Irrigation Lowers Substrate Temperature and Enhances Survival of Plants on Green Roofs in the Southeastern United States

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SUMMARY. Green roofs are becoming increasingly prevalent in the United States due to their economical and environmental benefits as compared with conventional roofs. Plant selection for green roofs in the variable climate of the southeastern United States has not been well evaluated. Shallow substrates on green roofs provide less moderation of temperature and soil moisture than deeper soils in traditional landscapes, necessitating empirical evaluation in green roof environments to make informed recommendations for green roof plant selection. Nineteen species and cultivars, including succulents, grasses, and forbs, were evaluated under seasonal irrigated and non-irrigated conditions in experimental green roofs. Plants were planted on 26 Oct. 2009 and each evaluated for survival and increase in two-dimensional coverage of the substrate during establishment, after overwintering, and after the first growing season. The winter 2009–10 was colder than normal, and some plants, such as ice plants (*Delosperma* spp.), considered to be cold-hardy in this climate did not survive through the winter. Irrigation influenced survival for the summer period and only succulent plants like stonecrops (*Sedum* spp.) survived without irrigation. Irrigated experimental green roofs had significantly lower summer substrate temperatures (up to 20 °F lower) and plants survived in irrigated conditions. Plants that survived both winter and summer under irrigated conditions include pussytoes (*Antennaria plantaginifolia*), mouse-ear tickseed (*Coreopsis auriculata*), eastern bottlebrush grass (*Elymus hystrix*), glade cleft phlox (*Phlox bifida stellaria*), and eggleston's violet (*Viola egglestonii*). Irrigation is recommended on extensive green roofs to increase the palette for plant selection by protecting against plant mortality due to drought and extreme soil temperatures.

Green roofs are engineered ecosystems that rely on protection, insulation, and plant evapotranspiration from a layer of soil-like substrate and plants to provide benefits such as reduced heat transfer in and out of buildings (Wong et al., 2003), decreased stormwater runoff and delayed peak flow (Carter and Butler, 2008), introduction of new urban habitats (Kadas, 2006), fire resistance (Köhler, 2003), and aesthetic and psychological benefits to urban dwellers (Hartig et al., 1991). Green roofs may also promote increased longevity of roof membranes from reduced membrane temperatures (Liu, 2004) and help reduce the urban heat island effect (Liu and Bass, 2005). Green roofs can be divided into intensive and extensive types. Intensive green roofs, which resemble ground-level landscape installations and usually provide additional outdoor recreational space to building inhabitants, typically have greater than 8 inches of substrate, and thus, may only be installed on buildings with structural capacity sufficient to support the additional weight. Plant selection for intensive green roofs is vast: within climatic limitations, selected small trees can be successfully integrated into green roof flora if provided sufficient soil depth and irrigation. Extensive green roofs have <8 inches of substrate (typically 4 inches in the southeastern United States). Their reduced weight enables them to be retrofitted onto existing buildings without substantial structural modifications to increase load-bearing capacity. Extensive green roofs are employed for more utilitarian purposes than intensive roofs, mainly to gain the benefits noted previously.

Compared with an impervious conventional roof, the benefits derived from the living ecosystem of a green roof are numerous, but an extensive green roof is typically a harsh environment for plants. In shallow substrates, entire root systems may be subjected to temperature extremes that are normally moderated by substrate depth (Dunnett and Kingsbury, 2008). Plants regarded as cold-hardy may be damaged by extremely low temperatures in shallow soils (Boivin et al., 2001), and likewise heat-tolerant plants may become stressed in the high summer temperatures prevalent on rooftops (Butler and Orians, 2009). If the roof is not irrigated, plants must rely on natural rain events for water, which can be sporadic in the summer season in the southeastern United States. These stresses may contribute to weak growth and dieback or death, which expose the substrate, increase potential for weed invasion and erosion, and decrease the aesthetic value and stormwater and thermal benefits derived from a thriving plant cover on a green roof. Moreover, additional expense is incurred if plant material must be replaced.

Likely candidate plants for green roofs should be able to tolerate the environmental extremes of the rooftop and grow sufficiently to cover the substrate in a short time. Most research

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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
0.3048	ft	m	3.2808
0.0283	ft³	m³	35.3147
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
6.4516	inch²	cm²	0.1550
16.3871	inch³	cm³	0.0610
(°F – 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

on plant selection for green roofs has been conducted in climatic regions other than the southeastern United States and under non-irrigated conditions only: Massachusetts (Carter and Butler, 2008), Michigan (Durhman et al., 2007; Getter and Rowe, 2007, 2008; Monterusso et al., 2005), Oregon (Hauth and Liptan, 2003), and Minnesota (MacDonagh et al., 2006). Climatic conditions vary by region. For example, the average temperature in July in Lansing, MI, is 70 °F and average annual precipitation is 32 inches [National Oceanic and Atmospheric Administration (NOAA), 2011]. In Birmingham, AL, the average temperature in July is 83.5 °F and average annual precipitation is 55 inches (NOAA, 2010). A few studies have evaluated the effects of irrigation on plant selection and concluded plant types that can best tolerate non-irrigated conditions are succulent plants (Durhman et al., 2006; Oberndorfer et al., 2007; Thuring et al., 2010; VanWoert et al., 2005;). Irrigation is often not employed on extensive green roofs because of the additional expense of installing and maintaining an irrigation system.

Although succulent plants are often the preferred plant choice in the U.S. green roof industry, these (usually stonecrops) are generally non-native. Any non-native plants should be non-invasive or evaluated for invasive behavior before being recommended for green roof applications to prevent suppression of regional biodiversity. Also, green roof plants are responsible for much of the cooling effects of green roofs (via evapotranspiration) on buildings (Gaffin et al., 2006) and for helping to remove stormwater from the soil between rain events. It is possible that transpiration rates of the selected plants would significantly influence the degree of benefit that a vegetated roof may provide (Wolf and Lundholm, 2008). Körner et al. (1979) found that succulents had the lowest maximum transpiration rate of 13 morphologically distinct plant groups tested. Bell and Spolek (2009) compared different types of plants for use in increasing the thermal resistance (*R*-value) of green roofs and found that ryegrass (*Lolium perenne*) delivered the highest effective *R*-value compared with bare soil, large periwinkle (*Vinca major*), white clover (*Trifolium repens*), or spanish stonecrop (*Sedum hispanicum*). Rather than using only succulent plants, planting a green roof with plants of different growth forms or functional groups may maximize benefits associated with water loss throughout the growing season if those selected have high water uptake rates under different soil moisture conditions (Wolf and Lundholm, 2008) and different times of the year. Expansion of the list of non-succulent, preferably native, plants appropriate for green roofs would be desirable, and potential plants should be evaluated by regional climates and under both irrigated and non-irrigated conditions.

The objectives of this study were to evaluate 19 morphologically, texturally, and physiologically diverse plant species and cultivars under irrigated and non-irrigated conditions by measuring survival and growth and to characterize substrate moisture level and temperature in an extensive green roof over one growing season. Plant selection was based on previous biological and horticultural documentation of tolerance to growing conditions similar to green roofs, including high light, shallow rooting depth, size at maturity less than two feet, moderate to fast growth rate, good persistence, and aesthetic value.

Materials and methods

On 26 Oct. 2009, one plant each of 19 species and cultivars were planted in each of 12 experimental green roofs (2 × 4-ft mini-roofs) on the roof of Campbell Hall (a four-story structure) on the University of Alabama at Birmingham (UAB) campus. Each mini-roof was equipped with standard materials for a green roof on a commercial building, including a waterproof membrane (Bituthene® 3000 high density polyethylene film; Grace Construction Products, Cambridge, MA), insulation (1-inch ROOFMATE™ extruded polystyrene foam; Dow Chemical Co., Midland, MI), drainage mat (Mel-Drain rolled matrix system 5035-B; W.R. Meadows, Hampshire, IL), and 4 inches of green roof substrate [80% recycled Stalite Permatill® fines and 20% composted worm castings: Leadership in Environmental Energy and Design Extensive Mix; ITSaul Natural, Atlanta]. Half (six) of the mini-roofs were also equipped with subsurface capillary irrigation (KISSS Below Flow Flat; Irrigation Water Technologies America, Longmont, CO). The irrigation system had emitters spaced 15.7 inches apart and the lines were wrapped with a geotextile fabric for water dispersion.

Within each mini-roof, the planting locations of the 19 species/cultivars were randomly assigned. Plants are listed in Table 1. All stonecrops and ice plants were plugs (3.5 inch^3, 72/flat) propagated at UAB from stock plants supplied by ITSaul Plants (Alpharetta, GA). The grasses (side-oats grama and eastern bottlebrush) were grown from seed (supplied by Shooting Star Nursery, Georgetown, KY) in plug trays (3.5 inch^3, 72/flat). All other species were supplied in 3-inch pots by GroWild (Fairview, TN), with the exception of mouse-ear tickseed, which was supplied in bare-root divisions by Nearly Native Nursery (Fayetteville, GA).

Starting at planting [0 d after planting (DAP)], all 12 mini-roofs were hand-watered to field capacity using overhead irrigation every 2 d through 7 DAP. Subsequently, only the six mini-roofs equipped with irrigation were watered supplementally. The irrigation system was equipped with a timer that turned irrigation on for 30 min every 12 h (at 0600 and 1800 HR each day). Capillary irrigation emitted ≈1.3 gal of water to each mini-roof during each irrigation period. Irrigation was ended before the first hard frost on 10 Dec. 2009 (45 DAP) and resumed 15 Mar. 2010 (151 DAP). Though irrigation was applied only seasonally, the plants that received seasonal irrigation will be referred to as irrigated.

At the end of each month, starting on 1 DAP, overhead images of each plot were captured using a digital camera (DSC-W100, 8.1 megapixels, 3x optical zoom; Sony Electronics, San Diego, CA). Digital analysis software (NIS Elements BR 3.1; Nikon Instruments, Melville, NY) was used to analyze overhead photos. A meter stick was placed in each photo and used as a reference for calibration of distance. Because the program could not automatically distinguish color differences between plant shoots and substrate, individual plants were analyzed using the manual trace function to determine the total area of substrate the plant covered in square centimeters (cm^2). From these monthly photos, plant success was evaluated by survival and two-dimensional coverage at three

Table 1. Recommendation of plant species and cultivars for use in irrigated and non-irrigated extensive green roofs in the southeastern U.S. Recommendations are based on evaluation over 1 year while cultivated under irrigated and non-irrigated conditions in experimental green roof systems at the University of Alabama at Birmingham. Those not recommended did not maintain at least 50% survival. Plants were planted 26 Oct. 2009.

Common name	Scientific name	Growth form and texture	Irrigated	Non-irrigated	Not recommended
'Angelina' stonecrop	*Sedum rupestre*	Succulent dicot	√	√	
Eastern bottlebrush grass	*Elymus hystrix*	Non-succulent monocot	√		
Eggleston's violet	*Viola egglestonii*	Non-succulent dicot	√		
'France' white stonecrop	*Sedum album*	Succulent dicot	√	√	
'Fuldaglut' two-row stonecrop	*Sedum spurium*	Succulent dicot	√	√	
Ice plant	*Delosperma ashtonii*	Succulent dicot			√
'Jellybean' white stonecrop	*Sedum album*	Succulent dicot	√	√	
'Limelight' golden japanese sedum	*Sedum makinoi*	Succulent dicot			√
Limestone fameflower	*Talinum calycinum*	Succulent dicot	√	√	
'Mesa Verde' ice plant	*Delosperma* 'Kelaidis'	Succulent dicot			√
Mouse-ear tickseed	*Coreopsis auriculata*	Non-succulent dicot	√		
Orange stonecrop	*Sedum kamtschaticum*	Succulent dicot	√		
Pussytoes	*Antennaria plantaginifolia*	Non-succulent dicot	√		
Rattlesnake master	*Eryngium yuccifolium*	Succulent dicot			√
Red mountain ice plant	*Delosperma dyeri*	Succulent dicot			√
Side-oats grama	*Bouteloua curtipendula*	Non-succulent monocot			√
Starry glade phlox	*Phlox bifida*	Non-succulent dicot	√		
White ice plant	*Delosperma ousberg*	Succulent dicot			√
Yellow-star grass	*Hypoxis hirsuta*	Non-succulent monocot			√

key points during the first year: during establishment (15 Nov. 2009, 20 DAP), after overwintering (25 Apr. 2010, 192 DAP), and after the first growing season (25 Sept. 2010, 345 DAP). Percent changes in coverage were calculated from the data collected on 192 and 345 DAP, both relative to the data collected on 20 DAP.

Soil moisture and temperature sensors (EC-TM; Decagon Devices, Pullman, WA) were buried in the center (2 inches deep) of four mini-roofs (one per mini-roof); two were randomly assigned to two irrigated mini-roofs and two were randomly assigned to two non-irrigated mini-roofs. The sensors recorded the data each hour on a logger (EM50, Decagon Devices). A weather station (Vantage Pro2; Davis Instruments, Hayward, CA) recorded surrounding temperature, humidity, rainfall, wind speed and direction, solar radiation, and barometric pressure on the roof.

Coverage data were analyzed using a mixed model to determine main effects and interactions because data sets were unbalanced due to plant mortality (SAS version 9.1; SAS Institute, Cary, NC). Since species/cultivar and the interaction of irrigation and species/cultivar significantly affected change in coverage for both 192 and 345 DAP, the significance of irrigation in determining change in coverage was analyzed separately within each species/cultivar for each date using least significant difference at $\alpha = 0.05$. For 345 DAP coverage data, Tukey's pairwise multiple comparison ($\alpha = 0.05$) was conducted to determine differences in coverage values among surviving species/cultivars within each irrigation treatment. Survival rates by irrigation treatment within each species/cultivar were analyzed using a 2×2 contingency table with Yates correction. Data from soil sensors were analyzed for differences between irrigated and non-irrigated plots, by month for temperature values, and cumulatively during irrigation season for soil moisture values using a standard *t* test.

Results and discussion

WEATHER CONDITIONS. Average monthly highs and lows, monthly minimum temperatures, monthly maximum temperatures, and average daily temperatures collected by the weather stations for each month are presented in Fig. 1, and these values are compared with previous records held at the National Weather Service Database from the airport in Birmingham, AL (NOAA, 2010). The data collected by the weather station during the experiment was compared with data from the Birmingham airport for the same period to determine if weather station data could be compared with previous records from the airport. Although there were small differences, the data from the two locations were very similar.

The weather during the course of the experiment was atypical. December 2009 had almost 2 inches of precipitation above normal (data not shown). The monthly temperature average of Jan. 2010 was 4 °F below normal, the minimum temperature was below freezing for 20 d out of the month (4 d more than normal), and the maximum temperature was below freezing for 3 d of the month (2 d more than normal). The monthly temperature average of Feb. 2010 was 7 °F below normal, and the minimum temperature was below freezing for 21 d of the month (10 d more than normal). Finally, the monthly temperature average in Mar. 2010 was 4 °F below normal. Following winter, spring temperatures increased rapidly, and summer was warmer than normal. April through Sept. 2010 all had monthly average temperatures 4–5 °F above normal. August 2010 had 4 d with high record-setting minimum daily temperatures: 5, 13, 14, and 19 Aug.

Also, Sept. 2010 had 3 d with high record-setting maximum daily temperatures: 11, 12, and 21 Sept. While May 2010 had 4 inches of precipitation above normal (which encouraged rapid shoot growth), July and Sept. 2010 each had ≈4 inches less total precipitation than normal conditions (data not shown).

Substrate moisture and temperature. Minimum, average, and maximum substrate temperatures for each month are shown in Fig. 2. Substrate temperatures in all mini-roofs decreased to 10 °F in Jan. 2010. In the non-irrigated mini-roofs, substrate temperature increased to 125 °F in July 2010, while substrate temperature in irrigated mini-roofs only increased to 105 °F. Substrate temperatures were significantly lower in irrigated mini-roofs than in non-irrigated mini-roofs during May, June, July, Aug., and Sept. 2010. Thus, during warm months, irrigation treatment affected temperature of the substrate as well as moisture content. As would be expected, substrate moisture contents (by volume) moved from wet to dry extremes during natural rain event cycles in the non-irrigated mini-roofs, while moisture content in the irrigated mini-roofs was comparatively constant during the growing season. Substrate moisture contents of the irrigated and non-irrigated mini-roofs were significantly different for the months in which the irrigation system was on: Nov. and Dec. 2009, and May–Sept. 2010 (data not shown). The average substrate moisture content during these months in non-irrigated mini-roofs was 0.13 m^3 of water per cubic meter of soil, while the average moisture content in irrigated mini-roofs was 0.25 m^3 of water per cubic meter of soil. Moisture content in non-irrigated mini-roofs decreased to 0.01 m^3 of water per cubic meter of soil between rain events during summer months.

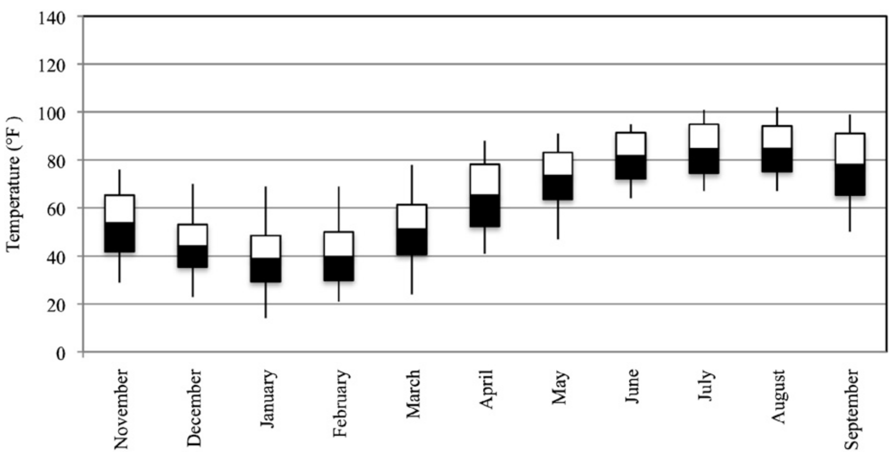

Fig. 1. Air temperature ranges for Nov. 2009 to Sept. 2010 at Birmingham, AL. For each month, the bottom of each box corresponds to the average daily minimum temperature, the black/white interface within the box corresponds to the average daily temperature, and the top of the box corresponds to the average daily maximum temperature. The bottom whisker extends to the lowest temperature recorded that month and the top whisker extends to the highest temperature recorded that month; (°F – 32) ÷ 1.8 = °C.

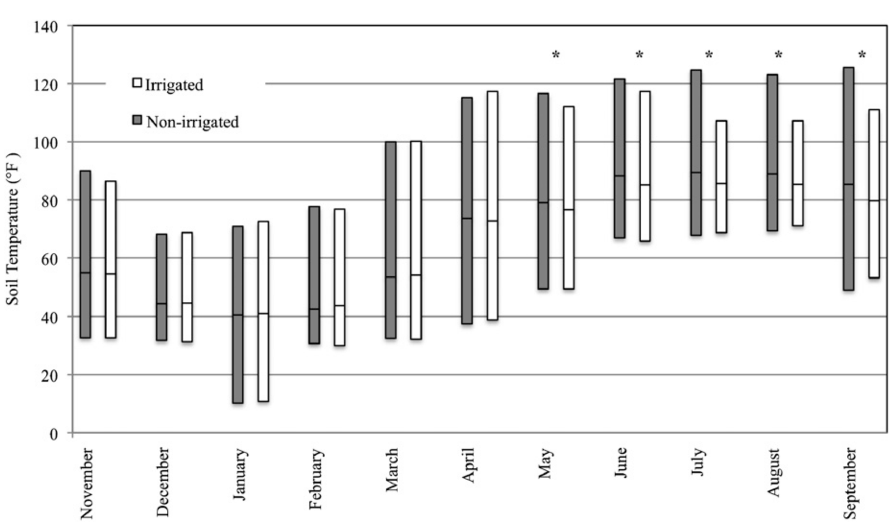

Fig. 2. Soil temperature at 3-inch (7.6 cm) depth in two replicates each of seasonally irrigated and non-irrigated experimental green roof systems with 4 inches (10.2 cm) of green roof soil, recorded Nov. 2009 to Sept. 2010 in Birmingham, AL. The bottom of each box corresponds to the minimum soil temperature recorded in that irrigation condition that month, the black line within the box corresponds to the average soil temperature, and the top of the box corresponds to the maximum temperature. Asterisks above boxes indicate statistically significant differences in values (at α = 0.05) for irrigated and non-irrigated soil temperatures that month. Irrigation was turned off for overwintering from Dec. 2009 to Mar. 2010; (°F – 32) ÷ 1.8 = °C.

Plant survival and growth. While irrigation may have helped establish plants from planting to Dec. 2010 when irrigation was discontinued for overwintering, prior irrigation was not significant in determining overwintering success (survival rates following winter). However, lower winter temperatures likely affected wintertime survival. Particularly, all ice plants evaluated were poor over winter survivors (Table 2). Though ice plants are generally hardy to U.S. Department of Agriculture Zone 6, which may experience winter temperatures as low as –5 °F, most other species/cultivars in the experiment are hardy to Zone 4 or less. Shallow soil depths and the high exposure of the green roof environment may make it difficult to define in terms of hardiness zones and thus plants thought to be hardy within a certain region may suffer unanticipated freeze stress (Boivin et al., 2001).

Irrigation was significant in determining survival rates only for the summer period (survival data collected at 345 DAP) and only for the non-succulent species including pussytoes, eastern bottlebrush grass, starry glade phlox, and eggleston's violet (all

Table 2. Survival over one year of 19 species and cultivars cultivated under irrigated and non-irrigated conditions in experimental green roof systems at Campbell Hall, University of Alabama at Birmingham. Plants were planted 26 Oct. 2009.

	Survival (%)[z]					
	Irrigated[y]			Non-irrigated		
Species/cultivar	Post-transplant survival[x]	Overwinter survival	Summer survival	Post-transplant survival[x]	Overwinter survival	Summer survival
‘Angelina’ stonecrop	100	100	100	100	100	100
Eastern bottlebrush grass	100	100	100	100	100	0
Eggleston’s violet	100	100	100	100	33	0
‘France’ white stonecrop	100	100	100	100	100	100
‘Fuldaglut’ two-row stonecrop	100	100	100	100	100	100
Ice plant	100	0	0	100	17	17
‘Jellybean’ white stonecrop	100	100	100	100	100	100
‘Limelight’ golden japanese sedum	100	33	17	100	50	0
Limestone fameflower	B[w]	100	100	B	83	83
‘Mesa Verde’ ice plant	100	0	0	100	0	0
Mouse-ear tickseed	100	50	50	100	50	0
Orange stonecrop	100	100	83	100	50	33
Pussytoes	100	100	100	100	50	0
Rattlesnake master	100	17	0	100	0	0
Red mountain ice plant	100	0	0	100	0	0
Side-oats grama	100	17	17	100	0	0
Starry glade phlox	100	100	100	100	67	0
White ice plant	100	0	0	100	0	0
Yellow-star grass	83	17	17	100	0	0

[z]Survival is reported as percentage of replicates per species with live shoot tissue remaining.
[y]Irrigation was supplied using subsurface capillary irrigation (KISSS Below Flow Flat; Irrigation Water Technologies America, Longmont, CO) pulsed twice per day for 30 min. System was shut off for overwintering from 10 Dec. 2009 to 15 Mar. 2009.
[x]Survival is reported at post-transplant period [20 d after planting (DAP)], overwinter (192 DAP), and after summer (345 DAP), corresponding to 15 Nov. 2009, 25 Apr. 2010, and 25 Sept. 2010. These dates were selected to depict initial post-transplant success, overwintering success, and tolerance of rooftop conditions during the growing season.
[w]Shoots had already died back as plants entered overwintering phase, leaving visible live tissue only in crown and roots.

P = 0.039). In general, irrigated plants that survived overwintering also survived to the end of the first growing season (Table 2). If a particular species/cultivar survived the abnormally cold temperatures of winter, irrigation enabled survival through the heat of summer by preventing drought stress. Under irrigated conditions, 10 species/cultivars maintained greater than 50% survival to 345 DAP (Table 2). Of these, the succulents ‘France’ and ‘Jellybean’ white stonecrops, as well as eastern bottlebrush grass, had significantly larger increases in coverage at 345 DAP than other plants under irrigated conditions (Table 3). There was some variation in coverage data among the replicates within each species/cultivar that led to high standard deviations for pussytoes and orange stonecrop in particular (Table 3), but the survival and coverage data are useful to determine which of the plants tested might be most appropriate for use on green roofs in the southeastern United States.

Extremely low substrate moisture contents likely made it difficult for non-irrigated plants to survive and support the large shoot canopies developed during the warm, rainy month of May. Under non-irrigated conditions, only five species/cultivars maintained greater than 50% survival to 345 DAP (Table 2). Of these surviving plants under non-irrigated conditions, ‘France’ and ‘Jellybean’ white stonecrops had significantly larger increases in coverage at 345 DAP than the other plants (Table 3). The surviving plants in non-irrigated mini-roofs were nearly all stonecrops, which corroborates previous work documenting the success of stonecrops in the green roof environment (Monterusso et al., 2005). The five species/cultivars that maintained greater than 50% survival in nonirrigated mini-roofs also maintained greater than 50% survival in irrigated mini-roofs.

Generally, if a particular species/cultivar could survive non-irrigated conditions, it did not have larger two-dimensional coverage when irrigated than when non-irrigated. Among surviving plants, irrigation generally did not affect two-dimensional coverage, except for starry glade phlox and ‘France’ white stonecrop at 192 DAP; both had larger coverage in the irrigated mini-roofs (Table 3). In contrast, non-irrigated plants of ‘Angelina’ stonecrop had better coverage than irrigated plants at the end of the first growing season (Table 3), perhaps since most other plants had died and there was little competition for space and resources. The succulent limestone fameflower shoot had already died back for winter at 20 DAP, thus changes in coverage could not be calculated, but this species managed to disperse seeds before winter and numerous small plants grew from the dispersed seeds throughout the plots with pink flowers developing all summer in both irrigated and non-irrigated mini-roofs. Despite early winter dieback relative to other plants, this species may be considered for filling in any gaps in coverage on an irrigated or non-irrigated green roof.

General recommendations for utilization of the plants tested in this experiment on extensive green roofs are presented in Table 1. Overall, ‘France’ and ‘Jellybean’ white stonecrops were most successful regardless of whether they were irrigated. Under periods of water stress, white stonecrop is known to shift from C3 metabolism to crassulacean acid metabolism (CAM) so that water loss is minimized (Castillo,

Table 3. Average change in two-dimensional substrate coverage of surviving plants of 12 species and cultivars cultivated under irrigated and non-irrigated conditions in experimental green roof systems at the University of Alabama at Birmingham. Plants were planted 26 Oct. 2009.

	Change in coverage (%)[z]							
	192 DAP[y]				345 DAP			
Species/cultivar	Irrigated[x]	n[w]	Non-irrigated	n	Irrigated	n	Non-irrigated	n
'Angelina' stonecrop	345 ± 161	6	730 ± 451	6	1059 b ± 641	6	3745 a ± 2044	6
Eastern bottlebrush grass	1477 ± 1052	6	2404 ± 866	6	6564 ± 4405	6		0
Eggleston's violet	137 ± 279	6		2	342 ± 260	6		0
'France' white stonecrop	3612 a ± 1434	6	1832 b ± 931	6	13262 ± 6893	6	9612 ± 3373	6
'Fuldaglut' two-row stonecrop	629 ± 408	6	412 ± 212	6	4316 ± 2552	6	2614 ± 1748	6
'Jellybean' white stonecrop	3721 ± 1671	6	2624 ± 344	6	15608 ± 8939	6	11674 ± 1488	6
Limelight golden japanese sedum		2	−56 ± 33	3		1		0
Limestone fameflower	B[u]		B		B		B	
Mouse-ear tickseed	−41 ± 13	3	−58 ± 28	3	210 ± 163	3		0
Orange stonecrop	−55 ± 30	6	72 ± 265	3	247 ± 219	5		2
Pussytoes	88 ± 89	6	16 ± 13	3	138 ± 147	6		0
Starry glade phlox	718 a[v] ± 130	6	365 b ± 188	4	1071 ± 292	6		0

[z]Overhead digital photos were analyzed with digital analysis software using a manual trace function to determine coverage area (square centimeters) of the substrate for each plant. Percent changes in coverage at both 192 and 345 d after planting (DAP) are relative to values at 20 DAP; 6.4516 cm^2 = $inch^2$.
[y]Coverage analysis dates depict initial post-transplant success (20 DAP), overwintering spread (192 DAP), and tolerance of rooftop conditions during the growing season (345 DAP).
[x]Irrigation was supplied using subsurface capillary irrigation (KISSS Below Flow Flat; Irrigation Water Technologies America, Longmont, CO) that pulsed twice per day for 30 min. System was shut off for overwintering from 10 Dec. 2009 to 15 Mar. 2009.
[w]Number of surviving replicates, out of initial six planted. Where there were less than three replicates surviving (less than 50% survival), change in coverage data are not shown.
[v]Where letters are present, difference in coverage changes between irrigated and non-irrigated plants within a species/cultivar and measurement date was significant, analyzed by least significant difference (α = 0.05).
[u]At 20 DAP, shoots had already died back as plant entered overwintering phase, so change in coverage could not be calculated.

1996). This may allow white stonecrop to survive periods of drought while capitalizing on well-watered periods to maximize growth and survival. However, if irrigation is provided, pussytoes, eastern bottlebrush grass, orange stonecrop, starry glade phlox, and eggleston's violet may be used and contribute visual interest beyond the typical succulent green roof landscape. In this experiment, the species/cultivars were interspersed in randomized fashion within each plot due to the increasing interest in mixed plots rather than monocultures in the green roof industry. This planting style resembles a meadow or rock outcrop habitat and may be more resistant to pests and disease than monocultures. The plants in this experiment will remain in place to observe their performance beyond the first growing season, in years with more typical weather patterns, and their potential for ecological succession and competition within this planting style.

Conclusions

Previous horticultural documentation of tolerance to growing conditions similar to those found on an extensive green roof are helpful for initial plant selection, but plants must also be evaluated in situ to determine if they will be successful in a specific green roof environment in a given climatic region. The shallow soils of extensive green roofs provide less protection of roots from freezing conditions and from high temperatures than do deeper soils, so it is important to select plants that can tolerate periods of extreme heat and cold both above- and below-ground. As the year in which this experiment was conducted shows, weather patterns are unpredictable, and factors such as temperature and precipitation cannot be controlled. Unusual years with record-setting high and low temperatures and sporadic rain events will always occur, therefore irrigation during the growing season is recommended. Irrigation moderates substrate moisture and temperature extremes, which may improve growth and survival of some plants and offer long-term economic benefits resulting from minimal replanting and maximal canopy coverage. Irrigation systems that employ non-potable water, such as those that capture roof stormwater runoff in a cistern and pump the water back to the roof for irrigation, are good options to decrease the environmental impact of using irrigation. In addition, selecting plants that need irrigation requires that the green roof must have the option of irrigation application for the lifetime of the roof, at least in times of severe drought.

This study illustrates that plant selection options are increased with irrigation. The drought tolerance of stonecrops was reinforced; essentially nothing survived without irrigation except some stonecrops and limestone fameflower. However, even many stonecrops in this study could not tolerate the summer season in the southeastern United States without irrigation. Further research is needed to evaluate more plants for use on green roofs, particularly those already adapted to conditions similar to green roofs, such as rock outcrop natives. Selecting plants that will be successful in the green roof environment and incorporating irrigation when necessary can form entire urban ecosystems that provide habitats for invertebrates, birds, and other small vertebrates.

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