PRAIRIE-BASED GREEN ROOFS: LITERATURE, TEMPLATES, AND ANALOGS

Richard K. Sutton,[a] John A. Harrington,[b] Lee Skabelund,[c] Peter MacDonagh,[d]
Reid R. Coffman,[e] and Gord Koch[f]

ABSTRACT

Native prairie species have been both promoted and questioned in their ability to serve as vegetative covers for green roofs. The green roof environment with its exposure to intense sun and wind and limited moisture restricts the capacity for a large diversity of species. The result has been, in many cases, a standard, low-diversity mix of Sedum *species often focused on ornament and minimizes the potential for wider environmental benefits. We reviewed the ecological literature on prairie and grassland communities with specific reference to habitat templates from stressed environmental conditions and examined analogs of prairie-based vegetation on twenty-one existing green roofs. We found that many, but not all prairie and grassland species will survive and thrive on green roofs, especially when irrigated as needed or given adequate growing medium depth. We raise several important questions about media, irrigation, temperature, biodiversity and their interactions needing more study.*

KEYWORDS

extensive, semi-intensive, green roof, habitat templates, prairie plants

INTRODUCTION

A green roof, also called an eco-roof, consists of a multi-layered roof topped with a specified engineered media planted to living vegetation. Green roof construction as a sustainable element of the built environment is a relatively new and interdisciplinary practice in North America. Because of weight limitations and lower costs designers often choose the shallow extensive or semi-intensive type green roofs (Table 1) with media depths of 8–20 cm (3–8 in). Green roof benefits include detaining and delaying stormwater runoff (Moran and Hunt 2005, Mentens et al. 2006, Carter and Jackson 2007, Stovin 2009), reducing energy loads for

[a]UN-Lincoln, Department of Agronomy and Horticulture and the Program in Landscape Architecture, 279 Plant Sciences, Lincoln, NE, USA 68583-0915, 402-472-1127, rsutton1@unl.edu (Corresponding Author).
[b]UW-Madison 25 Agricultural Hall, 1450 Linden Drive, Madison, WI, USA, 54706, jaharrin@wisc.edu.
[c]Kansas State University, Department of Landscape Architecture and Regional and Community Planning, 3031 Seaton Hall, Manhattan, KS, USA, 66502, lskab@k-state.edu.
[d]Kestrel Design Group, 7101 Ohms Lane, Minneapolis, MN 55439 USA, pmacdonagh@tkdg.net.
[e]University of Oklahoma, Division of Landscape Architecture, 830 Van Vleet Oval, Room 162 Norman, OK 73019-6141, rrcoffman@ou.edu.
[f]Olds College, Environmental Horticulture: Landscape Management, 4500 50th Street, Olds, AB, Canada T4H 1R6, gkoch@oldscollege.ca.

TABLE 1. Green Roof Types, Substrate Depths and Weights (adapted from GRHC 2006).

	Depth	Weight[a]
Extensive	7.5 to 15 cm (3–6 in)	98–195 kg/m^2 (20 to 40 lbs/ft^2)
Semi-intensive	10 to 20 cm (4–8 in)	122 to 244 kg/m^2 (25 to 50 lbs/ft^2)
Intensive	> 15 cm (6 in)	> 195 kg/m^2 (> 40 lbs/ft^2)

[a] Substrate weight varies with depth and physical makeup

heating and cooling (Simmons et al. 2008, Chen and Williams 2009), extending roof membrane life (USEPA 2000), attenuating noise (Connelly and Hodgson 2008), and protecting and increasing local biodiversity (Brenneisen 2006, Dunster 2010). Many questions remain, however, about the more complex and diverse system of media and plants on green roofs.

Based on research at the time, Getter and Rowe (2006) concluded that green roofs provided numerous environmental benefits, but that additional research was needed. Five years later a number of research studies and reviews have been published (e.g., Oberndorfer et al. 2007, Beck 2010, Dvorak and Volder 2010, Hodgson 2010, Lundholm et al. 2010, Rugh 2010). But these, too, asked for additional research. For example, Dvorak and Volder (2010) reviewed green roof implementation policies and building codes, and evaluated both ecological and horticultural approaches for assembling, planting and maintaining green roof plants. They concluded, and we concur, that drought tolerant native and introduced herbaceous plants can be effectively used on green roofs, but that these may be best suited on deeper substrates with some provision for irrigation. More research is needed to determine specific species success and under what specific green roof environmental parameters.

This review has particular interest in prairie and grassland ecosystems because a number of extensive and semi-intensive green roof plantings have successfully utilized species from those ecosystems. We describe and delimit the efficacy of the prairie and its grassland flora as a large background ecosystem within which occur local "habitat templates" (Southwood 1977, Lundholm 2005), adapted to shallow or droughty soils and other stressed conditions. MacDonagh et al. (2006:2) connect habitat templates to green roofs noting, "An estimated 10,000 years of plant selection have led to a suite of dry plant communities on cliffs, bedrock, eskers, kames, and scree beds that are adapted to harsh growing conditions similar in many ways to conditions found on extensive green roofs: hot, dry, windy environments with shallow, free-draining soil profiles."

BACKGROUND

Green roofs and their modern equivalents were initially pioneered in Germany in the 1980's and 1990's, before their use spread to Switzerland, Scandinavia, and Britain (Peck et al. 1999, Herman 2003). Advanced materials and emerging design and installation techniques coupled with mandates and incentives moved the use of green roofs into the mainstream European market. The green roof industry developed assemblages from rock garden plants, particularly stonecrop (*Sedum* spp.), or from communities found on well-drained higher elevation talus in cool humid environments. *Sedum* spp. became the default standard for the green roof vegetative layer because of their ability to withstand drought and yet display showy flowers. Three-hundred (Bailey 1951) to six-hundred (Snodgrass and Snodgrass 2006) species of *Sedum* grow worldwide in the northern hemisphere.

Although the application of green roofs occurs in geographically varied regions such as Mexico, Greece, Japan, China and Singapore, the plant selections have often been dominated by species of *Sedum* and other hardy succulents that are mostly native to Europe, the Middle East, and western and northern Asia (Snodgrass & Snodgrass 2006). Similarly, North American green roof developers frequently plant green roofs with *Sedum* spp. while ignoring local plant communities. Growing interest in regional flora has led designers in several regions: British Columbia (Connery 2009, Hemstock 2010), Saskatchewan (Ngan 2010), Colorado (Bousselot et al. 2009), and Minnesota (MacDonagh et al. 2006) to explore using admixtures of *Sedum* spp., native forbs, and grasses.

Monterusso et al. (2005) introduced some skepticism in the green roof industry by concluding that native prairie plants from Michigan, particularly grasses, were unable to succeed on extensive green roofs without supplemental irrigation during hot, dry periods. Their study found that after ceasing irrigation during mid-summer, the major growth period for warm-season or C4 grasses, many native species declined relative to *Sedum* spp. The C4-cycle adapts these grasses to dry environments providing for higher rates of CO_2 fixation at higher light intensities and temperatures but with lower transpiration rates. Many grassland forbs have alternative mechanisms for high tolerance to sun, heat and drought including extensive roots and above-and- below-ground water storage organs. The Monterusso et al. study eliminated irrigation during the second year of the study. They did not take into consideration that most prairie grasses and forbs require several years to establish supportive root systems (Schramm 1990). Additionally, Dvorak and Volder (2010) suggest that the 7.5 cm media depth in which Monterusso et al. (2005) planted the prairie grasses was inadequate.

General Growth Characteristics of Green Roof Living Systems

In North America, describing a typical green roof environment for plants becomes difficult because of its numerous, variable, diverse and dynamic environments (Koehler 2003, Dunnett and Kingsbury 2007, Dvorak and Volder 2010). However, several general characteristics are typical of green roof environments and the stressed environments from which prairie templates may arise. Importantly, western shortgrass prairies, like green roofs, have functionally shallow substrate (growing medium) depths and restricted root space because annual precipitation rarely permeates deeply (Lee and Lauenroth 1994), thus allowing an impenetrable hardpan to form (Weaver and Crist 1922). Because substrate makes up the single largest weight factor in both live and saturated dead loads on green roofs, it poses severe restrictions for many plant species (Westbury and Dunnett 2007, Dunnett et al. 2008). Shallow substrate depth reduces roof weight, but holds less water and nutrients and becomes a poor insulator for roots. Coupled with limited soil resources, high insolation and elevated growing season temperatures create an environment that is stressful to many plant species and limits the survival of microbes and invertebrates (Reeder et al. 2001). In addition, high wind exposure (Sutton 2008), may, depending on the design and location of a particular green roof, lead to substrate loss by scouring and increased evapotranspiration (Hadlock 1998, Rezaei et al. 2005). The result is an environment that severely limits the ability of green plants to establish and flourish (Koehler 2003, Lundholm 2005, Dunnett 2006, Snodgrass and McIntyre 2010). An advantage of native grassland plant community templates emerges from the relatively high diversity of species available for planting. Nagase and Dunnett's research on water use of green roof plants (2010:318) emphasized, "A diverse plant mix was more advantageous than a monoculture in terms of greater survivability and higher visual rating under dry conditions."

Irrigation also allows a wider range of plants to grow successfully on hot, dry, windy green roof sites, but does represent an additional initial capital expense and ongoing resource cost for water (Koehler 2009) and one that plants can come to depend on. Assuming that minimized water use is a goal for prairie-based green roofs, water conservation strategies for green roof applications include: (1) storing and recycling excess runoff as irrigation, (2) using irrigation only during establishment and dry spells, (3) using subsurface drip irrigation or carefully timed spray irrigation thus reducing evaporative loss, (4) incorporating hydrophilic gels, (5) using moisture monitoring sensors to control irrigation, and (6) planting into a deeper medium with more moisture storage. Green roof plantings will grow following all these strategies (Koehler 2009), though incorporation of gels alone may not be enough for native species to thrive on green roofs (Sutton 2008).

Fertility also has significant influence on plant establishment and growth. Like shallow soils, the shallow growing medium on green roofs does not maintain its levels of nutrients over time (Emilsson 2006, Emilsson 2008). Media, designed with a fraction of compost, leach significant nitrogen and phosphorous as well as organics found in humic acid during the first years after planting (Hunt et al. 2006, Berghage et al. 2007, Oberndorfer et al. 2007, Beck 2010) restricting the use of species on extensive green roofs to those that efficiently capture and hold nutrients.

Plant roots are very sensitive to temperature both directly (Boivin et al. 2001) and indirectly through effects on water transfer. Roots are highly sensitive to temperature changes, but soils can be an excellent insulator protecting roots from rapid heating and cooling, particularly in northern winter and high elevation desert climates. Although species specific, the growth and water uptake of plant roots becomes less efficient and may cease when soil temperature climbs above 25°C. With little shade and litter to protect the media surface the growing media temperatures on green roofs can, for example, exceed 35°C in Texas summers (Simmons et al. 2008).

METHODS USED IN THIS REVIEW

We examined the concept of prairie plantings for green roofs in three separate, but related ways. First, we surveyed pertinent prairie and grassland literature for an overview of such ecosystems beginning with research syntheses (e.g., *The True Prairie Ecosystem* (Risser et al. 1981) and *Ecology of the Shortgrass Steppe* (Lauenroth and Burke 2008)). Second, within such research literature we explored specific stressed templates (e.g. the shortgrass, midgrass and tallgrass prairie environments) for both constituent species and those species' community and ecological relationships. Importantly, although a plant trial roof has been planted at the Chicago Botanical Garden to examine many native prairie and grassland species, (CBG 2010), no replicated research green roofs featuring those plants exists across North America. Thus, the best available information about prairie and grassland plantings comes from examining established green roofs albeit ones with differing, ages, media, irrigation, and planting regimes. Many existing green roofs have published species lists consisting of what was planted; most have not published lists of plants that failed overtime.

Third, through published accounts (e.g., Peck 2008), web databases (e. g., www.greenroofs.com) and formal academic and informal industry networks, the authors identified nearly two-dozen, non-residential green roofs successfully using prairie or grassland plants. Although still not common, descriptions of green roof plantings published in proceedings or journals have been increasing in recent years. For some of the included projects, we contacted roof designers or researchers for more detailed information about a green roof's age, irrigation regime, medium depth, prairie analog (if any) used, and species planted. We were able to obtain survival information for only a small number of roofs. This did not allow reasonable cross roof comparisons so that information was not included.

While the native plant use we have cited comes from a large region of North America, we have attempted to synthesize a ranked species list by the number of times each was used by green roof designers based on the roofs we examined. While such a ranked species list gauges potential plant usability, it must be repeated that the lists were of initially planted species only, do not indicate the number of specimens per species planted on any one roof, and do not account for plant vigor or survival. At least one small green roof in Kansas has systematically documented plant survival and plant growth over three growing seasons, and this research is expected to continue for at least several more years (Skabelund 2011).

The review of literature about prairie and grassland templates, and green roof case studies then led us to propose a series of needed research studies to test the selection, installation and ongoing viability of prairie and grassland plants on green roofs; we also speculate on less supported or well understood findings that also need study.

ECOLOGY OF NORTH AMERICAN PRAIRIES/GRASSLANDS

Globally, grasslands occur in open, humid, sub-humid and arid and semi-arid environments typical of continental interiors except Europe and Antarctica. Adapted to grazing, fire and low, or negative water balance, grasslands compose approximately one-quarter of the world's landcover. Negative water balance occurs when more available water for plant uptake is lost yearly through evapotranspiration than falls as yearly precipitation.

Changnon et al. (2002) suggest that four climate extremes explain the existence of the North American tallgrass prairie: (1) occasional severe droughts, (2) frequent dry, cold seasons, (3) reduced evapotranspiration rates, and (4) fire, abetted by the previous three. Clark et al. (2002) and Hayes et al. (2005) would add the occurrence of well to excessively drained soils and high solar exposure and wind exposure to these characteristics. North American grasslands' environments have numerous similarities to that of green roofs, particularly the combination of high exposure to wind and sun, limited and erratic precipitation, low humidity, high evapotranspiration rates, and frequent drought-like conditions. Soil depth and fire, particularly that of the eastern tallgrass prairie, however, are two differences between the green roof environment and grassland environments.

The major North American grassland or prairie ecosystem (Figure 1) ranges from Canada to Mexico and the Rockies to the Ohio Valley and sub-divides into three narrow bands running north to south. These bands developed with wind and precipitation patterns, along a predominately west to east moisture gradient and north to south temperature gradient (Riser et al. 1981, Cochrane and Iltis 2009). The far western band composed of shortgrass prairie, steppes (Lauenroth and Burke 2008), and barrens (i.e., stressed communities on shallow soil) of the western grassland can be conceptualized as habitat templates (Southwood 1977) similar

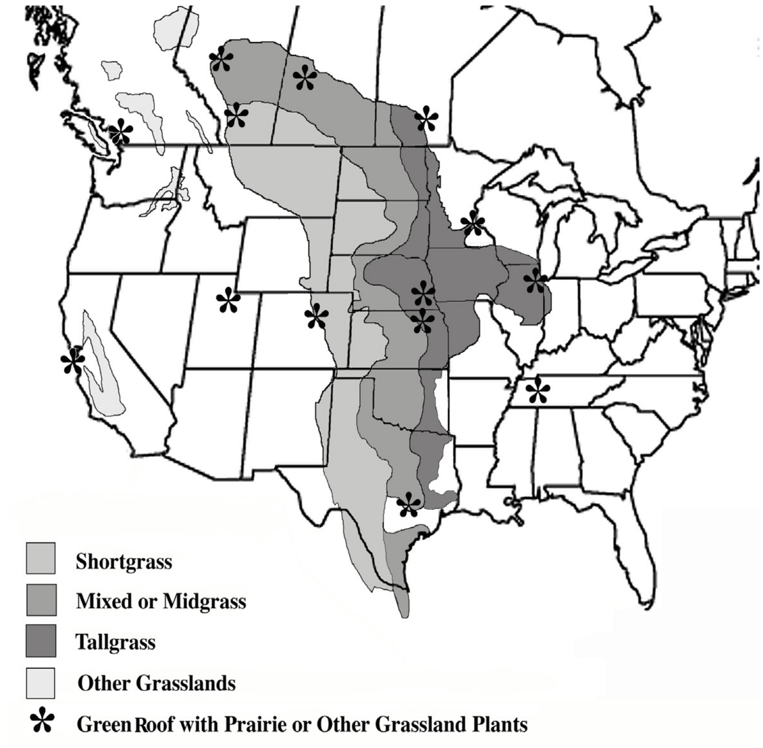

FIGURE 1. Map of North America showing extent of native grassland coverage and locations of reviewed analog green roofs with prairie or grassland plants.

to green roof conditions (Lundholm 2005). They offer likely sources of green roof plants (Dunnett and Kingsbury 2007, Oberndorfer et al. 2007, Sutton 2008).

East of the above band, and within the bands of mixed grass and tallgrass prairies, lay additional xeric communities, barrens with shallow or sandy soils, steep calcareous bluffs (Wovcha et al. 1995), sand prairies (White and Glenn-Lewin 1984), limestone prairies and glades (Quarterman 1950, Hutchinson 1994), and inland dunes consisting of thin soils with minimal organic matter limiting moisture retention and nutrients. These xeric environments possess relatively high species affinities with the drier mixed and shortgrass prairies to the west (Cochrane and Iltis 2000) and should be explored as potential habitat templates containing plant candidates for extensive and semi-intensive green roofs.

The Rooting Network of the Prairie

Rooting networks of prairie species, often described as deep and dense, have led green roof designers and plant growers to question the ability of these species to survive on extensive or semi-intensive green roofs (Snodgrass and Snodgrass 2006). Indeed, many forb species form large taproots that extend several feet into the soil substrate. Similarly, many grasses have a large fibrous network of roots that reach depths of one to two meters and rhizomes that extend horizontally for a meter or more. However, many prairie species root less deeply, and deep-growing roots, such as tap roots, have been observed to adapt to shallow soils by growing horizontally. Prairieclovers (*Dalea candida* and *D. purpurea)* have large taproots that have grown laterally at both the Pioneer Nature Center in Lincoln, Nebraska and the Chicago City Hall (Sutton 2010). Similar horizontal orientation developed for several grasses and forbs (*Carex bicknellii*, *Sporobolus heterolepis*, *Schizachyrium scoparium*, and *Potentilla simplex*) on a small, private extensive green roof in Ann Arbor, Michigan, as observed by Robert Grese (2008).

The root systems of many prairie species appear to be adapted to growing in a diversity of soil depths and to occasional disturbance (Reeder et al. 2001). In the shortgrass prairie Gill et al. (2002) found root production greatest in the top 20 centimeters of soil and Coffin and Lauenroth (1991) noted that the majority of blue grama (*Bouteloua gracilis*) roots grew within five centimeters of the soil surface and no deeper than ten centimeters. Fair et al. (2001) concluded in shortgrass prairie that removal of up to 90 percent of the tillers in blue grama (*Bouteloua gracilis*) did not kill the plant and such disturbance did not diminish a plant's ability to spread. Coffin and Lauenroth (1992) conclude seedling recruitment appeared inconsequential in maintaining blue grama (*Bouteloua gracilis*) dominance, but was critical for colonizing bare areas. Sutton (2010) has observed a similar process for hairy grama (*Bouteloua hirsuta*) and side-oats grama (*Bouteloua curtipendula*) on the Pioneers Park Nature Center green roof.

The majority of grassland biomass occurs in the root system and not above ground (Reeder et al. 2001). During the first and second year of establishment, much of a prairie plant's resources are directed toward developing an extensive root system-horizontally, vertically or both. Root systems respond less rapidly to annual precipitation variation than aboveground biomass; the aboveground:belowground biomass ratios are generally smaller during dry periods (Milchunas and Lauenroth 2001). The energy allocation to building a strong rooting network characterizes many prairie species and allows them to survive periods of inhospitable weather and limited resources.

Establishing a vigorous rooting network is critical to maintaining prairie species in rooftop plantings. Plugs or seedings are often used for the initial planting of prairie perennials; and, unlike annuals that are dependent on seed production, it is the roots and tillers that are important for regeneration and the continued presence of most prairie perennials. The green roof plant studies conducted in preparation for a new prairie-based green roof at the Botanical Research Institute of Texas utilized native soil that contained many annual seeds which led to establishment of a large number of annuals, but few perennials (Kinder 2010). Many species require a stable moisture regime and temperatures for seeds to germinate and seedlings to successfully establish (Briske and Wilson 1976, Briske and Wilson 1978, Briske and Wilson 1980). Environmental variability can leave these requirements unsatisfied, thus increasing the importance of species' vegetative growth. However, restorations and new plantings of prairie frequently and successfully use both seeds and plugs (Harrington 1994).

Breakdown of minerals adds small amounts of nitrogen and phosphorous each year to the prairie ecosystem, but the bulk of those nutrients come from the decomposition and recycling of organic matter (Risser et al. 1981, Lauenroth and Burke 2008). Grass roots have an annual turnover of one-third or more of their root mass, becoming a source for much of the belowground carbon (Reeder et al. 2001). Nitrogen arrives from rainfall (Fisher and Oppenhiemer 1991) and is fixed by many legume roots (Blair et al. 1998, Knops and Tilman 2000). Soil microbial webs, pathways, and communities also play major roles in the mineralization of key nutrients (Ransom et al. 1998). Complex webs of bacteria, fungi and nematodes directly reduce detritus and in turn, become available in the microbial food chain (Hunt et al. 1987). In semi-arid environments soil moisture is the key variable that controls the size of microorganisms' populations and thus rate of organic matter breakdown (Austin et al. 2004).

Besides the breakdown of organic matter, many perennials' root systems interact with soil organisms to enhance nutrient uptake. Mycorrhizal fungi play a unique and significant role within the microbial community by way of their symbiotic connection with roots of many grasses (Smith et al. 1998). In this symbiotic relationship, mycorrhizae utilize sugars from fine roots, but also extend and increase the host's access to moisture and nutrients, particularly phosphorous. Allen et al. (1981), for example, found that for blue grama (*Bouteloua gracilis*) infected with arbuscular mycorrhizae (AM) transpiration rates increased 100 percent and leaf resistance to water vapor diffusion was reduced. They concluded, "AM-induced physiological changes could substantially alter survivability of blue grama."

Resource Strategies Provide for High Diversity

Minimal water storage in green roof media, exposure to winds that desiccate and carry abrasive materials and intense sunlight are limiting factors for selecting species to plant on green roofs. Plant density in the prairie can reach 80 individuals representing many different species per square meter or higher because of the variety of strategies species have for obtaining scarce resources and limiting competition (Tilman 1997), many of which are applicable to the green roof environment. Such high species diversity often provides for resilience in plantings to weather extremes as well as disease (Mitchell and Tilman 2002) and insect outbreaks that could otherwise be decimating. Drought-like conditions are common to prairies and its flora has adapted by (1) temporal structuring of growth in the C3 and C4 photosynthetic pathways, (2) avoidance and dormancy, primarily by annuals, biennials and C3 grasses, through depositing seeds into soil seedbanks (Coffin and Lauenroth 1992), (3) wide-spreading root systems able to absorb small rainfall events and a quick activation of physiological process (Weaver 1968, Sala et al. 1981, Sala and Lauenroth 1982), and, (4) the ability of many native grasses to form symbiotic liaisons with mycorrhizal fungi greatly extending their moisture absorption capabilities (Allen et al. 1981). Prairie species also have a broad range of morphological adaptations that appear to aid their ability to survive and thrive in these hot and dry environments i.e., narrow erect leafs, pubescence on stems and/or leaves, deep stomata, and above-and-below-ground water storage organs (Curtis 1959, MacDonagh et al. 2006). Grasslands are also composed of many species that can exist along a wide moisture gradient from dry to wet and respond with broad amplitudes to soil properties such as pH, fertility, texture and depth.

Another resource strategy is temporal stratification (life cycles, emergence, blooming and fruiting periods). The C3 and C4 physiology of the grasses are particularly good examples of temporal stratification. The physiology of C4 grasses supports tolerance to hot and dry environments and have their greatest growth and flowering in summer. The native C3 grasses, though supporting a different photosynthetic pathway, are morphologically adapted to this dry environment with hairs, erect and in-rolled leaves and the ability to proceed into dormancy during hot dry periods. These species, in particular, are prominent in spring prior to major growth by the warm season grasses.

Biodiversity

Grasses and sedges cover more than fifty percent of the North America grasslands, but the balance intermixes with forb or herbaceous broadleaf species (Curtis, 1959). This ecosystem supports high species diversity and many diverse species closely coexist (Tilman and Downing 1994). Prairie plant communities are rarely monospecific or monogeneric, but contain multiple species and guilds of species cohabitating spatially and temporally. Such multiple ecological niches therefore support high species richness and stability (Tilman et al. 1996), but also facilitate higher resource efficiency and nutrient sequestration through complementarities among species. (Cardinale et al. 2011).

In addition to the vast diversity in plants, prairies and grasslands also attract and support many native animals, invertebrates, and microbes. This biodiversity can also be measured by the interactions among its constituents where a full range of activities such as competition, predation, mutualism, and facilitation occur.

In designed green roofs, abiotic factors such as topography and soil properties influence plant and animal diversity. For example, Brenneisen (2003) recorded greater vegetation, beetle, spider and bird diversity on roofs containing micro-topography, or small surface undulations than those that possessing uniform slopes. In addition, large diameter stones and woody debris aided recruitment of invertebrates. In this study, he observed a relationship between plant structure and faunal recruitment, where tunnel and ground dwelling spiders were common to uniformly sloped green roofs, yet in topographically diverse roofs biodiversity increased as orb weaving spiders cast webs between vertical leafs and stems. While earthworms commonly inhabit prairies and contribute to soil nutrient recycling (James and Seastedt, 1986) severe winter freezing excludes their survival and presence on extensive and semi-intensive green roofs. Understanding natural processes in the regeneration and establishment of species has been important to successful restoration projects. Similarly, exploring how to introduce species to green roofs by mimicking natural processes may be necessary for success in establish certain species complexes on green roofs. Facilitation, or the change in habitat that provides opportunities for new species to colonize or establish on a site, is one concept that could potentially increase potential species for green roof plantings. Facilitation is often the result of colonizing species altering an environment in a way that allows other species to colonize. For example, in sand barrens colonizing an open, hot and dry landscape can be difficult for higher-level plants. Successful colonization by pioneering grasses and cryptogams may facilitate the later colonization of more stable plant communities (Suss et al. 2004). Sutton (2010) observed that shade and calm on the PPNC green roof created by the forb canopies under asters (*Aster* spp.), prairieclovers (*Dalea* spp.), and sages (*Artemisia* spp.) recruited and nursed grama (*Bouteloua* spp.) seedlings. Similarly, Skabelund (2011) observed that shade and calm conditions under grasses, especially little bluestem (*Schizachyrium scoparium)* recruit and nurse asters (*Aster* spp.) and allowing spiderwort (*Tradescantia ohioensis)* to survive on an infrequently irrigated roof.

Application to Green Roofs

Prairie and grassland ecosystems contain a widely diverse suite of species that adapt to and integrate across the low resource or stressed environments found in central North America. It would be neither possible nor desirable to completely reconstruct the prairie community outlined above on green roofs. However, the potential exists to adopt media admixtures, plant selection palettes, and installation techniques that allow regional, anthropogenic analogs to mimic stressed habitats found within the prairie. The potential also exists to move these prairie-based habitat templates beyond their region for use on green roofs in more temperate areas such as the eastern deciduous forest. Numerous examples, summarized below, of prairie templates being used on green roofs exist. However, most are rather recent and few have been tested over a decade or more of environmental conditions.

EXISTING PRAIRIE/GRASSLAND GREEN ROOF CASE STUDIES

Twenty-one planted green roofs from across Central and northern North America (Figure 1) were reviewed as case studies and placed in one of three categories: (1) Prairie-region Green Roofs Utilizing Native Plants (2) Prairie-region Green Roofs Utilizing Native Plants Intermixed

TABLE 2. Summary of Characteristics for Twenty-one Green Roof Case Studies.

	Table 3	Table 4	Table 5	
	Prairie-region Green Roofs Using Native Prairie Plants	Prairie-region Green Roofs Utilizing Native Plants Intermixed w/ Sedums or Exotics	Other Green Roofs Utilizing Native Grassland Plants	**Total**
Locations	AB to NE to IL	AB to CO to IL	BC to TN to CA	
Irrigated Regularly	4	6	6	16
Irrigated as Needed	5	0		5
Total				21
Green Roof Type				
Extensive	4	2	3	9
Semi-intensive	5	4	2	11
Intensive	0	0	1	1
Total				21

with Sedums or Exotics and (3) Other Green Roofs Utilizing Native Grassland Plants. For a summary of case studies and associated parameters see Table 2.

Nine prairie-region green roof analogs (Table 3) included four that are regularly irrigated and four that grow on extensive media depths. All were located in prairie eco-regions from Texas to Alberta and Nebraska to Illinois.

Six green roof case studies consisted of native and grassland plants intermixed with *Sedums* or exotic perennials (Table 4); all had regular irrigation and were widely distributed from Alberta to Colorado, to Illinois; two occur on extensive and four on semi-intensive media.

Six green roof case studies utilized other grassland plants (Table 5). Of those, three occupy and extensive, two a semi-intensive and one an intensive green roofs. Three regularly irrigated green roofs grew in locations from British Columbia to Tennessee to California. Although they occur outside the prairie eco-region, those in California and coastal British Columbia utilized local grassland templates.

Species List

We examined the species lists for the case study roofs and assembled a ranked species list of those grasses or grass-like plants and forbs used on prairie and grassland based green roofs (Tables 6 and 7). There were forty-two graminoids (grass or grass-like plants) used with five grasses (*Bouteloua curtipendula, Bouteloua gracilis, Schizachyrium scoparium, Sporobolus heterolepis* and *Koeleria macrantha*) used most widely, occurring as natural members of all prairie types in the Upper Midwest. Two-thirds of the graminoids were used on only one case study roof each. *Dalea purpurea, Geum triflorum* and *Allium cernuum* were the most widely used forbs yet almost three-fifths of the forbs were used on only one case study each.

TABLE 3. Prairie-region Green Roofs Using Native Plants.

Analog & Location	Planted	Ecosystem Context	Template Used	Irrigated	Medium Depth
Eco-enterprise Ctr. Minneapolis, MN	2003	Tallgrass Prairie	Bluff Bedrock Prairie	No	2–6 in (5–15.25 cm)
Native or Grassland Species Grasses or grass-like *Bouteloua curtipendula* *Bouteloua gracilis* *Koeleria macrantha* *Schizachyrium scoparium* *Sporobolus heterolepis* Forbs *Allium stellatum*		Forbs (cont'd) *Anemone patens* *Asclepias verticillata* *Campanula rotundifolia* *Geum trifolium* *Huechera richardsonii* *Liatris aspera* *Opuntia fragilis*		Forbs (cont'd) *Penstemon grandiflorus* *Ruellia humilis* *Sisyrinchium campestre* *Solidago nemoralis* *Symphyotrichum sericeus* *Tradescantia occidentalis* *Viola pedatifida*	
Comments			**References**		
Older, extensive green roof with no ongoing irrigation			MacDonagh et al., 2006; Greenroofs.com project database		
Analog & Location	**Planted**	**Ecosystem Context**	**Template Used**	**Irrigated**	**Medium Depth**
Aquascape HQ St. Charles, IL	2005	Tallgrass Prairie	Tallgrass Prairie	Yes	4–6 in (10–15.25 cm)
Native or Grassland Species Grasses or grass-like *Bouteloua curtipendula* *Carex muhlenbergia* *Carex bicknellii* *Eragrostis spectabilis* *Koeleria cristata* *Panicum leibergi* *Schizachyrium scoparium* *Sporobolus heterolepis* Forbs *Allium cernuum* *Anemone patens* *Anemone cylindrica* *Coreopsis lanceolata*	Forbs (cont'd) *Coreopsis palmata* *Dalea candida* *Dalea purpurea* *Echinacea pallida* *Eryngium yuccifolium* *Fragaria virginiana* *Geum trifolium* *Huechera richardsonii* *Lespedeza capitata* *Liatris aspera* *Liatris cylindracea* *Opuntia humifusa* *Penstemon digitalis* *Penstemon hirsutus*	Forbs (cont'd) *Ratibida pinnata* *Rudbeckia hirta* *Senecio pauperculus* *Solidago ptarmicoides* *Solidago rigida* *Symphyotrichum azureus* *Symphyotrichum ericoides* *Symphyotrichum laevis* *Symphyotrichum pilosus* *Symphyotrichum sericeus* *Teucrium canadense* *Tradescantia ohioensis* *Verbena hastata*			
Comments			**References**		
Sunny prairie			www.greenroofs.com project database; Daniels 2011		

continued

TABLE 3. *(continued)*

Analog & Location	Planted	Ecosystem Context	Template Used	Irrigated	Medium Depth
LBJ Wildflower Center Austin, TX	2005	Mid-grass Prairie	NA	As needed	4 in (10 cm)
Native or Grassland Species Grasses or grass-like *Bouteloua curtipendula* *Bouteloua dactyloides* *Bouteloua gracilis* *Bouteloua rigidiseta*		Grasses *(cont'd)* *Carex texensis* *Muhlenbergia reverchonii* *Muhlenbergia rigens* *Panicum hallii* *Schizachyrium scoparium*		Forbs (cont'd) *Dalea greggii* *Dalea purpurea* *Echinacea purpurea* *Penstemon triflorus* *Phyla nodiflora*	
Comments			**References**		
Research plot; 7–8 in (20cm) per week hand irrigated			Greenroofs.com project; Simmons et al. 2006		
Analog & Location	**Planted**	**Ecosystem Context**	**Template Used**	**Irrigated**	**Medium Depth**
Pioneers Nature Ctr. Lincoln, NE	2007	Tallgrass Prairie	Sand Prairie	As needed	3.5 in (9cm)
Native or Grassland Species Grasses or grass-like *Bouteloua curtipendula* *Bouteloua gracilis* *Bouteloua hirsuta* *Carex bicknellii*		Grasses (Cont'd) *Carex inops* *Muhlenbergia cuspidata* *Schizachyrium scoparium* *Stipa purpurea*		Forbs *Artemisia frigida* *Dalea candida* *Dalea purpurea* *Liatris punctata* *Symphyotrichum oblongifolius* *Tradescantia bracteata*	
Comments			**References**		
Research plots			Sutton, 2008; Dvorak & Volder, 2010		
Analog & Location	**Planted**	**Ecosystem Context**	**Template Used**	**Irrigated**	**Medium Depth**
KSU Seaton Hall Manhattan, KS	2008	Tallgrass Prairie	Flint Hills Prairie	As needed	4–7 in (10–18 cm)
Native or Grassland Species Grasses or grass-like *Bouteloua curtipendula* *Bouteloua gracilis* *Sporobolus heterolepis* *Schizachyrium scoparium* *Sorghastrum nutans*		Forbs *Callirhoe involucrata* *Ceanothus americanus* *Dalea purpurea* *Liatris punctata* *Ratibida columnifera*		Forbs (cont'd) *Ratibida pinnata* *Salvia azurea* *Solidago rigida* *Symphyotrichum laevei* *Tradescantia ohioensis*	
Comments			**References**		
Research plot			www.greenroofs.com database		

Analog & Location	Planted	Ecosystem Context	Template Used	Irrigated	Medium Depth
City Hall Minneapolis, MN	2008	Tallgrass Prairie	Bluff Bedrock Prairie	As needed	4–9 in (10–22.5 cm)
Native or Grassland Species Grasses or grass-like *Bouteloua curtipendula* *Bouteloua gracilis* *Carex gracillima* *Carex pensylvanica* *Carex sprengelii* *Carex vulpinoidea* *Juncus tenuis* *Schizachyrium scoparium* Forbs *Allium stellatum* *Antennaria plataginafolia* *Aquilegia canadensis* *Arctostaphylos uva-ursi*		Forbs (cont'd) *Arisaema triphyllum* *Cassia fasciculata* *Coreopsis palmata* *Dalea purpurea* *Delphinium virescens* *Fragaria virginiana* *Campanula rotundifolia* *Gaultheria procumbens* *Geum trifolium* *Huechera richardsonii* *Hystrix patula* *Liatris aspera* *Liatris cylindracea* *Maianthemum canadense*		Forbs (cont'd) *Penstemon grandiflora* *Phlox divaricata* *Polemonium reptans* *Pulsatilla patens* *Solidago flexicaulis* *Solidago nemoralis* *Symphyotrichum azureus* *Symphyotrichum ericoides* *Symphyotrichum lateriflorus* *Symphyotrichum macrophyllus* *Symphyotrichum sericeus* *Thalictrum dioicum* *Tradescantia ohioensis*	
Comments			**References**		
Sunny and shady prairie plants			Macdonagh 2011		
Analog & Location	**Planted**	**Ecosystem Context**	**Template Used**	**Irrigated**	**Medium Depth**
Tyner Interpretive Ctr. Glenview, IL	2008	Tallgrass Prairie	Tallgrass Prairie	Yes	4–8 in (10–20 cm)
Native or Grassland Species Grasses *Bouteloua curtipendula* *Schizachyrium scoparium* *Sporobolus heterolepis* Forbs *Amorpha canescens* *Allium cernuum* *Artemisia spp.* *Coreopsis lanceolata*	*Dalea purpurea* *Geum trifolium* *Liatris spicata* *Rudbeckia hirta*	Forbs (cont'd) *Solidago canadensis* *Solidago nemoralis* *Symphyotrichum ericoides* *Ratibida pinnata* *Tradescantia ohioenss* *Ruellia humilis*	Forbs (cont'd) *Symphyotrichum novae-angliae* *Verbena stricta*		
			References		
			http://www.eco-structure.com/vegetated-roof/the-evelyn-pease-tyner-interpretive-centerglenview-ill.aspx		

continued

TABLE 3. *(continued)*

Analog & Location	Planted	Ecosystem Context	Template Used	Irrigated	Medium Depth
Chicago Botanical Garden Glencoe, IL	2009	Tallgrass Prairie	N/A	As needed	4–8 in (10–20 cm)
Native or Grassland Species Grasses or Grass-like *Andropogon gerardii* *Bouteloua curtipendula* *Bouteloua gracilis* *Carex radiata* *Eragrostis spectabilis* *Koeleria macrantha* *Sporobolus heterolepis* Forbs *Allium cernuum* *Amorpha canescens* *Amorpha nana* *Anemone caroliniana* *Anemone cylindrica* *Aquilegia canadensis* *Arctostaphylos uva-ursi* *Artemisia caudata* *Artemisia frigida* *Artemisia stelleriana* *Asclepias tuberosa* *Baptisia australis* *Calamintha arkansana* *Callirhoe involucrata* *Campanula rotundifolia* *Campanulastrum americanum* *Cassia fasciculata* *Coreopsis lanceolata* *Dalea candida* *Dalea purpurea* *Dalea villosa*		Forbs (cont'd) *Echinacea pallida* *Echinacea purpurea* *Erigeron caespitosa* *Eryngium yuccifolium* *Fragaria virginiana* *Geum triflorum* *Helianthus mollis* *Heuchera elegans* *Heuchera micrantha* *Heuchera parvifolia* *Heuchera pulchella* *Heuchera abramsii* *Heuchera cylindrica alpina* *Heuchera grossulariifolia* *Heuchera parishii* *Heuchera richardsonii* *Kuhnia eupatorioides* *Lespedeza capitata* *Liatris cylindracea* *Liatris ligulistylis* *Lobelia siphilitica* *Lupinus perennis* *Monarda fistulosa* *Monarda punctata* *Oligoneuron album* *Oenothera macrocarpa* *Opuntia humifusa* *Penstemon digitalis* *Penstemon grandiflorus*		Forbs (cont'd) *Penstemon hirsutus* *Penstemon pachyphyllus* *Penstemon sps.* *Potentilla arguta* *Pulsatilla patens* *Phlox bifida* *Potentilla neumanniana* *Pycnanthemum virginianum* *Ratibida pinnata* *Rudbeckia fulgida* *Rudbeckia hirta* *Ruellia humilis* *Scutellaria resinosa* *Sedum oregonense* *Sisyrinchium albidum* *Symphyotrichum ericoides* *Symphyotrichum laeve* *Symphyotrichum novae-angliae* *Symphyotrichum sericeum* *Symphyotrichum oblongifolium* *Symphyotrichum oolentangiense* *Talinum calycinum* *Tradescantia tharpii* *Verbena stricta* *Viola sagittata* *Shrubs* *Ceanothus americanus* *Rosa carolina*	
Comments			**References**		
Phased-in plots w/ varied 10, 15, and 20 cm media depths			www.Greenroofs.com; Hawke 2011		

Analog & Location	Planted	Ecosystem Context	Template Used	Irrigated	Medium Depth
Williams Eng. Bldg. Edmonton, AB	2010	Moist Mixed Prairie	SE Alberta Dry Prairie	Yes	3–6 in (7.5–15 cm)
Native or Grassland Species Grasses *Bouteloua gracilis* *Festuca saximontana* *Koeleria macrantha* *Muhlenbergia cuspidata*		Forbs *Allium schoenoprasum* *Artemisia* sps. *Astralagus agrestis* *Chrysopsis villosa* *Galium boreale*		Forbs (cont'd) *Liatris ligulistylis* *Linum lewisii* *Penstemon procerus* *Oxytropis deflexa* *Symphyotrichum laeve*	
Comments			**References**		
Research Northern AB Institute of Technology			Nadeau 2011		

TABLE 4. Prairie-region Green Roofs Utilizing Native Plants Intermixed in Sedums or Exotics.

Analog and Location	Planted	Ecosystem Context	Template Used	Irrigated	Medium Depth
City Hall Chicago,IL	2001	Tallgrass Prairie	Tallgrass Prairie	Yes	4–8 in (10–20 cm)
Native or Grassland Species Grasses *Andropogon gerardii* *Sorghastrum nutans* *Bouteloua curtipendula* *Koeleria cristata* *Schizachyrium scoparium* *Sporobolus heterolepis* Forbs *Amorpha canescens* *Allium cernuum* *Anemone canadensis* *Aquilegia canadensis* *Artemisia spp.* *Astragalus canadensis* *Baptisia australis* *Callirhoe invulcrata* *Camassia quamash* *Campanula americana* *Coreopsis lanceolata* *Dalea candida* *Dalea purpurea* *Dodecathon media* *Cassia fasciculata* *Echinacea purpurea*		Forbs (cont'd) *Eschscholzia californica* *Epilobium coloratum* *Eryngium yuccifolium* *Eupatorium maculatum* *Eupatorium perfoliatum* *Fragaria chiloensis* *Gentiana andrewsii* *Geranium sanguineum* *Geum trifolium* *Helianthus mollis* *Heliopsis helianthoides* *Huechera richardsonii* *Hieracium canadense* *Lespedeza capitata* *Liatris aspera* *Liatris spicata* *Lobelia cardinalis* *Lobelia siphilitica* *Monarda fistulosa* *Opuntia humifusa* *Pathenium integrifoilum* *Penstemon grandiflora* *Phlox subulata* Polemonium epetans		Forbs (cont'd) *Potentilla anserina* *Potentilla arguta* *Pulsatilla vulgaris* *Ratibida pinnata* *Rudbeckia hirta* *Rudbeckia triloba* *Rudbeckia subtomentosa* *Ruellia humilis* *Sedum spathulifolium* *Sisyrinchium angustifolium* *Sisyrinchium bellum* *Solidago canadensis* *Solidago nemoralis* *Solidago sempervirens* *Solidago speciosa* *Symphyotrichum albus* *Symphyotrichum ericoides* *Symphyotrichum laevi* *Symphyotrichum novae-angliae* *Talinum calycinum aureum* *Tradescantia ohioenss* *Verbena stricta* *Verbena hastata* *Viola pedata*	
Comments			**References**		
Prairie plants admixed with Sedum exotics			www.greenroofs.com database		

Analog & Location	Planted	Ecosystem Context	Template Used	Irrigated	Medium Depth
Notebaert Museum Chicago, IL	2003	Tallgrass Prairie	Tallgrass Prairie	Yes	4–8 in (10–20 cm)
Native or Grassland Species Grasses *Bouteloua curtipendula* *Bouteloua dactyloides* *Carex bicknellii* *Koeleria macrantha* *Sporobolus heterolepis*		Forbs *Amorpha canescens* *Allium cernuum* *Asclepias tuberosa* *Dalea purpurea* *Geum trifolium* *Liatris aspera* *Phlox bifida* *Phlox pilosa* *Solidago speciosa*			
			References		
			www.GreenAnalogs.com		
Analog & Location	**Planted**	**Ecosystem Context**	**Template Used**	**Irrigated**	**Medium Depth**
Central Library Minneapolis, MN	2005	Tallgrass Prairie		Yes	4–8 in (10–20 cm)
Native or Grassland Species Grasses *Andropogon gerardii* *Bouteloua curtipendula* *Bouteloua gracilis* *Carex pensylvanica* *Koeleria macrantha* *Schizachyrium scoparium* *Sporobolus heterolepis* Forbs *Allium canadense* *Allium stellatum* *Anemone cylindrica* *Anemone patens* *Antennaria neglecta*		Forbs (cont'd) *Aquilegia canadensis* *Arennaria stricta* *Asclepias verticillata* *Astragalus canadensis* *Astralagus crassicarpus* *Cassia fasciculata* *Coreopsis palmata* *Dalea purpurea* *Delphinium virescens* *Fragaria vesca* *Fragaria virginiana* *Geum trifolium* *Hedyotis longifolia* *Huechera richardsonii* *Symphyotrichum sericeus*		Forbs (cont'd) *Liatris aspera* *Liatris cylindracea* *Liatris punctata* *Liatris spicata* *Penstemon grandiflora* *Ruellia humilis* *Solidago nemoralis* *Symphyotrichum ericoides* *Symphyotrichum oolentangiensis* *Talinum parviflorum* *Talinum rugospermum* *Tradescantia occidentalis* *Viola pedata*	
			References		
			www.greenroofs.com database; MacDonagh 2011		

continued

TABLE 4. *(continued)*

Analog & Location	Planted	Ecosystem Context	Template Used	Irrigated	Medium Depth
Law Building Saskatoon, SK	2007	Moist Mixed Prairie	N/A	Yes	5–8 in (12.5–20.5 cm)
Native or Grassland Species Grasses *Bouteloua gracilis* *Koeleria macrantha* *Sporobolus heterolepis*		Forbs *Allium cernuum* *Artemisia frigida*			
Comments			**References**		
Prairie plants admixture w/ *Sedum* spp. on extensive green roof			Ngan, 2010		
Analog & Location	**Planted**	**Ecosystem Context**	**Template Used**	**Irrigated**	**Medium Depth**
EPA Region 8 HQ Denver, CO	2008	High Plains	N/A	Yes	4 in (10 cm)
Native or Grassland Species Grasses *Bouteloua gracilis*	*Allium cernuum*	Forbs *Eriogonum umbellatum* *Opuntia fragilis*			
Comments			**References**		
Research on extensive roof			www.GreenAnalogs.com project database; Bousselot et al. 2009		
Analog & Location	**Planted**	**Ecosystem Context**	**Template Used**	**Irrigated**	**Medium Depth**
Target Center Minneapolis, MN	2009	Tallgrass Prairie	N/A	Yes	2.75–3.75 in (7–9.5 cm)
Native or Grassland Species Grass or Grass-like *Andropogon gerardii* *Bouteloua curtipendula* *Bouteloua gracilis* *Carex pensylvanica* *Koeleria macrantha* *Schizachyrium scoparium* *Sporobolus heterolepis*	Forbs *Allium stellatum* *Antennaria neglecta* *Aquilegia canadensis* *Astralagus crassicarpus* *Coreopsis lanceolata* *Dalea purpurea* *Fragaria virginiana*	*Geum trifolium* *Huechera richardsonii* *Lobelia siphilitica* *Penstemon grandiflora* *Solidago nemoralis* *Symphyotrichum ericoides* *Symphyotrichum oolentangiensis*	Forbs (Cont'd)		
Comments			**References**		
Prairie plants admixed with *Sedum* spp. and exotic ornamentals on extensive roof			www.greenroofs.com project database		

TABLE 5. Other Green Analogs Utilizing Native Grassland Plants.

Analog & Location	Planted	Ecosystem Context	Template Used	Irrigated	Medium Depth
Ducks Unlimited Canada Winnipeg, MB	1992	Tallgrass	N/A	No	18 in + (45 cm+)
Native or Grassland Species Grasses *Bouteloua gracilis* *Pascopyron smithii* *Schizachryium scoparium*		Forbs *Dalea purpurea*			
Comments			**Reference**		
Used soil not light-weight medium			www.GreenAnalogs.com project database		
Analog & Location	**Planted**	**Ecosystem Context**	**Template Used**	**Irrigated**	**Medium Depth**
GAP HQTRS San Bruno, CA	1997	Coastal Savanna	Coastal Savanna	No	4–8 in (10–20 cm)
Native or Grassland Species Grasses *Festuca rubra* *Festuca idahoensis* *Deschampsia holciformus*		Forbs *Nassella pulchra* *Lupinus nanus* *Eschscholtzia californica*			
Comments			**References**		
Supports habitat for endangered butterfly			www.greenroofs.com project database; Peck, 2008; Kephardt, 2011 Snodgrass and McIntyre 2010		

continued

TABLE 5. *(continued)*

Analog & Location	Planted	Ecosystem Context	Template Used	Irrigated	Medium Depth
LDS Visitors Center Salt Lake City, UT	2000	Mtn. Shrub	Coastal Savanna	Yes	4-12 in (10–30 cm)
Native or Grassland Species Grasses *Festuca idahoensis* *Sporobolus cryptandrus* *Stipa comata*		Forbs *Artemisia ludoviciana* *Artemisia frigida* *Coreopsis lanceolata* *Eupatorium maculatum* *Echinacea purpurea*			
Comments			**References**		
Varies Extensive to intensive. Plants listed for Extensive			www.GreenAnalogs.com project database; Peck 2008		
Analog & Location	**Planted**	**Ecosystem Context**	**Template Used**	**Irrigated**	**Medium Depth**
Neuhoff Packing Redevelopment Nashville, TN	2002	Deciduous Forest	Cedar Glade	No	4 in (10 cm)
Native or Grassland Species Grasses *Bouteloua curtipendula* *Eragrostis spectabilis* Forbs *Antennaria plantaginifolia* *Astragalus tennesseensis*		Forbs (cont'd) *Cuphea viscosissima* *Dalea purpurea* *Echinacea tennesseensis* *Hypoxis hirsut* *Manfreda (Agave) virginica*	Forbs (cont'd) *Opuntia humifusa* *Penstemon tenuiflorus* *Phlox pilosa* *Sedum pulchellum* *Sisyrinchium albidium* *Verbena canadensis*		
Comments			**References**		
One native Sedum			www.greenroofs.com database; Barnes 2011		

Analog & Location	Planted	Ecosystem Context	Template Used	Irrigated	Medium Depth
Vancouver Convention Centre Vancouver , BC	2008	Coastal Forest	BC Coastal Grassland	Yes	6 in (15.25 cm)
Native or Grassland Species Grasses or grass-like *Agrostis pallens* *Calamagrostis stricta* *Carex pansa* *Carex densa* *Carex pachystachya* *Carex tumulicola* *Festuca idahoensis* *Festuca ovina glauca*		Grasses or grass-like (cont'd) *Festuca ovina vulgaris* *Festuca rubra* *Koeleria macrantha* Forbs *Allium acuminatum* *Allium cernuum* *Anaphalis margaritacea* *Armeria maritima* *Brodiaea coronaria*	Forbs (cont'd) *Brodiaea hyancinthina* *Camassia quamash* *Eschscholtzia californica* *Fragaria chiloensis* *Potentilla anserina* *Sedum spathulifolium* *Sisyrinchium bellum* *Symphyotrichum subspicatus*		
Comments			**References**		
Used plugs, seeds and bulbs		www.greenroofs.com database; Hemstock 2008			
Analog & Location	**Planted**	**Ecosystem Context**	**Template Used**	**Irrigated**	**Medium Depth**
California Acad. of Sciences San Francisco, CA	2008	Coastal Dunes	Coastal Savanna	Yes	6 in 15.25 cm)
Native or Grassland Species Grasses *Festuca rubra*		Forbs *Fragaria chiloensis* *Armeria maritima* *Leymus mollis* *Sedum spathulifolium* *Prunella vulgari* *Lasthenia californi*a			
Comments			**References**		
This is a partial list			www.greenroofs.com database; Kephardt 2011; Snodgrass and McIntyre 2010		

TABLE 6. Seventy-six Forb Species Used On More Than One Green Roof.

Botanical Name	Times Used	Botanical Name	Times Used
Dalea purpurea	13	*Symphyotrichum laevis*	3
Geum trifolium	9	*Amorpha nana*	2
Allium cernuum	8	*Antennaria neglecta*	2
Symphyotrichum ericoides	6	*Antennaria plantaginifolia*	2
Huechera richardsonii	7	*Armeria maritima*	2
Liatris aspera	6	*Asclepias tuberosa*	2
Solidago nemoralis	6	*Asclepias verticillata*	2
Coreopsis lanceolata	6	*Astragalus canadensis*	2
Penstemon grandiflorus	6	*Astralagus crassicarpus*	2
Aquilegia canadensis	5	*Camassia quamash*	2
Fragaria virginiana	5	*Delphinium virescens*	2
Ratabida pinnata	5	*Echinacea pallida*	2
Ruellia humilis	5	*Eupatorium maculatum*	2
Symphyotrichum sericeum	5	*Helianthus mollis*	2
Tradescantia ohioensis	5	*Liatris ligulistylis*	2
Allium stellatum	4	*Monarda fistulosa*	2
Amorpha canescens	4	*Opuntia fragilis*	2
Artemisia frigida	4	*Penstemon digitalis*	2
Dalea candida	4	*Penstemon hirsutus*	2
Echinacea pupurea	4	*Phlox bifida*	2
Liatris cylindracea	4	*Phlox pilosa*	2
Opuntia humifusa	4	*Polemonium reptans*	2
Rudbeckia hirta	4	*Potentilla anserina*	2
Anemone cylindrica	3	*Potentilla arguta*	2
Anemone patens	3	*Pulsatilla patens*	2
Artemisia spp.	3	*Sisyrinchium albidium*	2
Callirhoe involucrata	3	*Sisyrinchium bellum*	2
Campanula rotundifolia	3	*Solidago canadensis*	2
Cassia fasciculata	3	*Solidago rigida*	2
Coreopsis palmata	3	*Solidago speciosa*	2
Eryngium yuccifolium	3	*Symphyotrichum azureus*	2
Eschscholtzia californica	3	*Symphyotrichum novae-angliae*	2
Fragaria chiloensis	3	*Symphyotrichum oolentangiensis*	2
Lespedeza capitata	3	*Talinum calycinum aureum*	2
Liatris punctata	3	*Tradescantia occidentalis*	2
Liatris spicata	3	*Verbena hastata*	2
Lobelia siphilitica	3	*Verbena hastata*	2
Sedum spathulifolium	3	*Viola pedata*	2

TABLE 7. Forty-two Graminoid and Three Shrub Species Ranked By Times Used.

Botanical Name	Times Used	Botanical Name	Times Used	Botanical Name	Times Used
Bouteloua curtipendula	13	*Agrostis pallens*	1	Shrubs	
Bouteloua gracilis	12	*Bouteloua hirsuta*	1	*Ceanothus americanus*	2
Schizachryim scoparium	11	*Bouteloua rigidiseta*	1	*Arctostaphyllos uva-ursi*	1
Sporobolus heterolepis	9	*Calamagrostis stricta*	1	*Rosa carolina*	1
Koeleria macrantha	8	*Carex densa*	1		
Andropogon gerardii	4	*Carex gracillima*	1		
Carex bicknelli	3	*Carex inops*	1		
Carex pensylvanica	3	*Carex muhlenbergia*	1		
Eragrostis spectabilis	3	*Carex pachystachya*	1		
Festuca idahoensis	3	*Carex pansa*	1		
Festuca rubra	3	*Carex radiata*	1		
Bouteloua dactyloides	2	*Carex sprengelii*	1		
Koeleria cristata	2	*Carex texensis*	1		
Muhlenbergia cuspidata	2	*Carex tumulicola*	1		
Sorghastrum nutans	2	*Carex vulpinoidea*	1		
		Deschampsia holciformus	1		
		Festuca ovina glauca	1		
		Festuca ovina vulgaris	1		
		Festuca saximontana	1		
		Juncus tenuis	1		
		Muhlenbergia reverchonii	1		
		Muhlenbergia rigens	1		
		Panicum hallii	1		
		Panicum leibergi	1		
		Pascopyron smithii	1		
		Sporobolus cryptandrus	1		
		Stipa comata	1		
		Stipa purpurea	1		

Several green roofs contained larger complements of native prairie and grassland species than others. In the twenty-one case studies the total number of species per roof (i.e., species richness) averaged 25 and ranged from 82 to 4 per roof discounting *Sedum* spp. that may have also been present. Seventeen of the twenty-one green roofs contained larger or equal numbers of forb species when compared with graminoids and on thirteen of the roofs, forbs out numbered graminoids 2 or 3 to 1. However, we have neither measure of nor information about the relative numbers of individuals of forbs or grasses or their relative dominance; we have not calculated species density. While thirteen of the forty-two graminoid species were dryland sedges, most were only used once. A suite of dryland sedges most awaits more study and use on green roofs.

In many cases we were unable to ascertain whether the species assemblages were chosen explicitly to interact in an ecological way with two exceptions. The California Academy of Sciences and the GAP Headquarters (Table 5) green roofs did use native species to support the habitat of threatened butterflies (Kephardt 2011). Only two case study plantings listed a native shrub and in general the case study roofs contained disproportionately fewer grass species and larger numbers of forbs species, most likely chosen for showy flowers.

FUTURE STUDIES AND CONSIDERATONS

Based on our review of prairie ecology, a subset of prairie habitat templates, and case examinations of green roof analogs using native prairie and grassland plants, it appears that grasslands are a potential source of native species, as well as diverse alternatives to *Sedum* spp., for planting onto green roofs; never-the-less, additional research is needed to understand and improve their success. Besides lack of replicated studies over a wide geographical area, we identify below a number of critical knowledge gaps that require further investigation.

For example, substrate, root structure, biomass and plant growth dynamics are closely intertwined but poorly understood for green roof applications. As media age, researchers need to explore how thatch and roots decompose and what may be the resulting impacts on medium permeability and leachate quality. Information needs to be compiled on nutrient turnover rates so that long-term fertility can be better accommodated. Even though prairie grasses can tolerate low available nitrogen, understanding the media modifications and changes to accommodate the long-term nutrient requirements of native species is also needed. While the Chicago Botanical Garden trial explicitly tests species in differing ranges of extensive, semi-intensive and intensive media depths (10, 15 and 20 cm, respectively) (Hawke 2011), optimum growing depths based on local water balances and plant species also need study.

Water–plant relations of the same rigor and experimental design expertise as Lundholm et al. (2010) within the green roof environment need to be expanded. Water quantity may not be as important as water quality and timing of application relative to season and the life stage of a plant (i.e., seedling, mature plant, flower production, fruit production). We suspect that extensive prairie-based green roofs will require supplemental irrigation, but only during periods of drought or extreme heat. What are the management, resource, and initial expense tradeoffs between the "as needed" irrigation and fully automated systems? Are there media amendments that are better able to support plants during drought periods? One study (Sutton 2008) used hydrophyllic gels to aid moisture stability for planting installation and some medium blenders are adding gels. He found the first year growth and survival enhanced. What is the long-term viability of such modifications? Sutton (2010, unpublished data) subsequently found no significant difference in plant growth on hydrogel plots the second year. Extensive depths such as the Eco-Enterprise Center green roof (Table 3) supported viable native plant growth for eight years without irrigation. Though in a cooler and more humid region (Minneapolis, MN), this roof has endured a major drought. What are the optimum media depths that effectively balance structural costs versus irrigation for various regions in North America? Understanding the important questions of how to balance the evapotranspiration rates that affect building cooling, and the ability of adapted prairie plants for long-term survival with and without irrigation have not, to our knowledge, been evaluated. We suspect that irrigation needs are small, but when needed, the timing of its application will be critical.

Closely allied with plant-water relations, temperatures on green roofs may be the limiting growth and survival factor. For example, Skabelund (2011) observed some hairy grama (*Bouteloua hirsuta),* sideoats grama *(Bouteloua curtipendula),* and little bluestem *(Schizachyrium scoparium)* did not completely brown out on the west side of the KSU Seaton Hall Green Roof when not supplemented by water during July-October 2011. This was despite over 20 days of >100°F temps, several dry periods, and elevated surface and sub-surface temps (ranging from 90-150°F for several weeks at a time). We know of no root/media temperature studies that have been done across varied geography or plant species, though Simmons et al. (2008) have begun such work for central Texas.

Investigations of green roof biodiversity fostered through the use of prairie and grassland plants should include studies of birds and insects. Importantly, soil microbiological diversity and heterogeneous medium structure also need detailed, replicated study. Observations of seedling growth in the protection of larger plants leads us to ask why so few small native woody plants have been tried on prairie based green roofs? A more diverse assemblage of both plant species and local ecotypes, including shrubs and sub-shrubs, need to be identified for use.

Last, plantings of prairie and grassland species need several years for establishment followed by several more for evaluating their performance under extreme heat, drought, and cold temperatures. These studies should be long-term and replicated in diverse geographic locales.

Additional Considerations

Prairies and grasslands are the dominant vegetation type in many parts of North America and our review suggests abiotic conditions of green roofs, while synthetic, converge with those of the prairie and grassland species and might be suitable for use elsewhere. We speculate that the grassland-like climate of green roofs extends beyond the finite range of North American grasslands, and associated species have been and should continue to be tried beyond the natural range of prairie and grassland (e.g. see Hitchmough 2008)

Studies are needed on the environmental benefits that using native prairie species on green roofs might bring to North American cities. One benefit of green roofs is their ability to absorb rainwater and reduce and delay runoff. Plants that capture water in their leaves and have high evapotranspiration rates enhance this benefit. The lack of vegetation and evapotranspiration in cities is also a major contributor to the urban heat island effect. One question under study is what percent of roofs would need to be planted to significantly contribute to reducing temperatures in cities? Are some species better than others for doing so? For example, transpiration among prairie species occurs during the day, while the physiology of *Sedum* spp. results in transpiration occurring at night. We speculate this may affect the efficiency of cooling by green roofs. Another assumption for rigorous, detailed study would relate different vegetation types to greater biodiversity of fauna.

Fire has been synonymous with grassland management. Given the urban locations of most green roofs and new green fire regulations (ANSI 2010) it may be unwelcome, unsafe, and/or regulated (i.e., requiring permission from the property/building owner(s) as well as a special permit from the fire department). Given the limited growth and litter buildup that occurs on green roofs (due to shallow media) fire may be unnecessary and there are other mechanisms to handle litter buildup when and if it occurs.

Should *Sedum* spp. remain the default green roof genus (Snodgrass and McIntyre 2010)? Perhaps the rigorous, geographically replicated research called for above should pair sedums and diverse assemblages of native prairie and grassland plants.

Green roofs with prairie and grassland plants are currently being used widely on green roofs in North America. As a concluding thought, it is important to understand how they are performing and what we do not know about their futures. This will only happen with rigorous evaluation of a sufficient number of long-term, detailed, replicated green roof studies and trials.

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