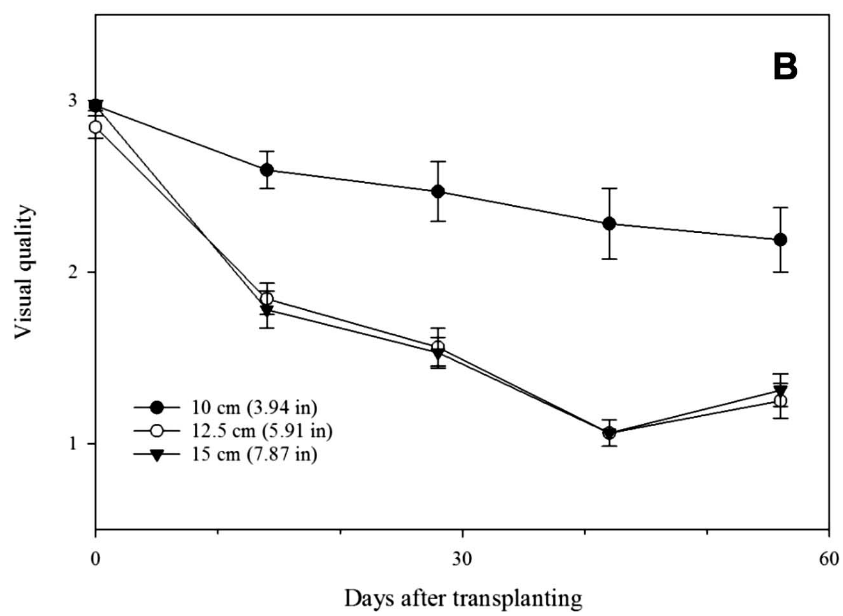


Fig. 6. Mean quality, determined visually, of (A) iceplant (*D. nubigenum*) and (B) hens and chicks *(S. calcareum*) over time when grown in an outdoor arid environment in 10, 15, and 20 cm (3.9, 5.9 and 7.9 in) substrate depths. Vertical bars represent one standard error in each direction.

Table 3. Shallow and deep root length density (RLD) of icplant (*Delosperma nubigenum*) and hens and chicks (*Sempervivum calcareum*) plants grown in 10, 15, and 20 cm (3.9, 5.9 and 7.9 in) substrate depths in a simulated green roof experiment conducted in outdoor plots at New Mexico State University.

	Substrate depth for *D. nubigenum*			Substrate depth for *S. calcareum*		
Parameter	**10 cm**	**15 cm**	**20cm**	**10 cm**	**15 cm**	**20cm**
Shallow RLD (cm/cm^3)	5.7 ± 0.7 ce[z]	7.3 ± 0.7 e	3.5 ± 0.7 a	1.2 ± 0.2a	1.8 ± 2.0 b	1.8 ± 0.2 bd
Deep RLD (cm/cm^3)	1.0 ± 0.3 ac	2.1 ± 0.3 b	0.4 ± 0.2a	0.4 ± 0.5a	2.1 ± 0.5 bc	0.3 ± 0.5 a
Log-transformed RLD ratio[x]	-1.7 ± 0.6 ae	-1.7 ± 0.6 ae	-2.8 ± 0.5 cde	-1.5 ± 0.5 a	-0.1 ± 0.5 b	-2.3 ± 0.5 ad

[z]Means within a row sharing the same letter do not differ significantly at $P < 0.05$.

[y]Ratio of deep RLD to shallow RLD.

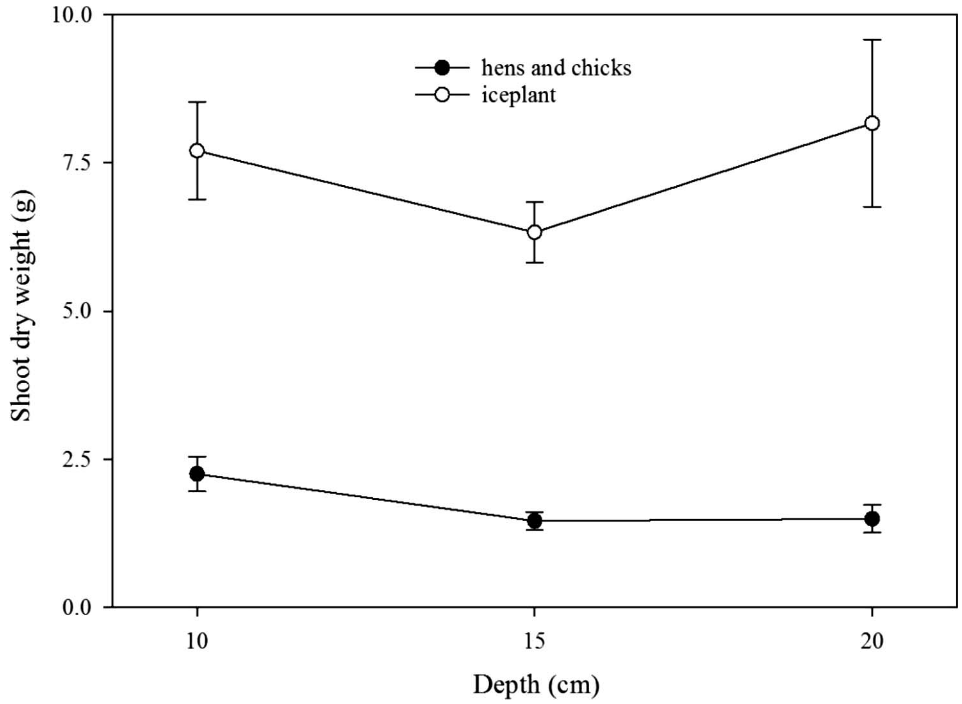


Fig. 7. Shoot dry weight (SDW) of iceplant (*D. nubigenum*) and hens and chicks (*S. calcareum*) plants over time when grown in an outdoor arid environment in 10, 15, and 20 cm (3.9, 5.9 and 7.9 in) substrate depths. Error bars represent one standard error in each direction.

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