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Catalyzing design-science feedback loop in green roof optimization for hot climates

John Hart Asher[1], Michelle Bertelsen[1], Mark Simmons[1]

[1]*Lady Bird Johnson Wildflower Center, School of Architecture, University of Texas at Austin*

ABSTRACT

Synthetic ecosystems such as rain gardens, green roofs, engineered wetlands and urban meadows are becoming increasingly popular for their intrinsic environmental and ecological benefits as well as for their aesthetic value. But, as in many emerging technologies, communication between the academic institutions generating basic and applied science and the design disciplines is not as efficient as it could be, and strengthening this link will improve the performance of these systems. The case study serves to illustrate the process of linking research, design and implementation. Scientific research, performed by the authors and found in the literature, is used to inform design, and design challenges are used to suggest avenues of research. The research itself is briefly outlined where appropriate, but the focus of this paper is the process of linking science and design in a feedback loop.

Keywords: *performance measures, growing substrate, native plants, sub humid, extensive green roof*

RESEARCH AS THE FIRST STEP

Green, or 'vegetated,' roofs can offer multiple benefits to performance of individual buildings and urban areas. They can cool the building, detain and filter storm water, clean air (reducing low level ozone and particulate matter), reduce the urban heat island effect and increase the lifetime of the roof (Getter and Rowe, 2006). Additionally, in densely developed urban areas, roofs may offer the only viable space to add green infrastructure, which positively impacts the human experience and contribute to urban biodiversity.

However, the research and implementation of green roof technology has been acknowledged by researchers in this field Dvorak and Volder (2010) in North America and Kohler et al (2002) in Germany - to be limited to northern, cool, temperate climates. This apparent oversight is unfortunate because green roof performance could exhibit even greater benefits in hot climates where they can help mitigate sustained high urban temperatures and flash floods which characterize these sub tropical and tropical regions. Many existing 'off-the-shelf' extensive green roof systems and industry standard plant species although successful in cooler regions of North America, are simply not suitable for warmer climates and have been prone to poor performance or even failure.

Carefully researched native plantings *and* growing substrate provide a science-design-implementation approach and green roof example that follows a broader model suggested by Nassauer and Opdam (2008). The green roof example discussed here is located in Austin, Texas (30°11'N. 97°52'W, elevation 247 m mean annual rainfall 870 mm) where sustained high temperatures and sporadic rainfall patterns (Figures 1a and 1b) characterize climactic conditions Its sub humid, subtropical climate with a bimodal rainfall pattern peaks in spring (April—June) and fall (September—October). During the summer months, the average high temperatures range between 87°F in May and 97°F in August. Additionally, nighttime temperatures tend to remain

a **b**

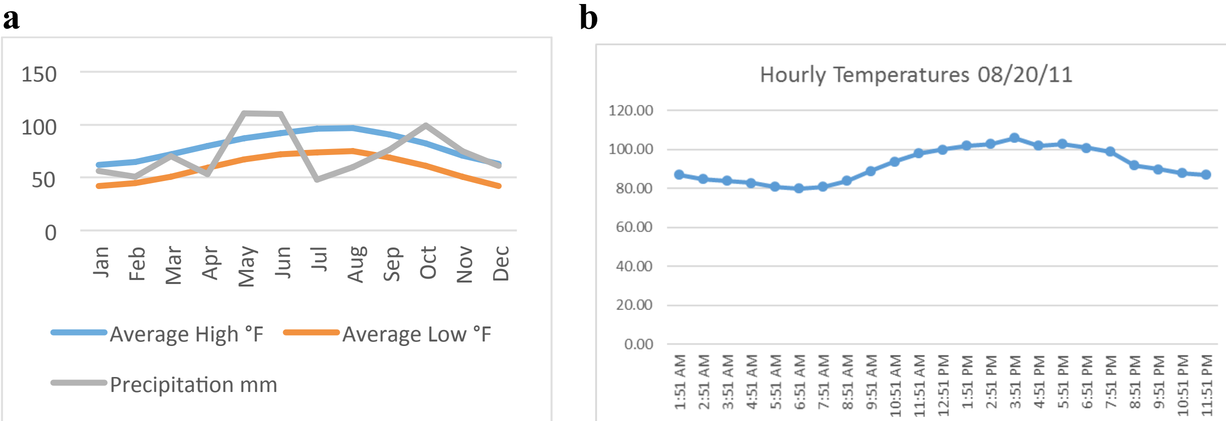

Figure 1a. Average temperature (°F) and precipitation (mm) in Austin, TX, 1981—2010. Source: U.S. Climate Data http://www.usclimatedata.com, 1b. Hourly Temperatures (°F) on 08/20/2011 in Austin Texas. Source: Source: U.S. Climate Data http://www.usclimatedata.com. Nighttime temperatures in the summer often remain above 75° F.

high in the summer months (>75°F) During periods of drought, temperatures range even higher, precipitation levels fall, and the time between precipitation events increases. Understandably, warmer climates pose a number of problems for green roof design due to high air and soil temperatures, sporadic rainfall patterns and high evapotranspiration rates. Since 2005 we have been examining different green roof systems, growing substrates and suitable plants for lightweight, shallow (less than 152 mm deep) extensive green roofs.

First feedback

At the Lady Bird Johnson Wildflower Center (LBJWC) initial research has shown that some green roof designs are not meeting performance expectations. Based on the failure of the vegetation planted on a variety of available media types to thrive or even persist in the harsh summer conditions of Austin, TX (Simmons et al., 2008). Our investigation compared the performance of six extensive green roof designs to reflective and non-reflective roofs in a replicated study. Hydrologic and thermal profile data indicated not only differences between green and non-vegetated roofs, but also among green roof designs. Maximum green roof temperatures were cooler than conventional roofs by 100.4 °F at the roof membrane, and 64.4 °F inside air temperature, with little variation among green roofs. However, maximum run-off retention was 88% and 44% from medium and large rain events, with some green roof types showing limited retention. Initial results indicated that water retention largely depended on green roof layer structure (Figure 2) and potentially upon plant leaf area index (LAI) and transpiration characteristics.

We began to examine the design of green roof from multiple angles. First, we tested suites of alternative prairie species native to multiple Texas ecoregions, consisting of succulents, shrubs, forbs, and grasses, including: Crossvine *(Bignonia capreolata),* Sideoats grama (*Bouteloua curtipendula),* Blue grama (*Bouteloua gracilis),* Texas grama (*Bouteloua rigidiseta),* Buffalograss (*Bouteloua dactyloides),* Texas sedge (*Carex texensis),* Gregg's dalea (*Dalea greggii),* Purple coneflower (*Echinacea purpurea),* Red-flowered yucca (*Hesperaloe parviflora),* Curly mesquite (*Hilaria belangerii),* Spice lily (*Manfreda maculosa),* Mexican feathergrass (*Nassella tenuissima),* Hill Country penstemon (*Penstemon triflorus),* Mealy bluesage (*Salvia farinacea),* White sage (*Salvia greggii),* Wright's skullcap (*Scutellaria wrightii),* Wooly stemodia (*Stemodia lanata),* and Four-nerve daisy (*Tetraneuris scaposa)*. Sutton et al. (2012) had similarly suggested that native prairie species are likely candidates for green roofs due to tolerance of drought, warm soil temperatures and occasional inundation. Two plant guilds emerged as winners, based on plant survival and coverage across roof types, and are currently under further examination:

1. a *native succulent* suite suitable for applications where no supplemental irrigation exists and
2. an *herbaceous suite* - where supplemental water is available (from potable or grey water, HVAC condensate, or rain water).

These plant guild suites had consistent physiological function and help to optimize air quality, thermal performance, and storm water handling by a green roof as well as addressing criticisms of compromised performance. In particular, tolerance to drought, high temperatures, and media

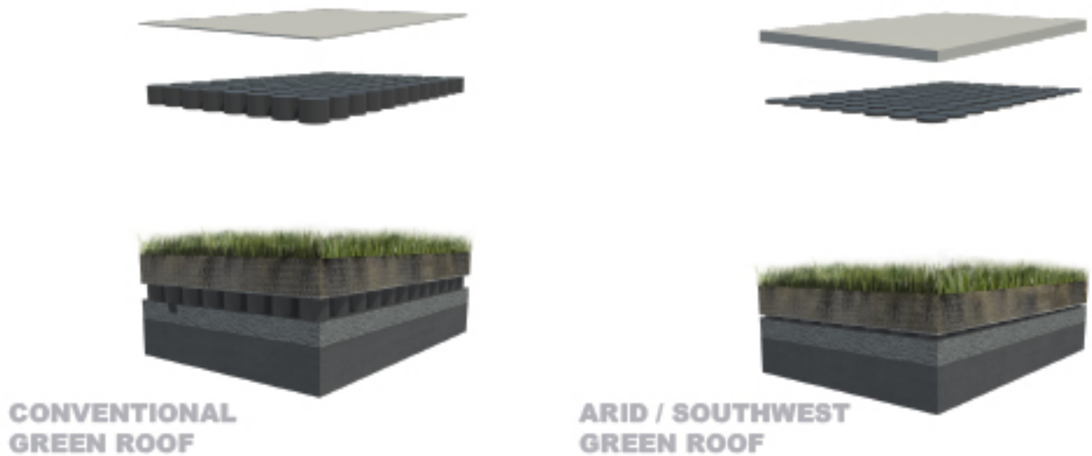

Figure 2. Revision of extensive green roof design for hot climates includes thinner drainage layer to decrease loss of plant available water, removal of root barrier so that water can access retained water. Substitution of retention layer by hydroponic foam to allow access to retained water, use of low embodied energy recycled components.

saturation are important to survivability (Simmons 2015) while traits such as evapotranspiration rate and root biomass play specific roles in thermal and stormwater handling performance (Lundholm & Willliams 2015).

We also examined how the growing media and layer structure of green roofs could be optimized for warmer subtropical or tropical climates. Generally, green roofs are comprised of a protective layer above the roof waterproof membrane, a drainage layer (which may or may not retain storm water), a root barrier or material to separate drainage and growing substrate, a growing substrate, and the plants themselves. Many different materials can comprise substrate including heat-expanded clay or shale, sand, organic material, and perlite among other components tailored to be lightweight, have good water retention and drainage characteristics to support sedum-like succulent plants.

When placed in the climate of Austin, TX, several green roof systems, appeared to have high temperatures which may promote desiccation at the root level. During the summer, we measured critical temperatures above 90°F (severe stress) and above 95°F (death). Roots have reduced function above 90°F and die above 95°F – and in some of the growing media that we tested critical temperatures were easily exceeded during the summer. Several roof types also had thick drainage layers of 60 mm which could potentially form a dry air layer immediately below the roots. Therefore, it was important reduce the size of the drainage layer thickness to reduce warm air below the roots and to increase plant available water in the growing media.

Plant water availability in shallow substrates is critical for survival in drier climates, yet, many commercial systems separate roots from detained water via a root barrier, which works appropriately in a moist climate, but can be less effective in an arid setting. Looking for ways to increase plant available water, we placed several modified profiles under examination which removed the root barrier entirely and decreased the drainage layer above the membrane to less than 6.35 mm Additionally, above this layer we tested a layer of VYDRO® substrate hydrophilic polyurethane foam (Huntsman International LLC) which not only retains liquid water but also accommodates roots to allow hydroponic uptake. Finally, because many commercial green roof products have highly embodied energy footprint we tested media that consists of 100% recycled content (compost, pecan hulls, crushed brick and other materials) that can be sourced locally throughout the continental United States. This patent pending media, SkySystem™, has now been used on multiple projects including the University of Texas' newly constructed Dell Seton Medical Center. Encouraged by exploration of alternative moister, cooler substrates more suitable for this region we applied our research insight to a local residential green roof project.

Continuing the feedback loop - design/build

Bercy Chen Studio, the architects for a proposed residence in Austin, Texas, designed a residence that merged ground and roof planes so that there was a seamless transition between ground surface and the green roof (Figure 3). The Wildflower Center partnered with them, designing the green roof media and plant palette and restored the soil and native plant communities in the surrounding landscape. The roof is 141.73 m^2 (1524 ft^2), with slopes averaging 26º, supports a roof load of 488.24 Kg/m^2 (100 $pound/ft^2$) and is fitted with an above ground drip irrigation system that consists of 4.55 l/hr (.47 g/hr) emitters spaced at 30.5 cm (12") and lines spaced at .46 m (1.5 ft). The goals for the roof were native plant community restoration, water retention, and thermal regulation.

Many native species already existed on site, but we needed greater diversity in order to create the target restored native plant community for both the extensive green roof as well as the surrounding landscape. But the potential plant palette was large - Austin is located at the junction of several ecoregions at the southern end of the Great Plains and is a biodiversity hotspot particularly for prairie species, so we supplemented our known list with those with similar traits to those already tested. Because sterile components essentially comprise a typical green roof growing substrate base, we modified ours to include high quality, fully mature (static piled) compost as well as an inoculum of soil from mature prairie remnants (Kemery and Dana 1995) to encourage the development of soil biota (Harris 2009). The SkySystem™ growing substrate did not utilize specific formulated inoculants. For restored native systems this attention to soil flora and fauna can be crucial. In this project, some of the native later successional plant plugs we included were obligatorily mycorrhizal fungi species, such as big bluestem (*Andropogon gerardii*) Indian grass (*Sorghastrum nutans*), and little bluestem (*Schizachyrium scoparium*) (Tallaksen 1997). These species are characteristic dominant species of Blackland Prairie – which is an endangered ecosystem (from 15 million acres pre-European settlement to only a few thousand acres today) and their restoration on the site could represent the regeneration of an

Figure 3. The Edgeland Residence in Austin allows for native prairie to be a continuum from grade up over the roof.

island ecosystem embedded in an urban matrix. This goal was of particular importance to the client, and he tracked the developing ecology following installation:

"The native flowering plants do more than fill the house and yard with color. They bring a menagerie of butterflies and other insects that attract all sorts of vertebrates that one otherwise rarely sees—frogs and toads who like the moist sanctuary of the roof's undergrowth, small snakes (including at least one coral snake) that feed on the smaller reptiles, squadrons of cliff swallows who devour the flying bugs on summer evenings, all sorts of songbirds rarely seen around here, hawks and owls who read the house as a hill rather than a human den and sometimes swoop right up to the living room window to nab their prey, and even the occasional fox or armadillo."

"[The project] has completely changed my ideas about how the city can develop. I see the immense potential for thinking of the city as ecology. I am confident my experiences could easily be replicated on other roofs and small parcels of land, cultivating wild biodiversity and natural beauty in a way that coexists with urban growth. It's quite a revelation to tangibly experience how new construction can actually add to, rather than diminish, the natural environment, while creating an aesthetically and existentially superior space in which to live."

In order to evaluate the green roof plant community development more objectively, we assessed its cover using the point intercept method on May 2017, 5 years after installation. The assessment revealed a diverse community of 39 species dominated by perennial prairie grasses and forbs (Figure 4a). Sideoats grama (*Bouteloua curtipendula*) is the most widespread grass, with little bluestem locally dominant and forbs such as frogfruit (*Phyla* n*odiflora*) and gaura (*Oenothera* sp.) common (Figure 4b).

The 5 most dominant species account for 48.5% of cover, with the remaining cover comprised of 33 species. Native species comprise 85.8%, with exotics comprising 5.2% of cover and bare ground taking up 9%. The end result is a biodiverse hybrid ecosystem, but like any restored natural system, it is important not to view the plant community as an instant landscape but rather a dynamic successional community that, with proper management, will evolve along a plant composition trajectory that embraces climatic and temporal dynamics thereby increasing sustainability.

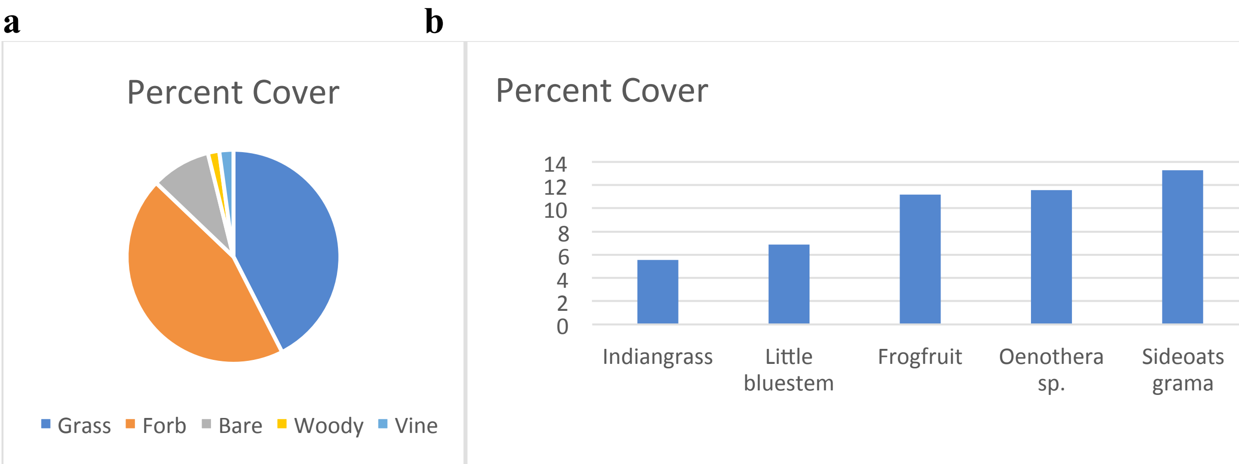

Figure 4: a) Overstory percent cover by life-form . Data taken 05/2017 using the point intercept method. b) Percent cover of five dominant species on the Edgeland Residence in 2017

CONCLUSION

Green roofs have several dynamic and interdependent parts and implicit performance characteristics cannot be assumed, but must be stated as goals for which the roof can be designed. As green roofs become more accepted as important part of sustainable urban landscapes across North America, regional constraints of climate and plant palette will likely encourage the industry to demand more definitive research to help guarantee success. From the design perspective, what is most important is identifying the performance goals for synthetic ecosystems before designing them. Framing the design decisions based on the limitations of a given structure or merely for aesthetics is not optimal. Scientific examination of native landscapes is essential to identify potential function. Furthermore, using native plants to solve the challenge of designing green roofs that will thrive in semi-arid conditions also helps create a vernacular visual language that celebrates a sense of place.

A strong feedback loop between research, design, and implementation can facilitate a meaningful dialogue between our living spaces and natural environments and will allow us to explore the issue of restoring ecosystem performance in urban areas. Ideally, information transfer between industry and research institutions will improve the design of green roofs with regional constraints of climate and plant palettes taken into consideration. If this protocol is further developed, and developed regionally, the future for enhanced ecosystem function in any climate is very promising.

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