CITIESALIVE
12TH ANNUAL GREEN ROOF & WALL CONFERENCE
NASHVILLE: NOVEMBER 12 - 15, 2014

Session Number 5R

Semi-arid Green Roof Research 2009-2014: Resilience of Native Species

Lee R. Skabelund[1] and Carolyn Blocksome[2], Dede Brokesh, Hyung Jin Kim, Mary Knapp, and Maryam Hamehkasi

Kansas State University, [1]Landscape Architecture and Regional & Community Planning; [2]Horticulture, Forestry & Recreation Resources

Abstract

Green roofs in Kansas, U.S.A. experience temperature and wind extremes and periods of drought and intense rainfall, requiring hardy, resilient vegetation. In 2009, 15 species of plants native to the central Great Plains were planted on a 28.5 m2 (305 ft2) semi-intensive green roof, retrofitted above a third-floor breezeway on a university building in Manhattan, Kansas. This demonstration project offered an accessible setting to observe plant vigor and survival, and develop research strategies in a region with few green roofs. Plantings included 130 native grass plugs (4 species), 98 native forb plugs (11 species), plus 232 sedum plants (4 species). Substrate depth varied from 7-10 cm (3-4 inches) nearest roof edges, to a maximum of 17.78 cm (7 Inches) at the center of this integrated green roof. Vegetation was evaluated yearly at the end of the growing season for six years (2009-2014). Irrigation varied over the six growing seasons with only the east side hand-watered during dry periods in 2011, and with irrigation eliminated in mid-August 2012. Plant survival was near 100% during years one and two. By the end of year five (November 2013), 52.3% of the original grasses and 21% of the original forbs remained. Many new seedlings of native grasses and forbs were observed between 2010 and 2014, with vigorous native species numbers decreasing following extended hot, dry periods—particularly in 2013 and 2014 when no supplemental water was provided. Total survival (10 of 130 original grasses as of mid-October 2014) was 7.7%. Additionally, more than 80 native grasses generated from seed were visibly green in mid-October 2014. Except for three of four spiderwort, all other original forbs were absent as of November 2014, but two additional forbs were visible at this time. While original *Bouteloua gracilis* (blue grama) plants showed a 16.1% survival rate by October 2014, other original grasses and forbs remained completely brown above the substrate. It is evident that supplemental irrigation is critical for longer-term survival and growth of individual native plants installed on highly-exposed 7-18 cm green roofs in the Flint Hills Eco-region. Nevertheless, some native species can survive with no supplemental irrigation.

Acknowledgements: The Upper Seaton Hall Green Roof was partially funded by USEPA / Kansas Dept. of Health & Environment $5,000 WaterLINK Water Quality Restoration & Protection Service Learning Mini-Grant, with monitoring partially supported by a subsequent USEPA / KDHE “Clean Water Neighbor” grant. Many donations were provided in the creation of this green roof demonstration project. Derbigum, Inc. provided the waterproofing membranes, and American Hyrdotech, Inc. provided the green roof materials that made the project possible. Danker Roofing donated time to reduce pitch-tar removal and re-waterproofing costs. Faculty and students from the College of Architecture, Planning & Design and the College of Engineering contributed many, many hours to green roof design and installation. Weather monitoring equipment was loaned to the Seaton Hall Upper Green Roof project by the Kansas State Department of Agronomy climatologist.

Introduction

Dvorak & Volder's (3) literature review of vegetation for North American eco-regions noted that many published green roof studies lasted three years or less. Sutton et al. (10) indicate the need for green roof research focused on determining well-adapted native plants for resilient living roofs.

Successful implementation of green roofs in hot and dry climates is important as the environmental benefits are likely to be far greater in than in temperate climates (Simmons 2014). To date no research has been done in the Flint Hills Eco-region to determine the viability of native plants and succulents on green roofs nor the influence of different substrate depths in this seasonally hot, semi-arid to temperate climate.

Research on green roofs in drier climates is needed so that building designers and managers can understand what is required for green roofs to temper urban heat island effects and reduce air conditioning and other energy demands. Drought and frequent scarcity of water in arid and semi-arid climates compels us to explore ways to create resilient, water-conserving green roofs in these regions. Climate change likewise induces designers and managers to create adaptive minimally resource consumptive green roofs.

Since large numbers of people in urban areas in the United States and around the world live in hot climates it is important to find ways to provide cost-effective ways to provide ecosystem services while conserving precious potable water supplies (Simmons 2014; Volder & Dvorak 2014; Williams, et al. 2010).

Project Background:

A five-year integrated green roof demonstration project at Kansas State University was designed and implemented to better understand relationships between vegetation, substrate depths, substrate temperatures, micrometeorological variables, and other factors. Monitoring equipment was sited during the green roof installation to track a wide range of weather and soil moisture variables.

Individual plants were observed to determine plant growth and viability. Four grasses known to be frequently used in urban landscape and restoration plantings, along with 11 wildflowers, all native to the Flint Hills Eco-region and recognized as being drought tolerant, were chosen for use on the green roof, along with 4 sedum species. No attempt was made to test specific sedums and native species in an experimental way nor to use only already identified "well-adapted" native plants presented in the literature focused on green roofs.

Consultation with others who had previously planted green roofs in the Midwest (primarily in Colorado, Nebraska, Missouri, Minnesota, and Michigan) and discussions with a commercial native plant supplier having a knowledge of green roof plants used in Wisconsin and other Midwestern states informed the plant selection process. Overall, a mix of aesthetic and ecological concerns guided green roof species selection.

Primary Project Objective:

An approximately 28.5 square meters (305 square foot) roof surface above a third-floor breezeway that could easily handle additional loading was selected as the location for this demonstration project.

The primary objective of the project has been to observe how selected native tallgrass prairie grasses and forbs fare on a rooftop in semi-intensive 7.6 to 17.8 cm (four to seven inch) substrate without supplemental irrigation after a two-year (west side) establishment period, and a four-year (east side) establishment period. The three inner rows of west side grasses were spaced further apart than the three inner rows of grasses on the east side. 62 forbs were interspersed among the grasses on the west side, with 12 of these being nitrogen-fixing purple prairie clover. 38 forbs were interspersed among the grasses on the east side, with 12 of these being purple prairie clover. No fertilizer has been added during the study period.

Since 2009, a primary focus of this demonstration project has been the observation and interpretation of plant survival and vigor data collected for blue grama and other species planted on the Upper Seaton Hall Green Roof (UGR). Blue grama was selected and used in greatest abundance on the UGR because it is a hardy species found within native tallgrass prairies and is relatively short in above-ground stature (typically less than 30 cm in height), resulting in less biomass accumulation on the green roof.

Primary research questions were: 1) How well would blue grama and other grasses and forbs survive and thrive after being planted as live plants in May 2009? 2) How would differing green roof substrate depths influence the growth and survival of blue grama and other species? 3) What other variables influence vegetation growth and survival? The central focus of this paper is on the first question.

Regional Context - The UGR lies within the Flint Hills Eco-region, the largest remaining expanse of unplowed tallgrass prairie in the USA (Knapp et al. 1998). The regional native prairie plant community includes over 600 species of grasses, sedges, and wildflowers, and is dominated by warm-season grasses such as the drought tolerant blue grama, side-oats grama, and little bluestem. Little bluestem can grow to over one meter in height in years with favorable weather, but is much shorter during drought years (ibid). Weather is characterized by wide fluctuations in seasonal and interannual temperature and rainfall, with average temperatures ranging from a January low of -2.7° C to a July high of 26.6° C. About 75% of the 835 mm average annual total precipitation occurs during the growing season (KPBS 2014).

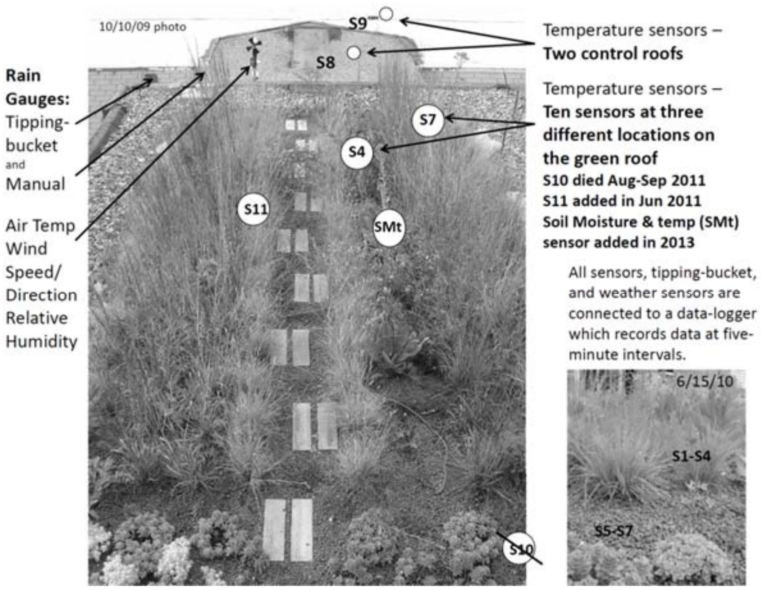
Methods: Employing an Informal, Adaptive, and Persistent Observational Monitoring Approach - While regular micro-meteorological and plant survival and growth observations documented growing conditions and plant responses on this south-facing (full-sun) green roof, no attempt was made to create a replicable experimental design. Rather, the project was foremost a demonstration of what a mixed-species green roof in the Flint Hills Eco-region could look like while providing an excellent opportunity to observe how this particular green roof would evolve over a multi-year period given the variability provided by different substrate depths; an artistically organized planting layout; changes in irrigation inputs; differing weeding and clipping strategies year to year; variable climatic conditions; the addition of seeds and berries brought by birds, wind, and people; and an informal, adaptive, but persistent observational approach to monitoring.

Design and Implementation - The project was installed by local contractors and university volunteers. Material used were root barrier (Hydrotech Root Stop HD), drainage mat (Gardendrain GR30), filter fabric (Systemfilter), mineral aggregate, and semi-intensive substrate (LiteTop). American Hydrotech, Inc. donated the substrate material. The precise percentage of substrate organic matter was/is unknown. Some, but an unknown amount of water, is held between the root barrier and drainage layer of the green roof.

Climate Monitoring System - Instrumentation installed on the Upper Seaton Hall green roof in June 2009 included: one data-logger (Campbell Scientific CR23X) and associated solar panel (BP 10W 16.8V), a wind monitor measuring speed and direction (RM Young), an air temperature/ relative humidity sensor (Vaisala), three Campbell Scientific 107 temperature probes on the green roof and two on adjacent control roofs (one silver-white and one asphalt gravel rooftop), six sub-surface “substrate” temperature probes (three beneath probe S4 and two beneath S7), and one tipping-bucket (Texas Electronics TR-525I). All instrumentation was connected to the data-logger via cable. In addition, one manual all weather rain-gauge (4-inch gauge) was mounted on a piece of plywood and held in place via three dowels roughly two feet from the tipping bucket and 18 inches from the wind monitor. On January 9, 2013 one temperature/ substrate moisture sensor

(Decagon Devices) was placed on the green roof, and on May 31, 2013 a relative humidity/temperature datalogger was installed (Onset Hoboware U23-002 Hobo Pro v2 Ext) was added (see Figure 1 and Figure 2). These devices were added in 2013 to better understand what surface and sub-surface temperatures and soil moisture were like in the deepest substrate (in the middle of the rooftop) and complement the micro-meteorological data being collected from other sensors (Skabelund et al. 2014).

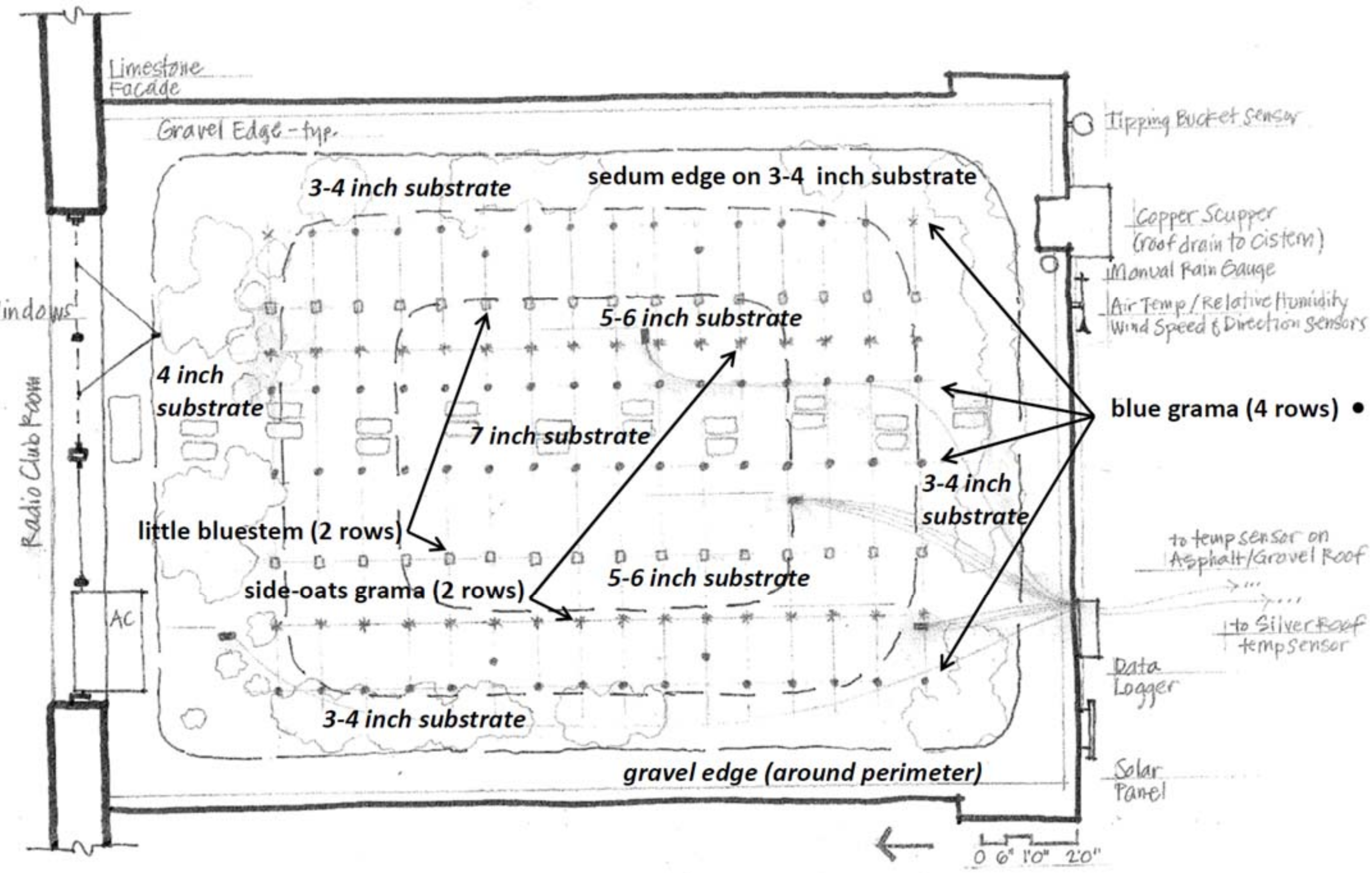
Figure 1: UGR monitoring equipment and sensor layout. Sensors were placed to collect rooftop and substrate temperatures, relative humidity, soil moisture, soil salinity, and rainfall. Photos by Lee R. Skabelund



Supplemental Irrigation - The entire green roof was irrigated with potable water by a drip irrigation system during the first year (2009). During year two (2010), plant material was watered by hand after the drip irrigation system was removed and broke during removal. During year three (2011), only the east side of the roof was watered when plants were visibly stressed. During year four (2012), the entire roof was watered by hand when plants were visibly stressed. No supplemental irrigation was applied in years five and six. All irrigation was applied when wilting was observed on forbs. Hand-watering provided good coverage.

Planting Approach - Fifteen species of grasses and forbs were planted in May 2009 as 3-inch deep plugs (supplied by Applied Ecological Services/Kaw River Restoration Nursery in Baldwin City, Kansas) in substrates ranging from 10 cm to 17 cm. Sedums were placed along the green roof edges in the shallowest (7.5 cm to 10 cm) substrate. Three primary species of grasses (blue grama, side-oats grama, and little bluestem) were planted in rows of 16 plants each on the UGR in May 2009 for a total of 126 plants, along with four prairie dropseed (two on the east side and two on the west side). Spacing between the three primary grass species on the east side was much tighter than on the west side (with the three rows inner rows on each side an average of 24 cm apart as compared to 45 cm apart on the west side). Spacing of native grasses north to south (in the rows of 16 planted grass plugs) were an average of 25 cm apart.
98 plugs of native forbs were planted interspersed between the rows of grasses. It is important to note that between 2011 and 2014 native plant seed (including hairy grama seed sent from Nebraska and prairie seed collected in various locations in Kansas, including little bluestem and dotted gayfeather seed from a local hilltop prairie and seed from grasses and forbs on the two Seaton Hall green roofs) was added in bare spots on the UGR. Nevertheless, it is not known how much of this seed germinated.

Figure 2. Diagram (by L.R. Skabelund) showing layout of three primary grasses in relation to approximate substrate depths. Four prairie dropseed plugs were also planted, along with 98 forbs (11 different species).



Plant Monitoring Methods - A primary focus of this research has been on what we can learn from our observations of blue grama and three additional grasses planted on the Upper Seaton Hall green roof. Blue grama was planted in greater numbers and received more attention because it has been used on many green roofs in the United States and it was expected by the lead project designer to do better than the other grass species selected due to its drought-tolerance, cold hardiness, and lower profile.

Due to the small number of plants and the desire to retain as many as possible, a non-destructive approach to assessing plant vigor was utilized (Cook & Stubbendieck 1986). Plant vigor for grasses was characterized by measuring survival, plant height, maximum plant diameter (as viewed from the top of the plant), basal circumference, and number of flowering stalks (Weaver 1947). As plants matured and grew together, basal circumference was no longer measured. Forb vigor was characterized by measuring survival, longest leaf length, number of stems, number of flowering stalks, and number of seedheads (Weaver 1947).

All measurements were taken at the end of the growing season but before complete senescence each year of the study (see Figure 3). To determine survival, plants were visually assessed for any greenness in the above-ground part of the plant. Plants with no visible evidence of green or any above-ground living parts were recorded as dead. A meter stick was used to measure plant height and diameter and a measuring tape was used to obtain the basal circumference of grasses. The number of flowering stalks were counted and recorded. Refer to Appendix A for an example of preliminary blue grama findings and analysis.

KSU personnel (faculty and students) monitored plant growth on the Upper Seaton Hall green roof at the end of each growing season. Consistency in collecting data was ensured via training and oversight provided by the lead authors (Skabelund and Blocksome).

Figure 3. First-Year Monitoring Activities on UGR (Oct. 2009). Photos by Lee R. Skabelund

Results and Observations

Microclimatic Conditions on the UGR – Micro-meteorological sensors measuring surface and sub-surface temperatures provided data at strategic locations on the green roof. Because it is buffered from cold north winds by building mass the UGR does not experience the full rigors of winter, but is still exposed to the vagaries of Great Plains' weather. The UGR experiences intense summer heat (with bare rooftop surfaces reaching temperatures greater than 60° C). This green roof likewise experiences high ambient air temperatures (between 32 and 46° C) during spring, summer, and fall. Average air temperatures during the period July 1 to Aug 31 following plant establishment were (2011: 30.97 C; 2012: 29.14 C; 2013: 26.53 C; 2014: 27.13 C). At times a blanket of snow on the green roof protects the vegetation from bitter cold temperatures, while the lack of snow cover during the coldest months of winter leave the roof exposed to temperatures well below -20° C. During the growing season, a completely vegetated green roof can keep rooftop surface temperatures (beneath native grasses and sedums) roughly the same as ambient air temperatures, while bare substrate surfaces can exceed 60° C in early afternoon. Average substrate temperatures 5 cm below sensor S4 during the period July 1 to Aug 31 were (2011: 33.57 C; 2012: 31.36 C; 2013: 29.6 C; 2014: 31.86 C)—with temperatures at or above an average of 32 C as follows (2011: 40 days; 2012: 31 days; 2013: 19 days; and 2014: 28 days). In short, substrate temperatures were very warm.

Plant Survival Observations - As of October 2014, six growing seasons had elapsed since planting the UGR. Plant survival was close to 100% during years one and two (see Tables 1a and 1b). By the end of year five (November 2013), 52.3% of the original grasses and 21% of the original forbs remained. Although many new seedlings of native grasses and forbs were observed between 2011 and 2014, most native species numbers dramatically decreasing during extended hot, dry periods (particularly in July 2011 on the west side and over much of the UGR in July 2013 and July 2014 when no supplemental water was provided). Survival rate for original grasses as of mid-October 2014 was 7.7%. Nevertheless, a total of more than 80 native grasses generated from seed were visibly green at this time. Original blue grama plants showed a 16.1% survival rate as of late September 2014, while other original grasses and forbs remained completely brown above the substrate. Except for three of four spiderwort, all other original forbs were absent as of November 2014, but two additional forbs were visible at this time.

It is evident from this research that supplemental irrigation is critical for longer-term survival of individual native plants installed on a highly-exposed integrated semi-intensive green roof in the Flint Hills Eco-region. Nevertheless, it was observed that native grass seedlings on such a green roof can remain resilient for up to four weeks with no to little summertime rainfall.

Table 1a: Number of grasses on the UGR in mid-July 2009 and their mid-summer 2010 survival rate.

Common name	Scientific Name	Surviving July 2009	Surviving July 2010	Plant Roof Location East	West
Side-oats grama	*Bouteloua curtipendula*	32	32	16	16
Blue grama	*Bouteloua gracilis*	62	62	30	32
Little bluestem	*Schizachyrium scoparium*	32	32	16	16
Prairie dropseed	*Sporobolus heterolepis*	4	4	2	2

Table 1b. Number of forbs on the UGR in mid-July 2009 and their mid-summer 2010 survival rate.

Common name	Scientific Name	Planted May 2009	Surviving July 2010	Plant Roof Location East	West
Purple poppy-mallow	*Callirhoe involucrata*	8	8	4	4
New Jersey tea	*Ceanothus americanus*	8	8	2	6
Purple prairieclover	*Dalea pupurea*	24	24	12	12
Tall gayfeather	*Liatris aspera*	8	8	2	6
Dotted gayfeather	*Liatris punctata*	8	8	3	5
Prairie coneflower	*Ratibida columnifera*	8	8	--	8
Gray-headed coneflower	*Ratibida pinnata*	8	7	8	--
Wild blue sage	*Salvia azurea*	8	8	--	8
Rigid goldenrod	*Solidago rigida*	8	8	--	8
Smooth aster	*Symphyotrichum leave*	8	8	2	6
Common spiderwort	*Tradescantia ohiensis*	4	4	4	--

Overall Findings following Six Growing Seasons:

During the first five years, deeper substrates typically promoted greater survival and growth of native plants than shallower soils on KSU's Upper Seaton Hall Green Roof. This corresponds to findings by Durhman et al. (2007) and other researchers that deeper substrates promote greater survival and growth for most species tested. Deeper substrates provide greater moisture retention and root protection from temperature fluctuations and allow more vertical space for plant roots to grow before they reach the filter fabric, drainage layer, or root barrier. A more stable environment allows plants to grow stronger and healthier, which affects their ability to survive harsh climatic conditions of drought and temperatures.

Nevertheless, even with deeper substrates, mortality during winter can result in the death of root systems, which are generally not as cold-tolerant as the tops of plants (Wu and Cosgrove, 2000), and, as shown in Table 2, brownout and dieback of native species can occur during prolonged dry periods. On the UGR brownout occurred July-August 2013 and July-August 2014. It is therefore very important to find species of plants that are well adapted to the seasonal temperature fluctuations common in a region—and to account for particular (likely/possible) microclimate, hydrologic (rain and snowfall), and human intervention patterns.
Table 2. Total number of plants showing visible above ground green per year (2009-2014).

Year and recorded date of observations	Native Grasses (number of original plants surviving)	Survival percentage	Native Forbs (number of original plants surviving)	Survival percentage
2009 installation (May 19, 2009)	130		100	
2009 (Oct. 16 & 20, 2009	130	100%	100	100%
2010 (Jul. 2, 2010)	130	100%	98	98%
2011 (Oct. 25, 2011)	98	75.4%	39	39%
2012 (Jul. 10 & Nov. 15, 2012)	97	74.6%	54	54%
2013 (Nov. 7, 2013)	68	52.3%	21	21%
2014 (Oct. 11 & Nov. 11, 2014)	10 (all Blue Grama)	7.7%	3 (all Spiderwort)	3%

UGR observations have been assisted by frequent photographs taken by the lead author (Figure 4). Photographic monitoring (with images taken from the same location month-to-month) provide a visual record of changes season-to-season and year-to-year. Following a four-week dry period in July 2014 (part of the sixth growing season), native grasses in substrates closest to sedums (typically in the 3-5 inch range) showed the highest rates of growth and survival on the UGR. This is likely due to the tempering of severe microclimatic conditions; average daily temperatures 5 cm below the surface between July 1 and Aug 31 during 2013 and 2014 were 2.36 to 3.51 C lower where sedums covered sensors S5-S7 (versus S1-S4). For an earlier period, Figure 5 shows high and low air temperatures July 1 to September 30, 2011 while Figure 6 reveals the influence of irrigation and non-irrigation on the UGR (leading to brownout on the west side).

Figure 4. Time sequence photos (looking south) of mid-season growth. Photos by Lee R. Skabelund


July 14, 2009


July 15, 2010


July 22, 2011


July 21, 2012


July 10, 2013


July 19, 2014

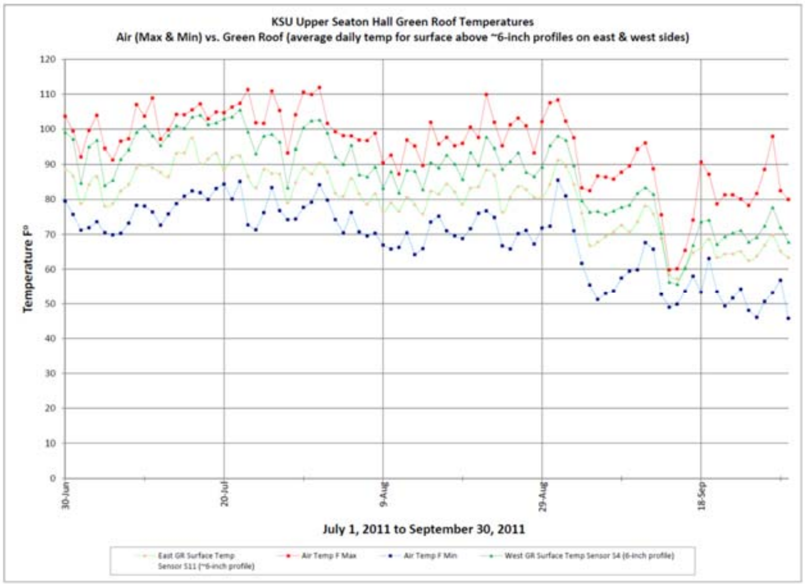


Figure 5. Selected UGR Temperature Data (July to September 2011). Since mid-summer 2011, a surface temperature sensor on the west side typically registered 5-10 degrees warmer (F) than one on the east side due to a general lack of vegetative cover (biomass) in the vicinity of the west side monitor.

Figure 6. Effect of irrigation on green roof vegetation, Aug. 2011. Photo by Lee R. Skabelund. Note that the west (right) side of the UGR did not receive irrigation in 2011.

Discussion of Observations Related to the Three Primary Research Questions

Researchers asked three primary questions related to native plant growth and survival: (1) How well will blue grama and other grasses and forbs survive and thrive over at least a five-year period? Based on observation of visible green above the substrate surface there was an 85.5% survival rate for original blue grama (see Table 2), and a 22% survival rate for other original grasses at the end of five years. Following a four-week dry-spell from July 11 to Aug 5, 2014 there was a much lower survival rate as of mid-October 2014 (16.1% for original blue grama and 0% for the other three taller prairie grasses).

Table 3. Blue grama (*Bouteloua gracilis*) survival (2009-2014)

Year	Number of living blue grama plants*	Survival percentage
2009 mid-summer	62	100%
2010 (mid-October)	62	100%
2011 (late October)	53	85.5%
2012 (mid-November)	53	85.5%
2013 (early November)	53	85.5%
2014 (mid-October)	10 (2 of 10 have seed heads)	16.1%

* number of living plants based on observable green blades above the substrate

During the first two years (2009 and 2010) growing conditions were favorable (given ample precipitation and supplemental irrigation during dry periods. This resulted in nearly 100 percent plant survival. Most grasses exhibited flowering stalks and increased basal diameter. After the first year many new native grasses and forbs grew from seeds produced by the original planting. Prairie coneflower and dotted gayfeather increased between October 2011 and May 2014 (with 67 prairie coneflower observed on July 10, 2012). Recruitment was particularly pronounced in 2010 and 2012 when supplemental irrigation was being provided. Nearly all native forbs were alive in mid-July 2010, however, most of the Jersey tea disappeared by mid-October 2010. In 2011, many of the original forbs disappeared. Many plants were classified as dead following an exceptionally dry summer followed by late summer rains in 2011. Evidence of succession was provided by numerous small plants apparently emerging from seeds or tillers.

Between 2010 and 2011 the number of plants from the original plantings decreased from 130 to 98 for grasses and from 98 to 39 for forbs. At the end of 2012, grasses with visibly-green above-ground biomass remained at 98 while forbs increased to 54. By November 2013, original grasses numbered 68 and forbs 21. In May 2014, original grasses numbered 65 and forbs 25. However, many second-generation plants from seed were present (especially blue grama, side-oats grama, and little bluestem). Species such as common spiderwort and prairie dropseed continued to survive on the Upper Seaton Hall Green Roof through the end of 2013 and into early July 2014. Despite no irrigation on the 10 to 18 cm substrate since mid-August 2012, more than 80 native plants were still alive in mid-October 2014 (refer to Appendix C1 & C2 for photos).

(2) How does green roof substrate depth influence the growth and survival of blue grama and other species? Live native plants (15 native species, including 130 grasses and 98 forbs) were installed on 10.16 cm (4 inch) deep and 17.78 cm (7 inch) deep substrate. Notably, blue grama plants were taller in deeper substrates than in shallower substrates, with 12-18 cm substrates producing plants approximately 10.5 cm taller than 7.5-9 cm substrates. Between 2009 and 2012, 15-18 cm substrates produced blue grama 10.8 cm taller (on average) than those in approximately 10 cm substrates. Nevertheless, after the four-week dry spell July to August 2014, the only visibly-green native plants were those found in shallower soils (either mixed in with or within a meter of hardy sedum varieties) and above water pools held above the root barrier.

(3) What other variables are likely influencing vegetation growth and survival? Overall, irrigated grasses fared much better than unirrigated grasses. Variable climatic conditions influence plant survival. Kansas precipitation occurs at irregular times. Rain events can occur two or more weeks apart. Air temperatures can exceed 43° C (110° F), while substrate surface temperatures can exceed 65° C (150° F) and subsurface temperatures 40° C (105° F). Notably, between July 11 and July 25, 2013 (roughly three weeks), only 0.64 cm (0.25 in.) of precipitation was recorded on the UGR (with volumetric water content in UGR substrates well below 0.1 in July-August 2013 and near 0.05 in July-August 2014—see Appendix B). Between July 11 and August 5, 2014 (roughly four weeks), only 0.23 cm (0.09 in.) of precipitation was recorded on the UGR. Since 2009, many native seedlings generated from seed, but the precise source (naturally falling on the roof or collected from various locations and lightly buried by the project designer year to year) is unknown.

Figure 7. Green roof without Supplemental Irrigation (Aug. 5, 2013; Oct. 21, 2013; May 14, 2014; and Sep. 29, 2014). Despite high temperatures and extended periods without rain (including the three-week dry spell in July 2013), native vegetation survived without any supplemental irrigation. However, following the nearly four-week dry-spell in July and August 2014, minimal regeneration has occurred (as of Oct. 15, 2014).

Photos by Lee R. Skabelund

Conclusions and Future Research Questions

This UGR demonstration project provided an opportunity to observe performance of four species of native grasses and 11 species of native forbs in an above-grade green roof setting.

In arid and semi-arid regions, knowledge about the function and dynamics of particular prairie species and sedums will help to determine the need for and frequency of irrigation for similar drought-tolerant species. Naturally there will be some differences in timing of irrigation due to species types and climatic patterns week to week. Figure 7 shows the resilience of selected sedums and native plants in Manhattan, Kansas.

Although green roofs in arid and semi-arid regions may require irrigation throughout their lifetimes, water efficiency can be significantly increased by adapting green roof designs to the particular regional and micro-climatic conditions. Irrigation requirements can be dramatically reduced by increasing substrate depth (where this is feasible), planting appropriate native and drought adapted species, and applying irrigation techniques best suited for the vegetation and substrate selected. In hot, dry and semi-arid climates, water availability from rainfall and substrate water retention properties should determine both plant and substrate selection. Per Farrell et al. (2012, 276) green roofs created "in seasonally hot and dry climates should be planted with species that have high leaf succulence and low water use to ensure plant survival."

Many bees, insects, butterflies, dragonflies, and birds have been observed on the Upper Seaton Hall green roof between 2009 and 2014. In company with drought-tolerant sedums, using native and drought-tolerant plants that thrive on infrequent precipitation and relatively shallow substrates can provide additional habitat for native birds and insects.

This observational study has raised additional questions about green roof plant survival in the Great Plains region of the United States. The following topics are pertinent for future research: 1) Expand current research in native plant survival in the Great Plains to study larger green roofs with increased numbers of drought tolerant native plants. 2) Expand current research in native plant survival in the Great Plains to study plant polycultures compared to monoculture viability and symbiosis. 3) Study supplemental irrigation timing and quantities, evaluating green roof plant survival under local rainfall conditions with and without supplemental irrigation after different types of plant establishment (live plants/plugs versus seed).

Critical questions that need to be addressed are: 1) What are the critical temperature and wilting point thresholds for specific species of native green roof plants and how are these thresholds influenced by substrate moisture? 2) Is there a relationship between the number of flowering stalks and plant vigor?

Based on observations of the Kansas State University Seaton Hall Upper Green Roof in 2013 and 2014 native grasses can survive and produce seed for self-renewal even after 3-4 weeks of drought. Nevertheless, as revealed by the UGR as well as other green roof research projects, many living roofs in arid and semi-arid hot to temperate climates need to be irrigated to insure essentially full vegetative cover—thus most effectively cooling urban areas and the interior spaces beneath a rooftop (Lambrinos 2014; MacIvor, et al. 2013; Simmons 2014). In the spirit of conclusions drawn by Klett et al. (2012) and MacIvor et al. (2013) it is hypothesized that with modest amounts of well-timed supplemental irrigation full coverage by a mix of grasses, forbs, and succulents on a full-sun green roof in Kansas and other semi-arid and arid regions can occur. It is also surmised that use of native plant seed could prove beneficial for those seeking to create lower-cost and lower resource demanding green roofs in the Great Plains and other regions. Employing non-invasive 'ruderal' or disturbance-tolerant plants could be a helpful strategy for those seeking to create green roofs that use little or no supplemental water and a dynamic ecosystem (Lambrinos 2014).

References:

Cook, C.W and J. Stubbendieck. 1986. "Chapter 3: Methods of Studying Vegetation." *Range Research: Basic Problems and Techniques.* Denver, CO: Society for Range Management. pp. 64-66.

Durhman, A.K., D.B. Rowe, and C.L. Rugh. 2007. "Effect of substrate depth on initial growth, coverage, and survival of 25 succulent green roof plant taxa." *HortScience* 42.3: 588-595.

Dvorak, B. and A. Volder. 2010. "Green Roof Vegetation for North American Ecoregions: A Literature Review." *Landscape and Urban Planning*, 96:197-213.

Farrell, C., R.E. Mitchell, C. Szota, J.P. Rayner and N.S.G. Williams. 2012. Green roofs for hot and dry climates: interacting effects of plant water use, succulence and substrate. *Ecol. Engineering*, 49:270-276.

Klett,J.E., J.M. Bousselot and R.D. Koski. 2012. Evaluation of green roof plants and materials for semi-arid climates. Prepared for USEPA, Office of Research & Development, Cincinnati, Ohio. EPA/6000/R-12-592.

Knapp, A.K., J.M. Briggs, D.C. Hartnett and S.L. Collins. 1998. *Grassland Dynamics: Long term ecological research in tallgrass prairie*. New York: Oxford University Press.

Konza Prairie Biological Station (KPBS). 2014. KPBS Website: http://kpbs.konza.ksu.edu/
KPBS Location and Habitats: http://kpbs.konza.ksu.edu/location.html

Lambrinos, J.G. 2014, in review. "Water through green roofs." In *Green Roof Ecosystems* (Ed. by R. Sutton). London: Springer Science.

MacIvor, J.S., L. Margolis, C.L. Puncher, and B.J. Carver Matthews. 2013. "Decoupling factors affecting plant diversity and cover on extensive green roofs." *Journal of Environmental Management*, 130:297-305.

Simmons, M.T. 2014, in review. "Climates and microclimates: Challenges for extensive green roof design for hot climates." In *Green Roof Ecosystems* (Ed. by R. Sutton). London: Springer Science.

Simmons, M.T., B. Gardiner, S. Windhager and J. Tinsley. 2008. Green roofs are not created equal: the hydrologic and thermal performance of six different extensive green roofs and reflective and non-reflective roofs in a sub-tropical climate. *Urban Ecosystems*, 11: 339-348.

Skabelund, L.R., K. DiGiovanni and O. Starry. 2014, in review. "Monitoring Abiotic Inputs and Outputs." In Green Roof Ecosystems (Ed. by R. Sutton). London: Springer Science.

Sutton, R., J. Harrington, L.R. Skabelund, P. MacDonagh, R. Coffman, and G. Koch. 2012. "Prairie-based Green Roofs: Literature, Templates and Analogs." *Journal of Green Building* 7(1):143-172.

Volder, A. and B. Dvorak. 2014. "Event size, substrate water content and vegetation affect storm water retention efficiency of an un-irrigated extensive green roof system in Central Texas." *Sustainable Cities and Society*, 10:59-64.

Weaver, J.E. 1947. "A Method of Measuring Vigor of Range Grasses." Ecology 28(2):146-162.

Werthmann, C. 2008. "Water and Green Roofs in Dry Climates – A Speculation." Expo Zaragoza 2008.

Williams, N.S.G., J.P. Rayner and K.J. Raynor. 2010. "Green roofs for a wide brown land: Opportunities and barriers for rooftop greening in Australia." *Urban Forestry & Urban Greening*, 9:245-251.

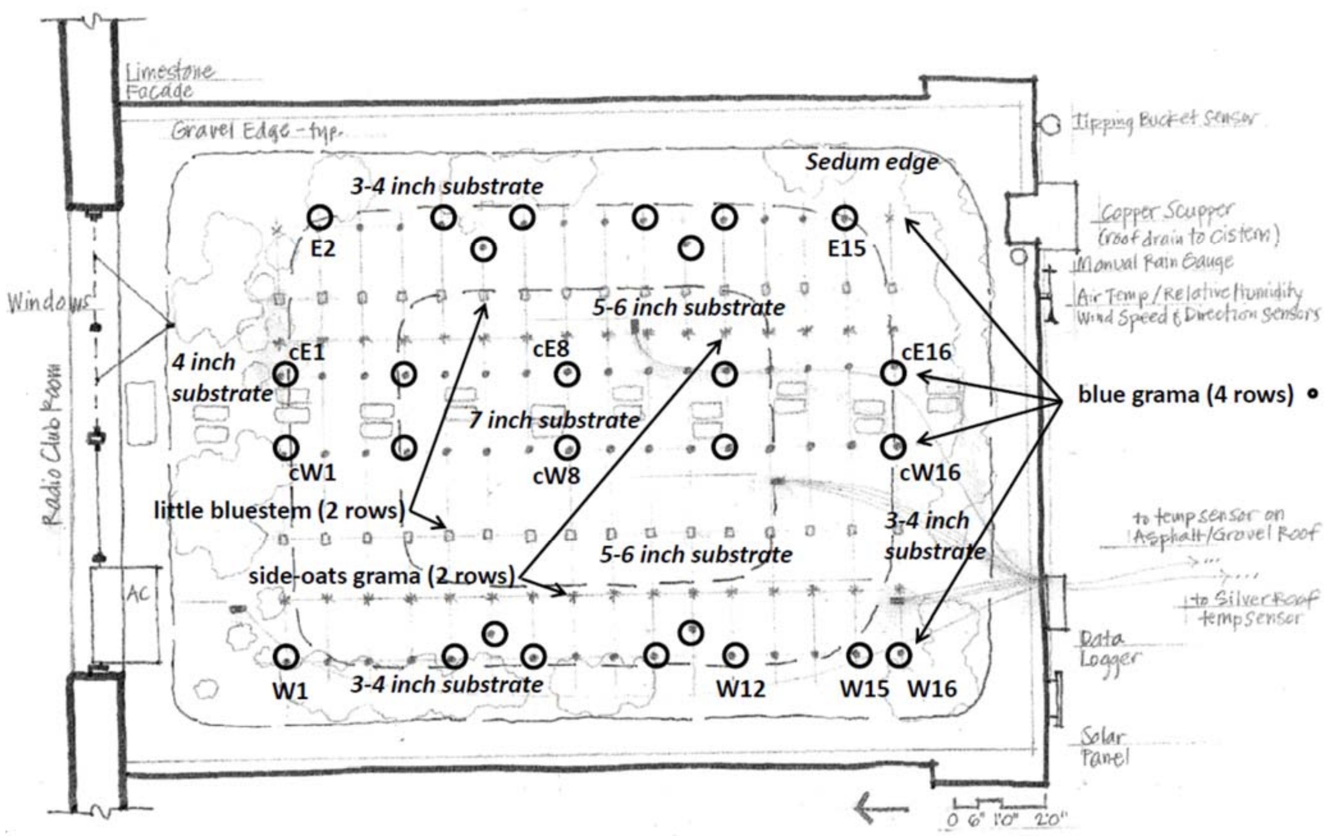
Wu, Y. and D.J. Cosgrove. 2000. "Adaptation of roots to low water potentials by changes in cell wall extensibility and cell wall proteins." *Journal of Experimental Botany*, 15(350): 1543-1553.

Xu, Q. and B. Huang. 2000. Growth and physiological responses of creeping bentgrass to changes in air and soil temperatures. *Crop Science*, 40:1363-1398.

Appendix A: Detailed Data Analysis of 27 Blue Grama Grasses - All original blue grama plants were sampled each year of the study between 2009 and 2014. Preliminary data analysis for 27 blue grama (observed and measured between 2009 and 2012) was completed in November 2012.

Figure A1 (below) indicates the 27 blue grama plants selected for comparative analysis.

Seaton Hall Green Roof – Bouteloua gracilis (Blue Grama) Monitoring (N = 27 plants)



Since seedhead production is vital for plant regeneration and long-term resilience of native plant communities (Knapp 1998; Sutton et al. 2012; MacIvor et al. 2013), the number of flowering stalks in the center rows for the blue grama plants were examined and are presented in Table A1.

Table A1. Plant vigor (or possible stress) as evidenced by number of flowering stalks, 2009-2012.

Plant	No. Flowering Stalks/Year 2009	2010	2011	2012	Soil Depth	Plant	No. Flowering Stalks/Year 2009	2010	2011	2012	Soil Depth
East Side						West Side					
cE1	22	8	8	2	10.16 (4)	cW1	16	6	2	0	10.16 (4)
cE4	15	9	1	0	15.24 (6)	cW4	38	5	10	3	15.24 (6)
cE8	22	3	0	0	17.78 (7)	cW8	46	15	27	22	17.78 (7)
cE12	15	0	0	0	16.51 (6.5)	cW12	37	5	12	6	16.51 (6.5)
cE16	30	2	0	0	10.16 (4)	cW16	46	4	0	0	10.16 (4)

Blue grama plant vigor was sampled by counting the number of seed stalks at the end of the growing season for five years. Plants noted in this table are in the center rows, with the deepest soils being associated with plants labeled 4, 8, and 12 on east and west sides. Plants with the highest numbers are located furthest from the building, thus experiencing more solar radiation and perhaps more wind.

As noted in Table A1, blue grama in center rows of the UGR typically showed decreases in the number of flowering stalks between 2009 and 2012. Declines were observed for 15 of 27 plants between 2010 and 2011. Additionally, blue grama in shallower substrates, were not as tall as those in deeper substrates. Heights increased with greater substrates depths, with an approximately 10 cm height difference between 3 to 3.5-inch (7.6-8.9 cm) and 5 to 7-inch (12.7-17.8 cm) substrate depths.

For the four-year time period, the two blue grama on the shadier, north part of the green roof (cE1 and cW1) grew on average 13.5 cm taller than the two blue grama on the sunnier, south part of the green roof (cE16 and cW16). Comparing these same four plants, east side plants grew on average of five inches taller than west side plants between 2009 and 2011.

Although this sampling of blue grama plants is quite small, this preliminary analysis provides a good sense as to the type of more detailed and more comprehensive analysis that needs to be done when researchers examine all of the data collected in a more probing manner in the coming months.

Seedhead production increased on southwest edge in 2012, however, the plants on the southwest portion of the UGR died in 2013. For center rows on the east side, competition between more tightly spaced plantings and the active growth of many seedlings are the likely cause of the declines in flowering stalks (thus seedhead production) over time. For center rows on the west side plants in 4-inch (10.2 cm) substrates produced far fewer flowering stalks in 2010-2011 as compared to the plants in 6-7-inch (15.25-17.8 cm) substrates. In 2012, further declines in seedhead production were observed for center rows, but there was a slight increase for the west side plants by the end of the growing season in 2013.

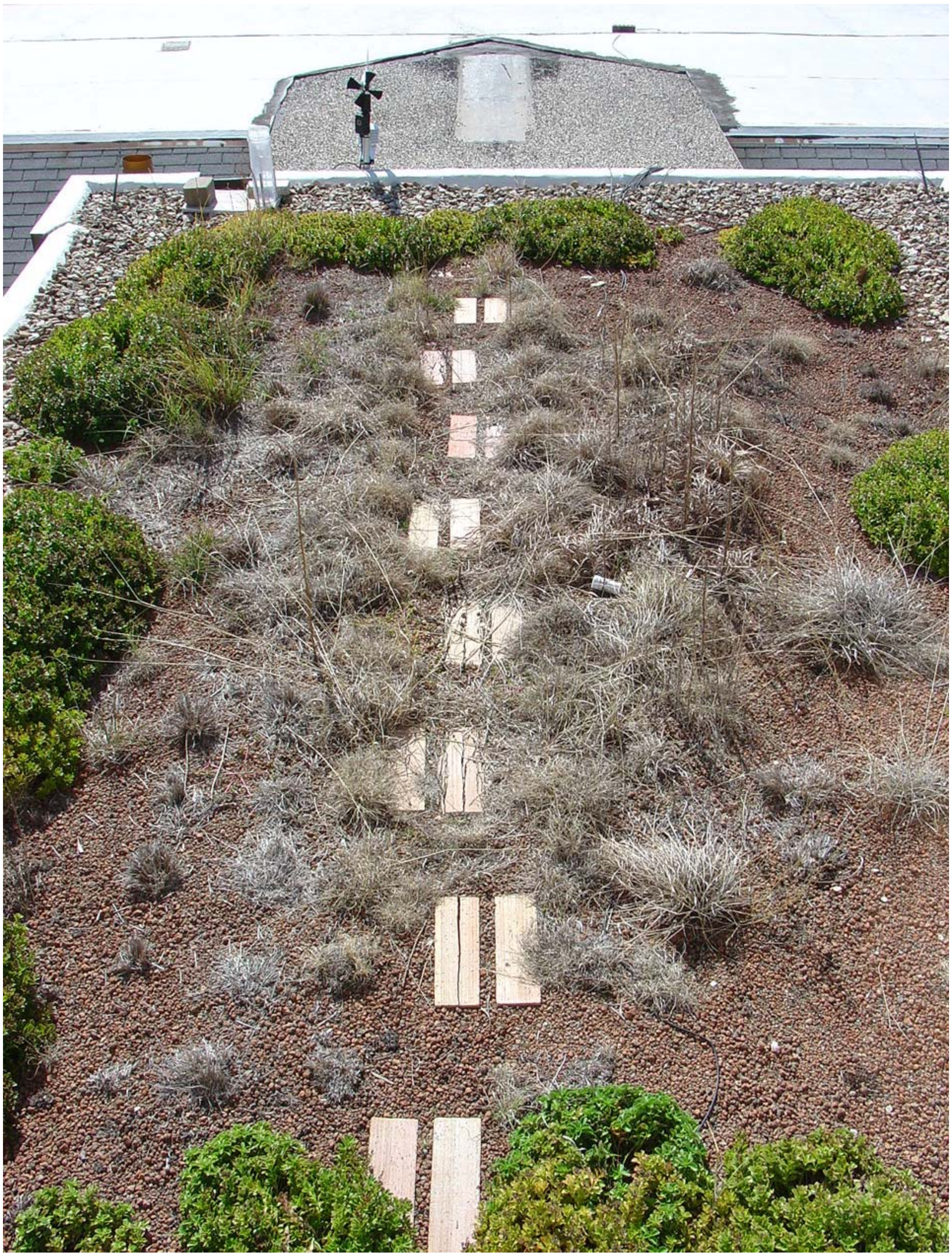
By mid-October 2014 only eight (8) of the original 130 grasses planted on the roof still showed visible green (and all of these were blue grama). What is not yet known is exactly how many of the original plants have actually died since it is possible that some have gone dormant and may show life (visible green about the substrate surface) in the spring of 2015.

Appendix B: General Ranges for Volumetric Water Content (VWC)

Category	***Typical water content (vol/vol)***	***Conditions***
Saturated water content	0.200–0.50	Fully saturated soil, equivalent to effective porosity
Field capacity	0.100–0.35	Soil moisture 2–3 days after a rain or irrigation
Permanent wilting point	0.010–0.25	Minimum soil moisture at which a plant wilts
Residual water content	0.001–0.10	Remaining water at high tension

Note: The average soil moisture conditions during the 2013 and 2014 growing seasons in the center of the KSU Seaton Hall UGR fell into the "permanent wilting point condition" for an extended period of time. This was especially true for the period between July 1 and August 31 each year.

Appendix C1: KSU Seaton Hall Upper Green Roof - October 17, 2014 Photograph – L.R. Skabelund
Two surface sensors are visible in this photograph, two other surface sensors are buried: one by sedums on the southwest corner (upper right of the photo), the other by prairie grass biomass in the center east.



Appendix C2: KSU Seaton Hall Upper Green Roof - October 17, 2014 Photograph Paired with Two Earlier Photographs (taken on October 21, 2013 and October 13, 2012) – L.R. Skabelund

Oct. 17, 2014

Oct. 21, 2013

Oct. 13, 2012