An experimental design to assess soil-plant-water relations on a Kansas green roof

by

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B.S., Southern Illinois University Edwardsville, 2014
M.S., Southern Illinois University Edwardsville, 2016

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Environmental Design and Planning
College of Architecture, Planning and Design

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2021

Abstract

Green roofs are increasingly common as cities seek environmentally sustainable approaches to mitigate climate change impacts while providing urban amenities. However, water availability is one of the most limiting factors in a green roof system and understanding the substrate-plant-water relationships within green roof ecosystems is key for understanding plant success and failures for individual green roofs. To provide insight on green roof plant and substrate selection for green roofs in the Flint Hills Ecoregion (Kansas, USA) and similar climates, three experimental research green roof beds were designed for the Kansas State University (KSU) College of Architecture, Planning and Design (APD) building and were initially planted in October 2017, with replacement plantings completed by June 2018. The three green roof beds provide three different depths (approximately 4, 6, and 8 inches [10.2, 15.3, and 20.4 cm]). The experimental design is a strip plot design within a randomized complete block design for each green roof depth. Each green roof depth contains two substrates (Rooflite® Extensive MC and Kansas BuildEx), and three different species mixes (all-Sedums, Sedums and native grasses, and all-natives). Each of the three specified mixes contain 6 different species planted in triplicate within each replication cell.

The main objectives for this APD Experimental Green Roof research are twofold: (1) understand how a locally blended substrate (Kansas BuildEx) and a commercially provided, regionally mixed substrate (Rooflite® Extensive MC) vary in the way they store and dispense water and how different plant mixes may affect the hydrologic processes within these substrates; and (2) understand how vegetative coverage and above-ground biomass of three mixed-species plantings and selected native plant species change over time. Using lessons learned from this experimental study of the two different substrate types, three different substrate depths, and three

species mixes, the desire was to improve our collective understanding of the selected plants and substrates and ultimately to improve the design, implementation, and management of green roofs in this part of Kansas and in locations with similar climates.

To realize these objectives, our interdisciplinary team has been investigating the relationships between micro-meteorological and subsurface temperatures and soil moisture dynamics, two different substrates installed at depths ranging from 2.4-5.2 inches (6.1-13.2 cm) called the 4-inch bed, 4.5-7.5 inches (11.4-19.1 cm) called the 6-inch bed, and 6.5-10.1 inches (16.5-25.7 cm) called the 8-inch bed, and vegetative coverage of specified mixes and biomass associated with the three distinct species mixes and seven native species (sideoats grama, blue grama, little bluestem, shortbeak or prairie sedge, purple prairie clover, prairie junegrass, and prairie dropseed). This dissertation research examined water holding capacities of the roof while soil moisture release curves were estimated to provide insight on how water is stored and the energy status of this water within the two selected green roof substrates. Lab tests to understand water holding capacities were done at KSU while lab tests on substrate-water energy status were sent to the Turf and Soil Diagnostics Lab in Linwood, Kansas. Soil moisture dynamics in each of the substrate types were investigated by analyzing the recession curve slopes for Rooflite® Extensive MC and Kansas BuildEx to provide insight as to how green roof substrate properties can cause variations in soil moisture retention and recession.

Soil moisture recession rates were analyzed for 1-hour and 24-hour periods following rainfall events in two configurations. Configuration 1 assessed soil moisture recession rates within the all-natives species mix planted in both substrates in all three green roof depths from March 2018 to early July 2019. Configuration 2 assessed soil moisture recession rates for the *Sedums* only and all-natives species mixes planted in both substrates for the 4- and 8-inch depths from late July 2019 to May 2020. For both configurations, soil moisture monitoring was done in situ. In terms of soil moisture, it was found that Kansas BuildEx (BuildEx) had a greater roof capacity than the Rooflite® Extensive MC substrate, and these substrates varied in the energy status of water within the soil. However, there was little to no difference in the rate at which these substrates dispense water (recession rates). For Configuration 1, there was only an effect of substrate in the shallowest bed (4-inch depth) when looking at a 1-hour recession period. For Configuration 2, there was only a slight effect of mix on recession in the 8-inch bed for the 1-hour recession period.

Plant coverage and above-ground biomass measurements were taken at the end of the 2018 and 2019 growing seasons. Coverage measurements utilized overhead photography. When looking at species mix performance in these beds, by the end of the second growing season there was a significant effect of mix type on amount of cover (or vegetative coverage within each plot), with the all-natives and *Sedum* and natives mixes having the greatest cover in the 4-inch and 8-inch beds. In the 6-inch bed there was a significant interaction effect between mix and substrate types. When looking at cover for each mix, Rooflite® Extensive MC yielded greater cover in the *Sedums* only mix; and when looking at cover in each substrate, the *Sedums* and natives mix having the greatest cover in Rooflite® Extensive MC, and the *Sedums* and natives mix and the all-natives mix having the greatest cover in Kansas BuildEx.

Regarding individual species performance, by the end of 2019, little bluestem had greater biomass in the Rooflite® Extensive MC substrate than in the BuildEx substrate for the 4-, 6-, and 8-inch beds. In the 6-inch bed, sideoats grama had greater biomass in the Rooflite® Extensive MC substrate than in BuildEx, while purple prairie clover had greater biomass in Kansas BuildEx substrate than in Rooflite® Extensive MC. Buffalograss was one of the species planted

in the *Sedums* and native grasses mix. Based on personal observations this grass performed exceptionally well throughout this study with photographs and visual assessments clearly indicating buffalograss dominance in most plots where it was planted, corresponding to findings in Liu et al., 2019.

The outcomes of this study show that there are important relationships occurring between substrate type and mixed-species performance in varying substrate depths for green roof systems associated with the APD Experimental Green Roof. Plant above-ground biomass can be affected by substrate type and particular species. Substrate types influence the percent cover of green roof species mixes, and how water is stored and taken up by plants.

The results and work related to this dissertation have enhanced the knowledge of soil-water relations of green roof ecosystems in this part of Kansas, which can help improve design, implementation, and management practices and make green roofs more sustainable. Future research should focus on analyses of how substrate chemical and physical properties change over time (if possible, five and ten after the first full growing season) and how these changes affect water movement within the substrate and plant species and mix performance over the long-term. It is likely that plant patterns will change over time depending on how well each species does over the long-term. Cover and biomass should continue to be monitored to see how the selected mixes and individual species perform over time.

Key Words: Experimental green roof, Species mix, Substrate type, Soil Moisture, Plant cover, Above-ground biomass

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Approved by:

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Lee R. Skabelund

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Acknowledgements

I have many people to thank for providing help and support throughout my doctoral endeavors at Kansas State University. First, I would like to thank my advisor, Professor Lee Skabelund, for providing me the opportunity to pursue a PhD and continue my passion of studying green roofs. Thank you for your support and patience over the last five years. I would also like to thank my committee members, Dr. Trisha Moore, Dr. Mary Beth Kirkham, and Dr. Gerard Kluitenberg, for their help as I worked through developing my project, completing preliminary exams, interpreting data, and finishing my dissertation. My research would not have been possible without the enlightening conversations and extremely helpful input from these amazing scientists. Many thanks to Richard Thompson for installing our data logger and sensor poles on the three experimental green roof planting areas and for building a camera stand for my use. I also thank Tim Todd for his help with data analysis and interpretation and Mary Knapp for her help in getting our weather station up and running.

I am also incredibly thankful for the Mary K. Jarvis Fellowship funding that made it possible for me to pursue a PhD in Environmental Design and Planning. I am also grateful for funding provided by the Kansas State University Small Research Grant and Green Action Fund used to purchase monitoring equipment for my research. I also appreciate support provided by Jeffrey Bruce and Co., Blueville Nursery, Rooflite®, and BuildEx.

Next, I need to thank all the incredible people that helped to monitor and maintain the green roofs. Thank you to Pamela Blackmore, Priyasha Shrestha, Lekhon Alam, Jialin Liu, and the many friends and LAR students that helped with planting, weeding, watering, and vegetation and soil sampling. You all have been great companions, and I hope to call you colleagues and friends for many years to come.

I have found so much joy in working on these green roofs during my time at K-State. Some of my greatest days in "The Little Apple" were spent up on the green roof with my radio and my thoughts. I hope these green roofs continue to bring joy to others for many years to come.

Dedication

I dedicate this dissertation to my family for their love and support during this journey. I would not have been able to complete my studies without having all of you pushing me along the way. My success is your success, and I am so lucky to have such an incredibly family and support system.

Chapter 1 - Introduction

Overview

Worldwide the effects of urbanization continue to increase. As the worldwide population continues to grow the amount of urban infrastructure and impervious surface increases. In comparison to the surrounding countryside, cities have warmer air temperatures, retain less water and soil moisture, emit more carbon dioxide and other pollutants, and typically have lower biodiversity (Dover, 2015). Urbanization commonly destroys natural ecosystems and replaces habitats that support native species. The reduction of natural land cover in urban areas decreases ecological functions in affected areas. Green roofs and other green infrastructure can be a useful tool to provide green space in urban areas without adding to pressures of land use at the ground level (Blanusa et al., 2013). Green roofs are becoming much more common in urban areas and are being promoted via climate change and stormwater management policies (USEPA, 2020; Carter and Fowler, 2008).

These designed ecosystems can be included in the design of new buildings or retrofitted to existing buildings (Oberndorfer et al., 2007). Implementation of well-designed green roof systems can also help designers, engineers, scientists, and other participants create more sustainable communities and linkages between urban environments and natural ecosystems (Cantor, 2008; Dakin et al., 2013, Snodgrass and McIntryre, 2010). These created ecosystems can likewise provide a range of benefits: removing pollutants, cooling air temperatures, insulating buildings, reducing stormwater runoff, providing habitat for pollinators and other species, increasing the value of adjacent properties, and boosting human health and well-being (Dover, 2015).

What is a Green Roof?

As defined by Oberndorfer et al. (2007), a green roof is a manmade ecosystem containing vegetation, substrate (also called grow media or growth medium), underlain by a drainage/water-holding layer, root barrier, and water proofing membrane(s); additional layers of insulation may also be added (Fig. 1.1). Insulation, beyond what the substrate and vegetation provide, is optional, and may be above or below the waterproofing system. The main purpose of the insulation layer is to increase the energy savings offered by a green roof installation. A waterproofing membrane is essential, and to be effective, must be designed and implemented to not permit water to contact the main deck and/or main structural support. On top of the waterproofing system lies the root barrier (Cantor, 2008; Dakin et al., 2013, Snodgrass and McIntryre, 2010). The root barrier or other protective layers prevent plant roots from growing into the layers below and damaging the structural components of the roof. The drainage layer is an important component of the roof installation because it aids in quickly removing any water that could inundate and thus harm the plant roots by being retained in substrate layers for too long during heavy or persistent rain events. The drainage layer also helps to alleviate the structural components of the roof from any stress caused by the weight from excess water while also holding some water in reserve for use by green roof vegetation. A root permeable filter layer can be installed between the substrate and drainage layer to prevent clogging of the drainage layer (ASTM 2020). The substrate provides a subsurface habitat for plants to flourish, but having a lightweight porous media is almost always essential to minimize weight and building construction costs (Snodgrass and McIntrye, 2010).

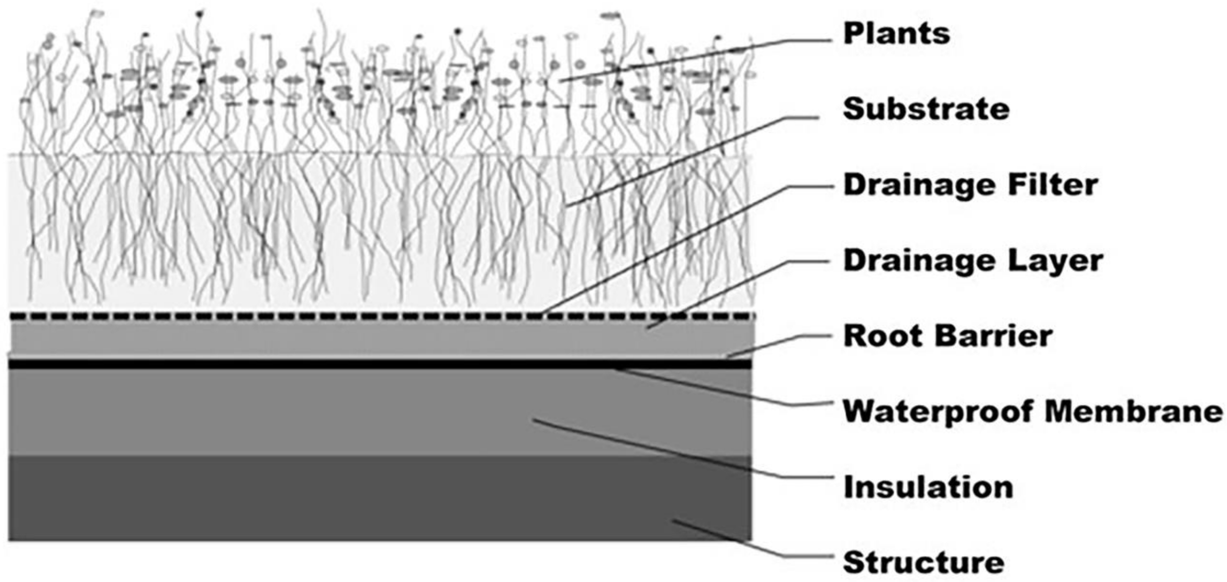


Figure 1.1. Cross Section of a Typical Extensive Green Roof System. Reprinted by permission from Springer Nature: Springer, *Green Roof Ecosystems* by Richard K. Sutton. 2015.

History of Green Roofs

Roof gardens and sod roofs were the precursors to modern day green roofs (Oberndorfer et al., 2007). The Hanging Gardens of Babylon are one of the earliest documented forms of roof gardens, around 605 BC (Getter and Rowe, 2006). Vegetated roofs were also used by the Norwegians from the 1600's to the 1800's in Norway as a form of insulation (Osmondson, 1999). During this time, soil was placed on roofs and grasses were used to keep the soil in place (Getter and Rowe, 2006). Sod-roofed homes were also common on the prairies in the Midwestern United States, and these sod roofs provided insulation and helped keep the rain out of a home (Celik et al., 2011). Vegetated roofs evolved from ancient forms to more modern design, which originated in Germany (Getter and Rowe, 2006).

Modern green roofs consist of vegetation growing in a lightweight substrate that is overlain with drainage layers, root barrier layers, and waterproofing membranes (Williams et al., 2014). Although green roofs have been around in various forms for centuries, the modern green roof movement formally began in the 1970's in Germany (Nawaz et al., 2015). During the late 1800's, Germany underwent rapid industrialization and urbanization. Inexpensive housing was built with roofing consisting of highly flammable tar; to reduce the fire hazard, roofs were covered with sand and gravel and eventually plants began to grow. Köhler and Keeley (2005) found that 100 years later, 50 of these vegetated roofs were still functional and totally waterproof. Beginning in the 1970's, many new green roofs were designed and implemented in Germany to increase building insulation and efficiency (Nawaz et al., 2015). It has been estimated that nearly 14 percent of German flat roofs are vegetated, and cities around the world have implemented programs to provide incentives for green roof installations (Mentens et al., 2006; Zhang and Guo, 2013). Advancements in building materials, innovative design strategies, and ideas regarding ways to build more sustainable environments have aided the green roof movement in the past 20 to 30 years (Getter and Rowe, 2006; Cantor, 2008; Weiler and Scholz-Barth, 2009; Sutton, 2015).

Since the 1990s the green roof industry has expanded rapidly in the United Kingdom, United States of America, and throughout the world (Williams et al., 2014). Because of the perceived environmental benefits provided by green roofs, incentive programs have been created in many cities, led by green roof researchers, designers, policymakers, and advocates in Germany and at least ten other European countries (Burszta-Adamiak and Fialkiewicz, 2019). Cities and government entities in countries implementing incentive programs for green roofs include the U.S. and Canada (GRHC, 2019), Australia, Singapore, and Japan. People and entities in many countries in Europe, North America, and across the world are either installing green roofs on newly constructed buildings or retrofitting old buildings so that green roofs can be added (Vijayaraghavan, 2016). Some cities in European countries (Austria, Belgium, Czech Republic, Germany, Netherlands, Poland, Sweden, and Switzerland) have created financial green roof incentives as motivators for green infrastructure growth (Burszta-Adamiak and Fialkiewicz, 2019). Similarly, some cities in the Czech Republic, Denmark, Great Britain, France, Germany, Sweden, and Switzerland have non-financial green roof incentives, such as requiring green roofs on newly constructed buildings (Burszta-Adamiak and Fialkiewicz, 2019). There are also incentives for green roofs in other cities around the world, including the U.S. and Canada.

Green Roof Types

Generally, there are two types of green roofs implemented or installed by contractors, practitioners, and researchers. The first type of green roof is "intensive" or deeper substrate systems. Intensive green roofs have a growth medium of at least six inches (approximately 15 cm) or deeper, which allows for a more diverse plant community and thus heavier substrate components. Intensive green roofs have deep substrates and taller plants that often resemble gardens found at the ground level (Oberndorfer et al., 2007). Due to deeper substrates and diverse plant communities more maintenance is usually required for intensive green roofs. The second type of green roof is "extensive" or shallow substrate systems. Extensive green roofs typically have two- to four-inch substrates (approximately 5 to 10 cm), often with low-growing plants that require less maintenance (Getter and Rowe, 2006). Extensive green roofs are typically less expensive than intensive green roof types when considering both installation and maintenance (Li and Yeung, 2014). Green roof designs may combine these two types, with some transitional portions, frequently called semi-intensive. Project budgets, planning/design goals, and the structural conditions of the new or existing building determine when each green roof type is used.

According to MacIvor and Lundholm (2011), experts recommend that extensive green roof plant species be able to establish fast and be capable of efficiently reproducing. Plant species used on green roofs are recommended to be low-growing or mat-forming with succulent leaves, or otherwise store water and/or have shallow spreading roots (MacIvor and Lundholm, 2011). There are four broad types of vegetation that possess at least one of these characteristics, namely mosses, S*edums*, grasses, and forbs (Li and Yeung, 2014). MacIvor and Lundholm (2011) and Li and Yeung (2014) outline recommended plant attributes.

Frequently used grow media or substrates for extensive and semi-intensive green roof systems include expanded shale, slate, or clay to ensure that excess water does not collect and create constantly saturated substrates and thus too great of a structural load or encourage the growth of molds and fungus harmful to specified plants (Snodgrass and Snodgrass, 2006).

Green Roof Benefits

Green roofs provide a range of benefits if designed, installed, and managed well. These benefits include economic, social, aesthetic, and environmental advantages. Given the focus of this research on green roof plant-soil-water (vegetation-substrate-hydrology) interrelationships, the following paragraphs highlight environmental benefits of living roof ecosystems. Potential environmental benefits of modern green roofs include reduced stormwater runoff, tempering the heat island effect, reduction of noise and air pollution, promotion of local biodiversity, and providing supplemental habitats for animals such as pollinators (Cook-Patton and Bauerle, 2012).

Vegetation plays a critical role in air temperature reduction at the city-wide scale (Blanusa et al., 2013). Plants influence cooling through direct shading and water transpiration through the stomata. Green roof plants and substrates also play vital roles in reducing stormwater runoff from rooftops where they are installed (Lambrinos, 2015). Vegetation and permeable soils combine to help reduce and clean stormwater runoff. In addition, other benefits, including habitat provisioning, are provided by living roofs. For example, living vegetation has the potential to provide habitat for a variety of different invertebrates and other animals (MacIvor and Ksiazek, 2015).

Prior to human developments that have caused significant disruptions to natural habitats, soils, and vegetation throughout much of the world, natural ecosystems dominated earth's bio-geophysical operations by effectively using and regulating rainfall, cycling nutrients, and tempering and using solar energy (Getter and Rowe, 2006). For example, soil and root systems store water and plant canopies absorb and reflect solar radiation. Vegetation and soil systems also cycle nutrients in ways that are beneficial to many organisms. Well-designed, installed, and managed green roofs can provide ecological benefits that help address a wide variety of current environmental issues (such as reducing stormwater runoff, decreasing energy use, alleviating the urban heat island effect, and creating habitat for pollinators and other organisms) while also providing a more aesthetically pleasing urban environment that simultaneously supports socio-economic needs and interests (Getter and Rowe, 2006).

Stormwater Quantity

A major benefit from a green roof installation is that it can reduce the amount of stormwater runoff that enters flows through developed urban areas and into natural systems (Monterusso et al., 2005). Slowing runoff by absorbing and delaying the release of stormwater reduces pressure on both urban and natural drainage networks (Mentens et al., 2006; Berndtsson 2010). The amount of stormwater runoff reduction depends on the type of green roof system. Some green roof characteristics that impact water retention and rate of runoff include roof slope, substrate depth, substrate composition, plant species, and rainfall patterns (Dunnett and Kingsbury, 2004; Mentens et al., 2006; VanWoert et al., 2005b, Oberndorfer et al., 2007; Lambrinos, 2015).

Green roofs also delay stormwater runoff because of the time it takes for substrate to become saturated and for the water to pass through the substrate. The lag in stormwater runoff can prevent stormwater sewer systems from overflowing. Green roofs can be responsible for 60% to 100% water runoff reduction (DeNardo et al., 2005; Moran et al., 2005; Rowe et al., 2003; VanWoert et al., 2005a; Getter and Rowe, 2006; Lambrinos, 2015). Nevertheless, the amount of water runoff reduction depends on the type and size of green roof system. A better understanding of green roof substrate water characteristics can provide insight into a green roof system's ability to slow and reduce volumes of water entering a stormwater system.

Tempering the Urban Heat Island Effect and Saving Energy

Green infrastructure (including green roofs) can be a critical component in alleviating the urban heat island effect, which is the phenomena that an urban area is significantly warmer than surrounding rural areas due to anthropogenic activities (Alexandri and Jones, 2008). Urban surfaces such as pavements, parking lots, rooftops, and other surfaces can raise air temperatures by absorbing, retaining, and re-emitting heat energy from the sun. Increased temperatures in urban areas create greater cooling (air-conditioning) and associated energy-use demands during summer seasons while loss of heat from buildings during winter months requires more heating and increased energy use. These energy demands lead to increased greenhouse gas emissions and contribute to poorer air quality, which can result in human illnesses such as asthma, heat exhaustion, respiratory problems, stroke, and sometimes death (USEPA-2, 2021).

Green roof vegetation and substrates can reduce air conditioning demands during warm months of the year, and in tandem with building insulation, may decrease winter-time heating demands; the capabilities of a green roof to assist during both warm and cool periods depends upon the depth of the substrate, the type of vegetation, and how vegetation is maintained during periods of cold temperatures (Collins et al., 2017). Kolb and Schwarz (1986) found that diverse green roof plant types created insulating air pockets resulting in cooler subsurface temperatures than green roofs planted with monocultures. Verheryen et al (2008) found that diverse planting also resulted lower temperatures; in this study the lower temperatures were due to higher evapotranspiration rates. Green roofs that are well-vegetated can reduce rooftop temperatures substantially on hot days (Skabelund et al., 2015) and thus have the potential to temper the urban heat island effect, especially during daytime hours (Santamouris, 2014).

Reducing Pollution

In urban areas, there are many sources of air pollution, and harmful levels are often elevated (Vijayaraghavan and Balasubramaniam, 2015). Per the World Health Organization (WHO), the most common source of urban air pollution is fuel combustion from city traffic (WHO, 2021). Another source of pollution is industry. Green roofs can mitigate air pollution through the process of dry deposition (collection of particles on surfaces), as well as through direct and indirect processes by plants. A number of studies have investigated green roof pollution reduction and have found that green roofs can be successful at purifying urban air. For example, Yok Tan and Sia (2005) found that a newly installed green roof reduced sulfur dioxide and nitrous acid from the air above by 37% and 21% respectively. Also, Deutsch et al. (2005) estimated that, if 20% of the infrastructure capable of supporting green roofs in Washington, D.C. were converted to green roof systems, the vegetation would have the same air purifying power as 17,000 street trees, and Yang et al. (2008) found that 1675 kg of air pollutants (NO_2, SO_2, and PM_{10}) were removed in one year by a 19.8 ha green roof. Yang et al. (2008) also found that tall herbaceous plants eliminated more ozone, small particulates, NO_2 and SO_2 than short grasses on green roofs. Air pollution is not the only type of pollution that has been investigated on green roofs. Some researchers are also interested in a green roof's ability to absorb sound.

Noise pollution is not only an annoyance, but it can also negatively impact human health by contributing to high blood pressure, sleep disturbance, hearing loss, stress related illnesses, speech interference, and lowered productivity (USEPA-1, 2021). Green roofs also serve as a sound absorbing layer because the porous mass of green roofs serves as noise attenuators (Connelly and Hodgson, 2008).

Providing Habitat and Other Benefits to Wildlife

With population growth and urbanization, land has been transformed, fragmented, or undergone complete loss of vegetation. Initially, extensive green roofs were thought to be species-poor supplemental habitats for animals and plants (Brenneisen, 2006). However, further research has found that, if an extensive green roof is properly designed and implemented, it can provide habitat, even for rare and endangered species that suffer from the negative impacts of land use changes (Brenneisen, 2003). Green roofs can potentially aid in habitat conservation of desirable target species in local communities (Getter and Rowe, 2006). Constructed plant communities, such as green roofs, can serve as supplemental wildlife habitats that have been destroyed or degraded by urbanization for numerous kinds of insects (beetles, ants, flies, bees, leafhoppers, and butterflies), spiders, soil invertebrates, and avian species (Colla et al., 2009; Coffman and Davis 2005; Brenneisen, 2006; Kadas, 2006; Schrader and Böning 2006, MacIvor and Ksiazek, 2015). Flowering plants (forbs) can help promote diversity of bees, butterflies, and other pollinators on green roofs (Sutton, 2015; Blackmore, 2019). Green roof plants can also serve as sources of food and nectar for invertebrate and avian species (Dakin et al., 2013). Blackmore (2019) found that green roofs can provide habitat for butterflies (and potentially many other pollinators) in urban settings.

For green roofs to be used as a tool for conservation, living roofs need to be viewed from a regional landscape and ecological perspective, instead of from an ornamental gardening or simply from an energy conservation perspective (Brenneisen, 2006; Dvorak and Skabelund, 2021b). When viewing green roof installations from an ecological perspective, a green roof can be employed to create new, self-organizing ecosystems that provide cover, shelter, food, and other resources for insects, spiders, birds, bats, small mammals, and soil-dwelling organisms (Sutton, 2015). Designed, implemented, and managed well living roofs can be multifaceted ecological assets (Dvorak and Skabelund, 2021b).

Regional Context and the Flint Hills Ecoregion

Manhattan, Kansas is part of The Flint Hills Ecoregion. The Flint Hills Ecoregion is primarily located between central and eastern Kansas and spreads south into northern Oklahoma; this ecoregion contains the more intact tallgrass prairie than any other region in North America and is the last intact tallgrass prairie with adequate size to provide full ecological function (USFWS, 2010). The Flint Hills Ecoregion is the smallest grassland ecoregion in the United States and is distinguished by the dominance of tallgrass species of forbs and graminoids (World Wildlife Fund, 2016). This unique Ecoregion consists of a thin layer of soil over residual flint that has been eroded from the limestone bedrock (USFWS, 2010). The thin, rocky soils composed of Permian shale and cherty limestone in parts of the Flint Hills Ecoregion makes certain prairie species ideal for green roof plantings because of similarities in harsh climatic conditions (Dunham, 2012). Because many prairie plants have evolved to survive periodic droughts their water requirements are less, however, a green roof presents much more challenging conditions than are found in on-the-ground ecosystems (Dvorak and Skabelund, 2021a).

Architecture, Planning & Design Experimental Green Roof

The College of Architecture, Planning and Design Experimental Green Roof (abbreviated to APD-EGR) is located atop the newly expanded East Wing of Seaton Hall at Kansas State University (KSU) in Manhattan, Kansas (39° 11′ 30″ N, 96° 35′ 30″ W). The APD-EGR was constructed during the summer and early autumn of 2017 and consists of three separate planting areas distinguished by substrate depths of approximately 4, 6, and 8 inches (10, 15, and 20 centimeters).

Starting from the bottom of the APD-EGR (above the roof deck and insulation), a modified bituminous roof protection membrane was created on the roof (Fig. 1.2). The waterproofing materials were supplied by Firestone Building Products LLC (Nashville, TN, USA). The entire roofing insulation structure was covered with thermoplastic polyolefin (TPO) membrane root barrier layer of 1.14mm thickness. Next the drainage panel (2.54 cm thick) was placed on the roof. The dimpled drainage panel was designed to provide a balance between water retention and aeration. Next, a 1.14 mm thick filter fabric was placed over the drainage panel to keep the substrate (growing media) in place and discourage intrusion by plant roots. A gravel layer was used to level the growing media depth in an attempt to maintain a consistent finish grade elevation. Another layer of filter fabric was placed above the gravel layer and Permaloc GeoEdgeTM was put in place to provide a restrain system for the edges of each of the three green roof beds. Aluminum metal dividers were placed on the green roof in a grid like pattern to create experimental cells. Each cell was designed to be the exact same size, but they were mistakenly installed with some variation. Each of the 72 cells were filled with one of two substrate types (called “growing media” in Fig. 1.2).

Once substrates were added to the 4-, 6-, and 8-inch (10-, 15-, and 20-cm) cells, the green roof was planted with one of three mixed-species vegetation mixes (side-by-side for the same species mix in different substrate types), with each cell receiving six species of live plants, repeated in same planting pattern. Actual substrate depths vary due to imperfect installation/construction error.

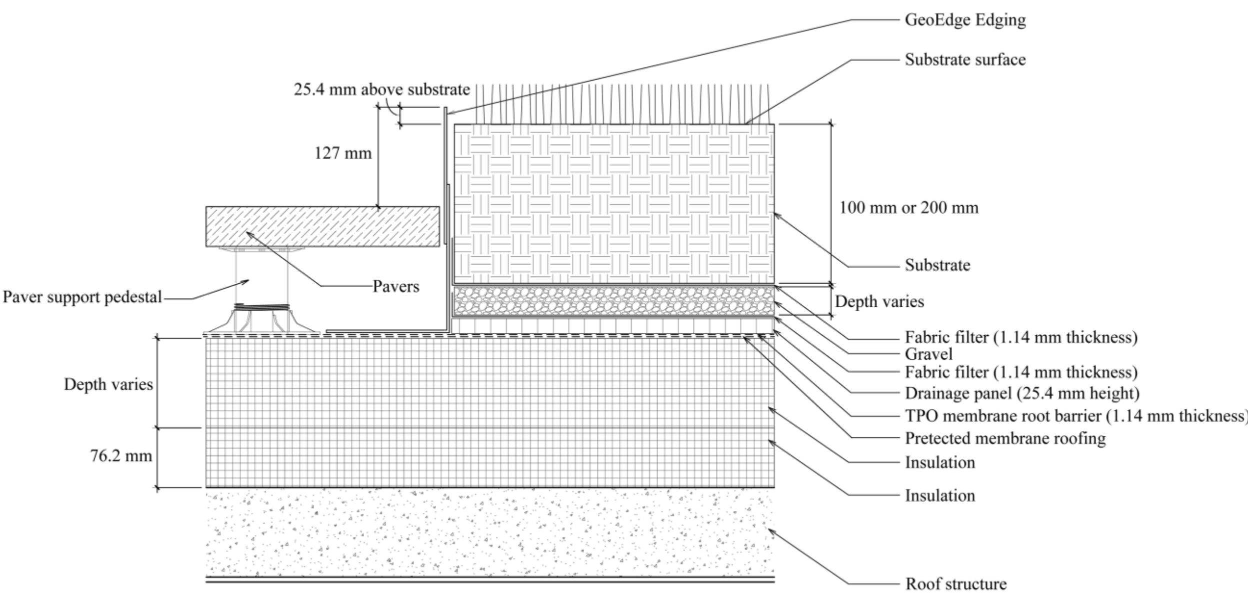


Figure 1.2. Cross Section of the APD Experimental Green Roof atop the new (2017) Architecture, Planning and Design Building at Kansas State University. (Source: KSU Seaton Hall and Seaton Court Renovation and Expansion Construction Documents**.** Adapted by Priyasha Shrestha**).**

Each planting area contains four blocks, that consist of six (approximately 4 ft x 4 ft or 1.2 m x 1.2 m) experimental cells (Figs. 1.3 & 1.4). Three different planting areas (beds) provide a total of 72 4’ x 4’ experimental cells on the green roof. As stated earlier, each 4’ x 4’ experimental cell is separated by metal (aluminum) dividers. The only portion of the cells that is not separated is the drainage layer (which lies as an integrated system beneath the filter fabric contained substrate for each cell).

Figure 1.3. Aerial Photo of the APD Experimental Green Roof. Small unmanned aerial vehicle (sUAV) infrared image taken July 18, 2018 by Harman Singh, showing the live plant planting pattern within each cell and the two different substrate types in four distinct blocks in each bed or area.


a.


b.


c.

Figure 1.4. Photos of the APD-EGR. Photos a, b, and c of the three planting areas—the 4-inch bed, 6-inch bed, and 8-inch bed (respectively), taken July 19, 2018 by Lee Skabelund (looking east at the three planting areas). Data-loggers attached to metal poles are connected to various sensors.

Green Roof Maintenance Methods

Weeding Protocol

The APG-EGR was weeded approximately once every two weeks to allow for coverage of planted species to be tracked. Weeding was especially important before coverage photos were taken. When weeding the APD-EGR, all non-originally planted species were pulled. Also, all grass seedlings were pulled due to the difficulty identifying small grass seedling species. All seedlings of the originally planted forbs were not weeded to allow for measurement of forb reproduction.

Fertilizer Use

In Fall 2017 and early Spring 2018, the APD-EGR planting areas were sprayed with a locally made product called Humic Balance that helps “eat up” dead vegetation and gives a boost to the plants. The active ingredients in Humic Balance are leonardite and potassium humate. The APD-EGR was not fertilized during this study—summer 2018 to late fall 2019 (Tim Sharp, Blueville Nursery, pers. comm., May 2021).

Research Objectives and Hypotheses

The benefits of green roofs previously described are just as achievable as aesthetic aspects of green roofs, but green roofs are not typically optimized to meet those goals (Vijayaraghavan, 2016). One of the main reasons green roofs do not meet their potential is due to a lack of research on specific aspects of green roof functions and dynamics (Lambrinos, 2015; Vijayaraghavan, 2016). It is evident there is a need for additional green roof research to better understand the various aspects of living roofs pertaining to substrate-plant-water relations and how to optimize green roof benefits within each regional climate. Although there has been great advancement in green roof technologies, there is still much to learn about the interrelationships occurring at the substrate surface and within subsurface environments, especially in the U.S. Great Plains and other similar humid continental, semi-arid, and arid regions. The interrelationships between substrate types, depths, and specific types of plant mixes need to be explored within each physiographic region.

Prior to Professor Lee Skabelund's Seaton Upper Green Roof research at Kansas State University (including observations of four different KSU green roofs between 2009 and the present) no green roof studies had been conducted to determine the viability of native plants and succulents on green roofs in Manhattan, Kansas. This research is the first to systematically examine the influences of different green roof substrate depths, plant species mixes, and management practices in the continental, drought-prone, and seasonally variable climate of the Flint Hills Ecoregion of Kansas, USA using the experimental design created for all three APD-EGR substrate depths (4, 6, and 8 in / 10, 15, and 20 cm), and builds upon and relates to green roof research in Manhattan, Kansas by Skabelund, et al. (2014), Skabelund, et al., (2017), Liu, et al. (2019), and Shrestha (2019).

Deepening our understanding of the interrelationships between soil moisture, temperature, vegetative coverage, and species biomass is expected to provide advancements in the design, implementation, and management of green roof ecosystems. Understanding key relationships between substrate type and soil moisture, vegetative coverage, and species biomass for three different plant species mixes will provide insight on how these systems work and the interrelatedness of green roof system components. This is particularly important since Butler et al. (2012)—as discussed by Li and Yeung (2014)—indicated that survival rates for native plants were lower than for non-native vegetation used on nine experimental green roofs in the U.S. and Canada, while Skabelund et al. (2014), Sutton (2015), and Liu et al. (2019) found that native plants had variable success on three different green roofs in the Central Great Plains. Understanding important relationships and limitations should lead to better design, implementation and management of green roofs and can help reduce the amount of supplemental irrigation on green roofs.

The primary goal of this dissertation was to understand the relationships between substrate type and depth, and mixed-species performance on our three-bed, 72-plot experimental green roof system on the KSU campus to allow for suggestions on what might happen on similar types of green roofs having 4-inch, 6-inch, and/or 8-inch substrates of similar composition in a similar climate regime. To achieve this goal, temporal changes in species performance (namely plant cover and dry biomass) by planted vegetative mixes were measured and soil water content monitored during two growing seasons (2018 and 2019). The following sections outline the organization of this dissertation. Note that chapters 2, 3, and 4 are written in a way that they can be readily submitted to a peer-reviewed journal, so there is some repetition with the information presented in Chapter 1.

Chapter 2 – Substrate Physical and Chemical Descriptions

According to the literature, substrate selection plays an important role in water retention capabilities and plant success on green roofs, yet we know little about how a commercially available substrate such as Rooflite® Extensive MC and a regionally mixed sand-and-expanded-shale substrate affect specific soil moisture and vegetation dynamics on green roofs in the Flint Hills Ecoregion. Before answering these questions, understanding the differences between the two selected substrates used for this project was essential. To help address this knowledge gap both substrate types were tested at the K-State Soils Testing Lab (Manhattan, Kansas) and Turf and Soil Diagnostics Lab (Linwood, Kansas) to provide information on the chemical and physical properties of the Rooflite® Extensive MC substrate and the Kansas BuildEx substrate. Chapter 2 discusses the physical and chemical properties of the two substrates used on the APD-EGR. Important differences between the two substrates are examined and the findings summarized. Potential influences on microclimate and vegetation (plant mixes) are also discussed.

Chapter 3 – Substrate Moisture Characteristics

There can be a large difference in green roof water retention between green roof systems with different properties. Green roof design has been motivated by the need for good stormwater retention to aid with stormwater management in highly developed areas. One of the challenges for designing green roofs with good stormwater retention is they also require good drainage to stay within the structural limitation for maximum weight capacities (FLL 2008; ASTM 2020). Plant available water can decrease quickly after precipitation or irrigation events, especially in shallow media (VanWoert et al. 2005b). Because plants survive off available water and not just the gravimetric water content it is important to know the energy status of the soil water. Knowing the potential energy state of the soil provides insights on how much work is required for plants to pull water from the substrate (Hillel, 2003). Water moves within the soil and plants because of the gradient in water potential (Hillel, 2003). Substrate water content and water potential are functionally related, and this relationship is dependent on the structure of the substrate (Hillel, 2003). We need to study the green roof soil-plant-atmosphere-continuum (SPAC) to understand what affects water availability, water uptake, coverage, and growth on the green roof. The goal of the research discussed in this chapter was to understand how the two substrates, Kansas BuildEx and Rooflite® Extensive MC, vary in the way they store and dispense water, and to understand how the two substrates vary in terms of energy status of soil water to provide insight on plant available water. In this chapter the following questions are addressed:

1. How does substrate type (Kansas Buildex and Rooflite® Extensive MC) and depth (4-inch, 6-inch, and 8-inch) impact roof capacity (the water content when the substrate can hold no more moisture under gravity) on the APD-EGR?
2. How does water recession vary for Kansas Buildex and Rooflite® Extensive MC following precipitation events on the APD-EGR?
3. How does the energy status of the soil water vary for Kansas Buildex and Rooflite® Extensive MC on the APD-EGR?

The following three hypotheses were tested:

1. Within each depth Rooflite® Extensive MC substrate will initially hold more water than Kansas BuildEx due to its high organic matter content.
2. Kansas BuildEx and Rooflite® Extensive MC will differ in the rate at which they dry following precipitation events due differing substrate physical properties.
3. Based on visual observation of large amounts of organic matter (composted plant bark) in Rooflite® Extensive MC, when comparing water content values Rooflite® Extensive MC will have a lower water potential than Kansas BuildEx.

Chapter 4 – Plant Cover and Biomass

Because of the characteristics of the Flint Hills Ecoregion, species native to tallgrass prairie ecosystems such as the Konza Prairie may be suitable choices for green roof plantings. Prior to Professor Lee Skabelund's Seaton Upper Green Roof research at Kansas State University (observations of four different KSU green roofs between 2009 and the present) no green roof studies had been conducted to determine the viability of native plants and succulents on green roofs in Manhattan, Kansas. Because there were few green roof analogues to draw from in the region, plant selection for the APD-EGR was based off lessons learned on green roofs at KSU and in Lincoln, Nebraska and from literature discussing drought tolerant species at Konza Prairie that thrive in habitats like green roofs (hot, well drained, exposed, with shallow soils). The purpose of Chapter 4 is to discuss how vegetative coverage and species biomass of three mixed-species plantings changed over a two-year period in relation to the two different substrate types (Kansas BuildEx and Rooflite® Extensive MC), and three different substrate depths (4 inches, 6 inches, and 8 inches). Understanding the relationships between substrate type and depth, and plant performance in terms of coverage and biomass has greater impacts on green roof design for the Flint Hills Ecoregion and can help guide future green roof design decisions for this ecoregion. The following questions are addressed:

How does the performance of the three plant mixes (A: all-*Sedums*; B: *Sedums* and native grasses; and C: native grasses and forbs) on the APD-EGR differ in each substrate in terms of vegetative coverage?

How does the performance of the native species on the APD-EGR differ in each substrate in terms of above ground biomass (as measured by dry weight)?

The following hypotheses were tested:

Coverage will be greater for the *Sedum* mix due to *Sedum* species adaptations to survive extreme stress.

Coverage and biomass will be greater in the Rooflite® Extensive MC substrate than in Kansas BuildEx due to Rooflite® Extensive MC being a commercially available green roof substrate.

Chapter 5 – Final Synthesis and Conclusions

Chapter 5 summarizes and reflects on the research findings from chapters 2, 3, and 4 and makes connections between the findings from each of these chapters. This concluding chapter summarizes new knowledge contributed to the green roof research field and discusses recommendations for future green roof research within the Flint Hills Ecoregion and other locations with similar climates. The limitations of this research are discussed. Also discussed are the opportunities for additional research that can build upon and relate to the APD-EGR data collected and analyzed between 2018 and 2020 for this research.

References

Alexandri, E., and P. Jones. 2008. "Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates." Building and Environment 43: 480-493.

ASTM International, 2020. ASTM E277-20, Standard Guide for Vegetative (Green) Roof Systems. (West Conshohocken, PA, US).

Blackmore, P. 2019. "Butterflies, Tallgrass Prairie, and Green Roofs." Master of Landscape Architecture Thesis. Kansas State University, Manhattan, KS. KREX thesis publishing.

Blanusa, T. M., M. Vaz Monteiro, F. Fantozzi, E. Vysini, Y. Li, and R. W. F. Cameron. 2013. "Alternatives to sedum on green roofs: Can broad leaf perennial plants offer better 'cooling service'?" Building and Environment 59 (1): 99-106.

Brenneisen, S., 2003. "The benefits of biodiversity from green roofs: Key design consequences." 1st North American Green Roof Conference: Greening rooftops for sustainable communities, Chicago, Illinois.

Brenneisen, S., 2006. "Space for urban wildlife: designing green roofs as habitats in Switzerland." Urban Habitats 4: 27-36.

Burszta-Adamiak, E. and W. Fialkiewicz. 2019. "A review of green roof incentives as motivators for the expansion of green infrastructure in European cities." Scientific Review – Engineering and Environmental Sciences 28(4): 641-652.

Butler C, E. Butler E, and C.M. 2012. "Native plant enthusiasm reaches new heights: perceptions, evidence, and the future of green roofs." Urban Forestry & Urban Greening 11:110.

Cantor, Steven L. 2008. Green Roofs in Sustainable Landscape Design. W. W. Norton & Company.

Carter, T. and L. Fowler. 2008. "Establishing green roof infrastructure through environmental policy instruments." Environmental Management 42, 151–164.

Celik, S., S. Morgan, and W.A. Retzlaff. "Thermal Insulation Performance of Green Roof Systems." 6th International Green Energy Conference: Eskisehir, Turkey., 5-9 Jun, 2011.

Coffman, R.R., and G. Davis. 2005. "Insect and avian fauna presence on the Ford assembly plant ecoroof." Paper presented at the Third Annual Greening Rooftops for Sustainable Communities Conference, Awards and Trade Show: Washington, D.C., 4-6 May.

Colla, S.R., E. Willis, and L. Packer. 2009. "Can green roofs provide habitat for urban bees (Hymenoptera: Apidae)?" Cites and the Urban Environment 2 (1): 1-12.

Collins, S., K. Kuoppamäki, D. J. Kotze, and Xiaoshu Lü. 2017. "Thermal Behavior of Green Roofs under Nordic Winter Conditions." Building and Environment 122: 206–14. https://doi.org/10.1016/j.buildenv.2017.06.020.

Connelly, M. and M. Hodgson. 2008. "Sound transmission loss of extensive green roofs: Field test results." Living Architecture Monitor 10(4) 24-29.

Cook-Patton, S. C., and T.L. Bauerle. 2012. "Potential Benefits of Plant Diversity on Vegetated Roofs: A Literature Review." Journal of Environmental Management 106:85–92.

Berndtsson, J.C. 2010. "Green roof performance towards management of runoff water quantity and quality: A review." Ecological Engineering 36:351-360

Dakin, K., L L. Benjamin, and M. Pantiel. 2013. The Professional Design Guide to Green Roofs. 1st ed. Portland, Or. Timber Press.

DeNardo, J.C., A. R. Jarrett, H.B. Manbeck, D.J. Beattie, and R.D. Berghage. 2005. "Stormwater mitigation and surface temperature reduction by green roofs." Transactions of the ASAE 48(4): 1491-1496.

Deutsch, B., H. Whitlow, M. Sullivan, and A. Savineau, 2005. "Re-greening Washington, DC. A green roof vision based on environmental benefits for air quality and storm water management." In: Proceedings of the 3rd North American: Green Roof Conference on Greening Rooftops for Sustainable Communities, Washington, DC, May 4–6. The Cardinal Group, Toronto. 379–384.

Dover, J.W. 2015. Green Infrastructure Incorporating plants and enhancing biodiversity in buildings and urban environments. Routledge.

Dunham, J.W. 2012. "Flint Hills Ecoregion." Kansas Geological Survey. Accessed Jan 2021. http://www.kgs.ku.edu/Publications/OFR/2012/OFR12_6/index.html

Dunnett, N., and N. Kingsburry. 2004. Planting Green Roofs and Living Walls. Portland, Oregon: Timber Press.

Dvorak, B. and Skabelund L.R. 2021a. "Green Roofs in Tallgrass Prairie Ecoregions." In: Dvorak B. (ed.) Ecoregional Green Roofs: Theory and Application in the Western USA and Canada. Cities and Nature Series. Springer; Springer Nature. https://doi.org/10.1007/978-3-030-58395-8_3

Dvorak, B. and L.R. Skabelund. 2021b. "Ecoregional Green Roofs, Infrastructure, and Future Outlook." In: Dvorak B. (ed.) Ecoregional Green Roofs: Theory and Application in the Western USA and Canada. Cities and Nature Series. Springer; Springer Nature. https://doi.org/10.1007/978-3-030-58395-8_11

FLL. 2008. Guideline for the planning, execution and upkeep of green-roof sites. English edition. Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau, Bonn.

Getter, K.L., and D.B. Rowe. 2006. “The role of green roofs in sustainable development.” HortScience 41: 1276-1286

Getter, K.L. and D.B. Rowe. 2008. “Media depth influences sedum green roof establishment.” Urban Ecosystems 11: 361–372

Hillel, D. 2003. Introduction to Environmental Soil Physics. San Diego, CA. Elsevier Science.

Kadas, G. 2006. “Rare invertebrates colonizing green roofs in London.” Urban Habitats 4: 66-86.

Klein, Petra M., and Reid Coffman. 2015. “Establishment and Performance of an Experimental Green Roof under Extreme Climatic Conditions.” Science of The Total Environment 512–513 (April): 82–93. https://doi.org/10.1016/j.scitotenv.2015.01.020.

Köhler, M., and M. Keely. 2005. “Berlin: Green roof technology and development.” In Green Roofs: Ecological Design and construction. 108-112. Schiffer Books, Atglen, Pennsylvania.

Kolb, W. and T. Schwarz. 1986. New habitats on the roof: the possibilities for the provision of extensive verdure. Anthos. 1:410.

Lambrinos, J. 2015. “Chapter 4 - Water Through Green Roofs,” In Green roof Ecosystems .” (Ed. by R. Sutton). London: Springer Science. 81–105. https://doi.org/10.1007/978-3-319-14983-7_4.

Li, W. C., and K. K. A. Yeung. 2014. “A Comprehensive Study of Green Roof Performance from Environmental Perspective.” International Journal of Sustainable Built Environment 3 (1): 127–34. https://doi.org/10.1016/j.ijsbe.2014.05.001.

Liu, J., P. Shrestha, L.R. Skabelund, T. Todd, A. Decker, M.B. Kirkham. 2019.” Growth of prairie plants and sedums in different substrates on an experimental green roof in Mid-Continental USA.” Science of the Total Environment 697(134089):1-11. doi: 10.1016/j.scitotenv.2019.134089.

MacIvor, J.S., and K. Ksiazek. 2015. “Chapter 14 - Invertebrates on Green Roofs,” In Green Roof Ecosystems (Ed. by R. Sutton). London: Springer Science. 333-355.

MacIvor, J. Scott, and Jeremy Lundholm. 2011. “Performance Evaluation of Native Plants Suited to Extensive Green Roof Conditions in a Maritime Climate.” Ecological Engineering 37, 3:407–17. https://doi.org/10.1016/j.ecoleng.2010.10.004.

Mentens, J., D. Raes, M. Hermy. 2006. “Green roofs as a tool or solving the rainwater runoff problem in the urbanized 21st century.” Landscape and Urban Planning 77: 217-226.

Monterusso, M., B. Rowe, and C. Rugh. 2005. “Establishment and persistence of Sedum spp. And native taxa for green roof applications.” HortScience 40(2): 391-396.

Moran, A., B. Hunt, and J. Smith. 2005. “Hydrologic and water quality performance from green roofs in Goldsboro and Raleigh, North Carolina.” In Proc. of 3rd North American Green Roof Conference: Greening rooftops for sustainable communities, Washington, DC, 4-6 May, 2005. 512-525. Toronto: The Cardinal Group.

Nawaz, R, A. McDonald, S. and Postoyko. 2015. “Hydrological performance of a full-scale extensive green roof located in a temperate climate.” Ecological Engineering 82:66 - 80. ISSN 0925-8574

Oberndorfer, E., J. Lundholm, B. Bass, R. Coffman, H. Doshi, N. Dunnett, S. Gaffin, M. Kohler, K. Liu, and B. Rowe. 2007. “Green roofs as urban ecosystems: ecological structures, functions, and services.” Bioscience 57: 823-833

Osmondson, T. 1999. Roof Gardens: History, Design, and Construction. New York: W.W. Norton and Company Inc.

Rowe, D.B., C.L. Rugh, N. VanWoert, M.A. Monterusso, and D.K. Russell. 2003. “Green roof slope, substrate depth, and vegetation influence runoff.” In Proc. Of 1st North American Green Roof Conferences: Greening rooftops for Sustainable Communities, Chicago, Illinois, 29-30 May 2003. Toronto: The Cardinal Group.

Santamouris, M. 2014. “Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments.” Solar Energy 103 (5): 682-703.

Schrader, S., and M. Böning. 2006. “Soil formation on green roofs and its contribution to urban biodiversity with emphasis on Collembolans.” Pedobiologia 50:347–356.

Shrestha, P. 2019. “Assessment of first-year survival, growth, and physiological performance of seven species of graminoids within two substrate types on a green roof in the Flint Hills Ecoregion.” Master of Landscape Architecture Thesis. Kansas State University, Manhattan, KS. KREX thesis publishing.

Skabelund, L.R., Blocksome, C., Brokesh, D., Kim, H.J., Knapp, M., Hamehkasi, M., 2014. “Semi-arid green roof research 2009–2014: resilience of native species.” Paper Presented at the 12th Annual Green Roof & Wall Conference, Nashville, TN.

Skabelund, L.R. K. DiGiovanni and O. Starry. 2015. “Chapter 2 - Monitoring Abiotic Inputs and Outputs.” In Green Roof Ecosystems (Ed. by R. Sutton). London: Springer Science. 27-62.

Skabelund, L.R., A. Decker, T. Moore, P. Shrestha, J.L. Bruce. 2017. “Monitoring two large-scale prairie-like green roofs in Manhattan, KS.” In Conference proceedings: Cities Alive 15th Annual Green roof & Wall Conference.

Snodgrass, Edmund C., and Linda McIntyre. 2010. The Green Roof Manual: A Professional Guide to Design, Installation, and Maintenance. 1st Edition. Portland: Timber Press.

Snodgrass, Edmund C., and Lucie L. Snodgrass. 2006. Green Roof Plants: A Resource and Planting Guide. Timber Press.

Sutton, Richard K. 2013. "Seeding Green Roofs with Native Grasses," Journal of Living Architecture 1:21.

Sutton, R. 2015. "Introduction to Green Roof Ecosystems." In Green Roof Ecosystems (Ed. by R. Sutton). London: Springer Science. 1-25.

United States Environmental Protection Agency (USEPA-1). 2021. "Clean Air Act Title IV - Noise Pollution." https://www.epa.gov/clean-air-act-overview/clean-air-act-title-iv-noise-pollution.

United States Environmental Protection Agency (USEPA-2). 2021. "Heat Island Effect." https://www.epa.gov/heatislands

United States Environmental Protection Agency (USEPA). 2020. "What is green infrastructure." Retrieved from: https://www.epa.gov/green-infrastructure/what-green-infrastructure

United States Fish and Wildlife Service (USFWS). 2010. "Area Descriptions and Resources." Land Protection Plan: Flint Hulls Legacy Conservation Area. Chapter 2.

Verheyen, K., H. Bulteel, C. Palmborg, B. Olivié, I. Nijs, D. Raes and B. Muys. 2008. "Can Complementarity in Water Use Help to Explain Diversity-Productivity Relationships in Experimental Grassland Plots?" Oecologia 156: 351-361.

Vijayaraghavan, K. 2016. "Green Roofs: A Critical Review on the Role of Components, Benefits, Limitations and Trends." Renewable and Sustainable Energy Reviews 57: 740–53

Vijayaraghavan, K., and R. Balasubramanian. 2015. "Is biosorption suitable for decontamination of metal-bearing waters? A critical review on the state-of-the-art of biosorption processes and future directions." Journal of Environmental Management 160: 283-96.

VanWoert, N.D., D.B. Rowe, J.A. Andersen, C.L. Rugh, R.T. Fernandez, and L. Xioa. 2005a. "Green roof stormwater retention: effects of roof surface, slope, and media depth." Journal of Environmental Quality 34(3): 1036-1044.

VanWoert, N.D., D.B. Rowe, J.A. Andersen, C.L. Rugh, and L. Xioa. 2005b. "Watering regime and green roof substrate design impact Sedum plant growth." Hortscience 40(3): 659-664.

Weiler, S.K., and K. Scholz-Barth. 2009. Green roof systems: a guide to the planning, design, and construction of landscapes over structure. Hoboken, N.J.: John Wiley & Sons.

Williams, N.S.G., J.T. Lundholm, and J.S. MacIvor. 2014. "FORUM: do green roofs help urban biodiversity conservation." Journal of Applied Ecology 51 (6): 1643–1649. https://doi.org/ 10.1111/1365-2664.12333.

William, Reshmina, Allison Goodwell, Meredith Richardson, Phong V. V. Le, Praveen Kumar, and Ashlynn S. Stillwell. 2016. "An Environmental Cost-Benefit Analysis of Alternative Green Roofing Strategies." Ecological Engineering 95: 1–10. https://doi.org/10.1016/j.ecoleng.2016.06.091.

World Health Organization (WHO). 2021. "Heath topics: Air Pollution." https://www.who.int/health-topics/air-pollution#tab=tab_2

World Wildlife Fund (WWF). 2016. "Flint Hills tall grasslands." http://www.worldwildlife.org/ecoregions/na0807

Yang, J., Q. Yu, P. Gong. 2008. "Quantifying air pollution removal by green roofs in Chicago." Atmospheric Environment 42: 7266–7273.

Yok Tan, P. and A. Sia. 2005. "A pilot green roof research project in Singapore." In Proceedings of 3rd North American Green Roof Conference: Greening rooftops for sustainable communities, Washington, DC: 4–6.

Zhang, S., Y. Guo. 2013. "Analytical probabilistic model for evaluating the hydrologic performance of green roofs." Journal of Hydrologic Engineering 18: 19-28.

Chapter 2 - Substrate Descriptions

Introduction

A green roof substrate can be defined as “the soil or medium in which things grow” (Dakin et al. 2013, 94). The green roof substrate is the foundation of a green roof ecosystem and ultimately determines the success or failure of green roof vegetation (Dakin et al., 2013, Chapter 5), making it one of the most important components of green roof design. Substrate weight accounts for a large portion of the dead load on a green roof (Sutton et al., 2012). As green roofs become more popular, various types of engineered substrates have become more readily available. Green roof substrates require inorganic components to provide much of the substrate’s structure and allow for rapid permeability during heavy rainfall events. Most green roof substrates consist of porous, lightweight aggregate material, sand, and organic matter. The aggregate material for green roof substrates is typically volcanic rock (i.e., pumice or pozzolan) or artificially vitrified elements (i.e., super-heated materials that create expanded shale or expanded clay) to help provide adequate drainage through the growing medium (Lata et al., 2018).

The organic component of green roof substrate serves the purpose of providing nutrients to the green roof plants while also increasing water holding capacities (Lata et al., 2018). Substrate organic matter content influences the amount of water held in the substrate profile and microbial communities, provides essential nutrients, and improves substrate structure (Sutton 2015). Substrate depth and composition, chemical and physical properties, and water retention properties should be designed in consideration with the local climate, specified plant palette, and intended benefits of the green roof (Bousselot et al, 2020).

Green Roof Substrate Challenges

One of the most important aspects of green roof design is specifying a substrate that sufficiently supports pant growth (Bousselot at al., 2020). It is recommended that green roof substrates be designed to be lightweight, maintain air gaps to limit anoxic conditions, and drain well—while still retaining enough water and nutrients to support plant growth. These substrate recommendations pose potential challenges to those designing and specifying a green roof substrate (Ampim et al., 2010). Due to weight constraints, substrates depths are generally kept shallow, especially in green roof retrofits, which frequently place limitations on vegetation suitable for green roof plantings (Lata et al., 2018). Shallow substrates dry out faster, are more susceptible to temperature variations, and can lead to stunted growth in some plant species due to root zone restrictions (ASTM, 2019). Shallow substrate depths create a growing environment with poor conditions such as limited water storage with periodic droughts with high sun and wind exposure (Lata et al., 2018). Nevertheless, some plants can adapt to these constraints and limitations.

Important Characteristics of Substrates: Physical and Chemical Properties

One of the biggest challenges in green roof design is finding a balance between the need for lightweight substrate materials while providing sufficient water retention. Green roof substrates are designed to have a somewhat coarse texture to ensure good infiltration, especially during heavy or persistent rainfall events, to limit the possibility of ponding and overweighting due to overabundant water retention. Green roof plant success is greatly influenced by substrate composition and many other aspects of green roof design (Ampim et al., 2010; Nagase and Dunnett, 2011; Ntoulas et al., 2013). Substrate composition is an extremely important consideration when designing green roofs because green roof species survival and growth can be greatly influenced by factors such as particle size, bulk density, organic matter type and content, nutrient levels and composition, and so forth (Best et al., 2015). Adequate texture, structure, and organic matter, nutrient availability, water retention capabilities, and good drainage are all substrate characteristics that are critical for the success of green roof vegetation (Best et al., 2015).

Particle size distribution is arguably the most important substrate physical property because it determines the physical amount of water a substrate can hold through adhesive and cohesive forces (Handreck and Black, 2002). Substrate texture and structure properties influence saturated water content, field capacity (FC), and permanent wilting point (PWP). Porosity is a very important physical property of green roof substrates. Soil structure characteristics affect plant available water (PAW) as increasing substrate porosity with a wide range of pore size distributions can increase PAW due to the ideal combination of meso and macropores (O’Green et al., 2010). Pores ranging from 0.0002 mm to 0.01 mm in size can hold water (Rousseva et al., 2017). Increases in substrate porosity result in an increase in the evaporative cooling potential of the green roof (Bousselot et al., 2020). Coarse textured substrates have lower water retention capabilities. Water available to plants is lowest in coarse textured soils due to pore size distribution dominated by large pores that are limited in water retention abilities (Kirkham, 2014). Fine textured soils have the greatest water storage capacities because of high porosity values. However, a large portion of the water in smaller pores is held too strongly for plant uptake and use (O’Green et al., 2010; Kirkham, 2014). Substrates with a range in pore size distribution consist of meso- and micro-porosity resulting in a high amount of plant available water (O’Green et al., 2010).

Organic matter can help the substrate retain water (Kirkham, 2014) while too much organic matter can result in hydrophobicity or water repellency which are caused when inorganic soil particles become coated with hydrophobic organic matter (Quyum, 2000). Organic matter can hold water up to nine times its weight (Hillel, 2003). In theory, increasing a substrate's organic matter content should increase its ability to hold water. Griffin (2014) found that increasing organic matter content from ten to 40 percent does not affect the flow of water through the media. Because hydrophobic soils repel moisture, water generally runs off for an extended period, until the organic coating can be broken (Griffin, 2014). ASTM (2020) recommends an organic matter content ranging from three to fifteen percent.

Services Provided by Substrates

Green roofs have been growing in popularity since the 1980's. One of the major reasons for interest in green roofs is the environmental benefits and ecosystem services they provide. The *Millennium Ecosystem Assessment* defines ecosystem services as "the benefits people obtain from ecosystems" (MEA, 2005). Lata et al (2018) argue that the role of green roof substrates in providing ecosystem services is dependent on substrate characteristics, especially substrate composition, porosity, and depth. Fertility and nutrient availability are directly affected by substrate composition, and both influence vegetative survival, growth, and health (Lata et al 2018). The primary services provided by substrates are support of living vegetation (that can then provide habitat for a range of fauna) (Colla et al., 2009; Coffman and Davis 2005; Brenneisen, 2006; Kadas, 2006; Schrader and Böning 2006, MacIvor and Ksiazek, 2015) , attenuation of stormwater runoff (to help reduce flooding and other negative impacts within a watershed) (Dunnett and Kingsbury, 2004; Mentens et al., 2006; VanWoert et al., 2005, Oberndorfer et al., 2007; Lambrinos, 2015), and insulation of buildings (to reduce rooftop temperatures during warm months and the urban heat-island effect more broadly by reducing the use of heat-creating HVAC mechanical systems) (Skabelund et al., 2015, Santamouris, 2014).

Substrate composition and porosity affect water retention. As noted above, water retention capabilities affect ecosystem services such as supporting vegetation and habitat, attenuating stormwater runoff, and reducing the urban heat-island effect—and water retention capacity is directly related to the substrate type used in a green roof design. Water retention affects substrate temperature by creating cooling dynamics, which influences both the growth and functions of plant root systems and building cooling performance (Lata et al., 2018). Lower temperatures on rooftops and within building interiors due to transpired stormwater aids in building cooling during the warmer months leading to less energy use and CO_2 emissions related to energy production (Sutton, 2015).

Green roof substrates can also affect the ecosystem services that are provided by deeper substrate depths. Typically, plant growth and water retention benefits from deeper substrates (Nagase and Dunnett, 2010). Increasing substrate depth increases the total volume of substrates available for roots and water on a green roof (VanWoert, 2005; Lambrinos, 2015). Thus, increasing total volume of substrate allows for a greater volume of water to be stored after a storm, making them more effective at stormwater management and increasing vegetative biomass and the shading, cooling, and habitat functions plants provide. Nevertheless, the cost of increasing structural capacity may not be feasible and will likely require more resources. Life-cycle costs and benefits are very important to consider during the planning and design phase of a structure. Guidelines and standards help designers, engineers, and others consider the best ways to create living rooftop systems and support the services they can provide.

Green Roof Guidelines and Standards

For decades, green roof designers in the United States and Europe have used the German Forschungsgesellschaft Landschaftsentwicklung Landschaftbau (FLL) guidelines which provide important information for planning, construction, and maintenance of green roofing. These guidelines are very useful for considering appropriate design, specification of materials, implementation techniques, and management protocols for green roofs. However, because green roof design needs to be very specific to the local climate, only relevant sections should be applied outside of Germany and similar climates (Dakin et al., 2013, Chapter 6). FLL guidance that is broadly relevant includes creating a required impermeable layer beneath the green roof, designing protections against wind uplift, providing a root barrier to protect the waterproofing layer(s), and provision of appropriate water retention materials, each implemented per structural capacity allowances (Dakin et al., 2013, Chapter 6).

In 2002, two German green roof experts released the FLL guidelines with the recommendation that the American green roof industry implement this guideline to improve the industry (GRT, 2020). A suggested selection of green roof substrate materials and performance characteristics were provided in the FLL Guideline with the assumption that each green roof need to be designed and implemented with plant species that possess low water requirements (Sutton, 2015). The FLL Guideline has since been widely accepted across North America and helps green roof designers and installers understand the function and importance of various green roof components. Commercial green roof substrate providers typically use substrates engineered based on the FLL guidelines (Sutton 2015, 8).

ASTM International, formerly known as American Society for Testing and Materials, is an international standards organization that puts out voluntary consensus standards for a wide range of materials, products, systems, and services. ASTM E2400 (2019) and ASTM 2777 (2020) outline important guidelines for green roof substrates and vegetation. ASTM (2019) lists common green roof substrate mineral aggregate components such as expanded shale, slate, clay, lava, and pumice. The mineral component of green roof substrates should fall in the range of 85 to 97 percent on a dry weight basis (ASTM, 2020). ASTM (2020) states that substrate design choices should take into consideration factors such as performance intentions, regional substrate material availability, costs, and dead load allowances. ASTM (2020) also suggests not using clay materials and limiting silt content to less than 15 percent for green roof substrates.

Need for Region-Specific Guidelines

Although the FLL and ASTM guidelines provide recommendations on green roof substrate materials and characteristics that can be considered and adapted anywhere around the world, there are very few region-specific guidelines developed for green roof substrates. On the other hand, there have been an increasing number of studies to assess the effectiveness of different green roof compositions for different region-specific plant species and communities. More region-specific guidance for green roof substrates is needed. Some designers recommend highly organic admixtures with up to twenty percent compost or peat moss, while others opt for lower amounts of organic matter in the five percent range (Friedrich 2008; Buist 2008), but how will these different mixes function in different climatic regimes? ASTM (2020) recommends an initial organic matter content of 3 to 15 percent. Heat expanded slate, shale, and clay; crushed brick or tile; volcanic ash; pumice; lava rock; perlite; sand and combinations of these are the most common types of inorganic green roof substrate material per ASTM (2020). In combination with the need for and lack of region-specific green roof guidelines, green roof substrates inherently present challenges that must be addressed during design and implementation.

Challenges of Artificial Substrates

The literature regarding soil science offers detailed and extensive studies about natural soils and particle fractions (such as sand, clay, sandy loam, etc.), however, for green roofs there is relatively little information (Sailor and Hagos, 2011; Bousselot, et al., 2020). Substrate composition influences plant communities primarily through moisture retention and nutrient availability (Rowe, 2015). Previous green roof studies highlight the lack of peer-reviewed literature on green roof substrates (Ampim et al., 2010; Olszewski and Young, 2011; Bousselot et al., 2020). As such, it is very important to characterize the differences in the selected Architecture, Planning and Design Experimental Green Roof (APD-EGR) substrates to provide insight on how these differences are influencing the hydrologic and vegetative parameters being assessed throughout the study.

Green Roof Substrates Used in This Study

As stated previously, green roof substrate specification and selection is an extremely crucial part of the green roof design process. For green roof design to be as sustainable as possible, use of locally sourced materials with minimal embodied energy (energy consumed by the process of building and construction) should utilized (Sutton, 2015). Currently it is unclear what substrate characteristics are ideal for green roofs in Manhattan, Kansas that are planted with several different plant mixes that include *Sedums*, Kansas native plants, and a combination of the two. Three experimental green roof beds were designed and implemented atop Regnier Hall at Kansas State University to compare two substrates that were specified for other green roofs on campus. The intent of the three APD-EGR planting areas (beds) was to provide information on how substrate type and depth affect plant survival and growth in a continental north-central Kansas climate and with similar growing conditions. During the design phase of the APD-EGR a lot of thought was given to where the substrates and plant materials could be obtained. It was the designer's intent to source as much of the green roof materials as possible within the region or even locally. Two substrates (with most of the materials available within 200 miles of the project site) were selected to compare how substrate type affects selected plant species survival and growth.

The first APD-EGR substrate is Rooflite® Extensive MC substrate, specified for several nearby green roofs designed by landscape architects at Confluence (Kansas City, Missouri) working in collaboration with the larger APD building project design team. Rooflite® Extensive MC substrate is a commercially provided engineered substrate produced by Skyland USA, LLC out of Landenberg, Pennsylvania. Skyland has provided Rooflite® soil for over 1,000 green roof projects in the Americas (Rooflite, 2020). Rooflite® Extensive MC utilizes a blender network of more than twenty regional partners that specialize in blending standardized substrate products specific to each region (Rooflite, 2020). The Rooflite® substrate used for this study was regionally blended by Missouri Organics in Kansas City, Missouri. Each regional blend utilizes cost effective raw materials that also account for the regional climate (Rooflite, 2020). The Rooflite® Extensive MC substrate consists of large (>2mm) heat expanded shale particles and organic components (likely composted plant bark). Rooflite® Extensive MC substrate contains BuildEx Haydite® (described in some detail below) as its' heat expanded shale particles component.

The second APD-EGR substrate, Kansas BuildEx, is a locally blended mix and was specified for the East Memorial Stadium Green Roof designed by landscape architects and an agronomist at Jeffrey L. Bruce and Company (Kansas City, Missouri) and the larger Memorial Stadium project team. BuildEx expanded shale lightweight aggregate is an important component of the Kansas BuildEx substrate, which is predominantly sand (approximately 68%), and less than 8% silt and clay combined.

BuildEx was founded in Ottawa, Kansas and ships over 225,000 cubic yards of BuildEx aggregate from its New Market, Missouri site for a broad spectrum of applications including asphalt preservation, lightweight structural concrete, internal curing, lightweight geotechnical fill, aquaponics, stormwater management and water treatment, masonry block, green roofs, and horticulture. BuildEx Haydite® is a soil media used for horticulture, green roof, and landscape products (BuildEx, 2020). BuildEx Haydite® is used in both extensive and intensive green roofs as a soil conditioner, meaning it is an amendment used to both lighten the substrate and improve soil structure. Soil conditioners are used to improve aeration, water retention capabilities, and nutrients to support healthy plant growth and increase drainage (Shinde et al. 2019). Some of the listed benefits of BuildEx are that it: (1) promotes strong root development, (2) improves aeration and drainage, (3) reduces nutrient loss and improves moisture retention, (4) enhances soil resiliency to climate change, and (4) resists compaction (BuildEx, 2020).

For the APD-EGR, BuildEx Haydite® was used in a blend created by Blueville Nursery, a local horticultural nursery and landscape contractor in Manhattan, Kansas. As noted above, the blend created by Blueville Nursery included a large percentage of sand (mined along the Kansas River near Manhattan), creating a blend with a good balance between BuildEx Haydite® and sand. The blend included 67 percent mason sand (2.0-0.075 mm), small percentages of silt (0.075-0.002 mm) and clay (<0.002mm), with 4.5 percent silt and 2.9 percent clay; this substrate also included fine grade peat moss, worm castings, cattle manure compost from the KSU Stocker Unit, and BuildEx Haydite®. BuildEx Haydite® and other large particles (>2.0 mm) made up about 25 percent on the Kansas BuildEx substrate blend (Skabelund et al., 2017).

Experimental Layout

The Kansas BuildEx and Rooflite® Extensive MC substrates were selected for this study because they were used for other green roofs implemented at Kansas State University and were shown (or assumed) to be suitable growing medium for *Sedum* species and selected Kansas native prairie plant species. An experimental layout was designed by Lee R. Skabelund (KSU-Landscape Architecture) and Timothy Todd (KSU-Plant Pathology). The layout of the substrates is shown below in Figure 2.1. The experimental layout of the green roof substrate is a strip-plot design in a randomized complete block design (RCBD). This layout is an important part of the experimental design for assessing the effect of substrate type on soil-water characteristics and plant cover and above ground biomass (Chapters 3 and 4). Figure 2.1 shows substrate arrangements on the APD-EGR as installed in mid-July 2017. At the outset, K-State researchers could see visible differences in these two substrates. Kansas BuildEx appeared lighter in color than Rooflite® Extensive MC due to the high sand content of Kansas BuildEx.

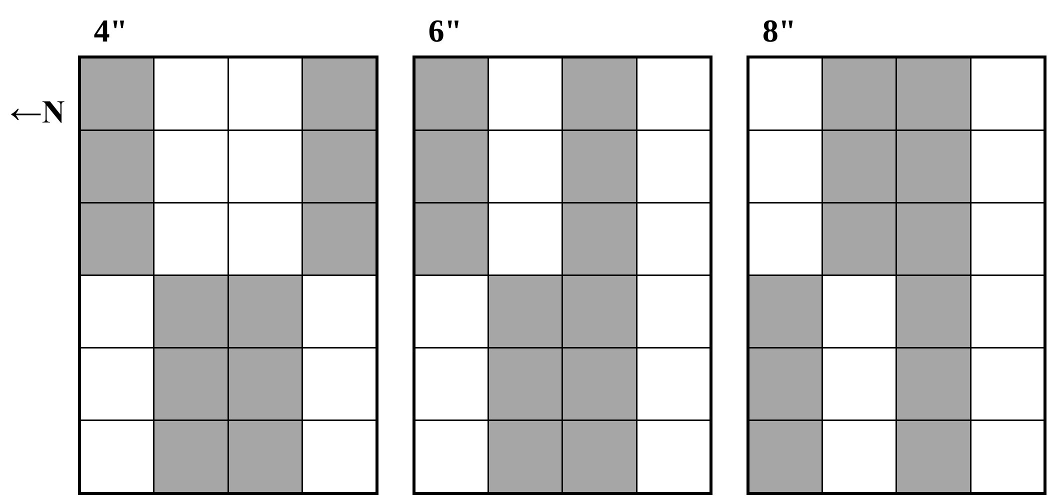


Figure 2.1. Substrate Layout for Each Planting Area. Shaded boxes represent experimental plots that consist of Kansas BuildEx substrate and non-shaded areas represent experimental plots that consist of Rooflite® Extensive MC substrate. The 4”, 6”, and 8” below each planting area.

Figure 2.2. Substrate Application on the APD-EGR, with most of the 6-inch and 8-inch Beds Shown. In the photo on the left one can see the filter fabric that is being placed atop the BuildEx Haydite® drainage layer, with the two different substrate mixes then placed atop the BuildEx Haydite® drainage layer, with the two different substrate mixes then placed on top of the fabric separator within each of the 72 green roof plots. Photos by Lee R. Skabelund (July 18, 2017).

Substrate Visual Observations

Based on substrate observations during sensor calibration and species planting, it was perceived that the two substrates were quite different. The Kansas BuildEx substrate had a higher sand content (67 percent for Kansas BuildEx, versus 52.4 percent for the Rooflite® Extensive MC substrate). The Rooflite® Extensive MC substrate appeared to contain more lightweight expanded shale (BuildEx Haydite®) as well as organic matter in the form of finely composted plant bark and possibly other organic materials (40.5 percent for the Rooflite® Extensive MC substrate, versus 25 percent for Kansas BuildEx). For the following two chapters of this dissertation, it is important to understand the physical and chemical differences between these two substrates since physical and chemical properties can affect both how water is stored within the substrate profile and plant success (which depends on available water).

Rooflite® Extensive MC substrate is a commercially supplied green roof substrate and Rooflite describes its extensive substrate as “a balanced blend of carefully selected lightweight mineral aggregates and premium organic components” (Rooflite, 2020). Because the specifications provided by Rooflite® provide such a wide range of values for bulk density, organic matter, permeability, maximum water-holding capacity and other properties, it was necessary to conduct further testing on this substrate to narrow the range of values for these important stormwater management and vegetation-supporting properties (refer to Table 2.1). A comparable list of specification is listed in Table 2.2.

As noted previously, Kansas BuildEx was specified for use on the East Memorial Stadium Green Roof (East MSGR) by Jeffrey L. Bruce and Company. Leftover material from this project (with substrates installed October-November 2016) was stored by Blueville Nursery at their Anderson Avenue site. This material was brought to the APD-EGR in mid-July 2017 after sitting in a large pile for nearly two years, being mixed with new materials, and then tested to match the East MSGR specification (Tim Sharp, Blueville Nursery, Project Manager, personal communication, March 2018).

Table 2.1. Rooflite® Extensive MC Substrate Specifications Highlighting the Range of Values in Maximum Water-Holding Capacity and Organic Matter Content (bolded on the right column).

Water/Air Measurements (ASTM E2399)	
Total Pore Volume (Vol. %)	> 50
Maximum water-holding capacity (Vol. %)	**40 – 60**
Air-filled porosity at maximum water-holding capacity (Vol. %)	> 7
Water permeability (saturated hydraulic conductivity) (in/min)	0.024 – 2.83
pH and Salt Content	
pH (in $CaCl_2$)	6.0 - 8.5
Soluble salts (water, 1:10, m:v) (g (KCl)/L)	< 3.5
Organic Measurements (LOI at 500°C SM 2540 G)	
Organic matter content (g/L)	**25 - 65**

Table 2.2. Kansas BuildEx Substrate Specifications Highlighting the Range of Values in Maximum Water-Holding Capacity and Organic Matter Content (bolded on the right column).

Test	**Criteria**
Infiltration rate (k-sat at 20C)	5 – 10 in/hr
Bulk density	1.5 to 1.7 g/cm^3
Total porosity	35% to 45%
Water retention at 0 to 75 cm SMP	Maximum value 60% saturation loss
Water release at 0 to 350 cm SMP	Minimum value 40% saturation
Organic matter (dry weight)	**1.5 to 2.5% (range only)**

Substrate Testing Methods

In March 2018, substrate samples were collected from the center of each of the 72 green roof plots to create a single composite sample of each substrate type at each depth (12 mixed samples for each). These samples were taken to the Kansas State University Soil Testing Lab (KSU-STL) in Manhattan, Kansas. Nutrient, electrical conductivity, cation exchange capacity, and pH tests were done for both Kansas BuildEx and Rooflite® Extensive MC substrates.

Additional substrate samples were collected from the supply of substrates used during installation but not placed on the APD-EGR. These samples were sent to Turf and Soil Diagnostic lab (TSD) in Linwood, Kansas. TSD was selected because it provides a suite of laboratory analyses of growing media, drainage material, and components for green roof systems and has conducted analyses for the Memorial Stadium Green Roof substrates at Kansas State University. TSD performed water retention, water permeability, bulk density, saturated density, total pore space, air-filled porosity, and organic matter measurements for each of the green roof substrates. Each of these tests was done with two replicates.

Table 2.3 shows the results for both KSU-STL and TDS tests. Physical property tests by TSD for bulk density, saturated bulk density, total pore space, air-filled pore space, water permeability, and maximum media water retention were conducted using ASTM E2399 (ASTM International, 2019). Particle size distribution tests used ASTM F1632 Method B (ASTM, 2018a, 2018b). Organic matter content was determined by TSD using FLL guidelines (FLL, 2008). Analysis of pH was conducted using ASTM D4972 and $CaCl_2$ was used for the analysis (ASTM International, 2018a, 2018b). Analysis of NO_3 by the KSU-STL was determined per the Alpkem Corporation (1986) using the Alpkem RFA300 Auto Analyzer by Alpkem, in Clackamas, Oregon, USA. The Melich-3 test was used to determine plant available phosphorus (Melich, 1984). Tests for K, Mg, Ca, Zn, Cu, Mn, and Na were conducted by KSU-STL using an Inductively Coupled Plasma (ICP) Spectrometer (Varian Australia Pty Ltd., Mulgrave, Australia).

Substrate Testing Analysis

Analyses of the TSD technical replications and KSU-STL data were completed in SAS version 9.4. A two-sample t-test was conducted to test for a difference between mean values for BuildEx and Rooflite® Extensive MC for the factors water retention, water permeability, bulk density, saturated density, total pore space, air-filled porosity, and organic matter ($\alpha = 0.05$). Two sample t-tests were also conducted to test for a difference between the mean values for BuildEx and Rooflite® Extensive MC for the testing done at KSU-STL for nutrient, electrical conductivity, cation exchange capacity, and pH tests ($\alpha = 0.05$).

Results and Discussion

There was strong evidence for a significant difference between Kansas BuildEx and Rooflite® Extensive MC substrate for both dry bulk density ($p = 0.002$) and saturated bulk density ($p = 0.0073$) with both values being greater for Kansas BuildEx (Table 2.3). The lower bulk and saturated densities of Rooflite® Extensive MC substrate make this substrate more commonly specified and used for buildings being retrofitted for green roofs. There was evidence for a significant difference between total pore space, maximum water retention, and water permeability mean values for Kansas BuildEx and Rooflite® Extensive MC ($p = 0.0205$, 0.0577, 0.0093 respectively).

Total pore space and air-filled pore space were both greater in Rooflite® Extensive MC substrate than Kansas BuildEx. Rooflite® Extensive MC substrate also had a greater maximum water retention and water permeability than Kansas BuildEx. These differences in water retention and water permeability likely influence the soil-water characteristics for each substrate type and how each substrate stores and dispenses water. Differing water characteristics likely influence vegetative cover and biomass because plant species have different preferences for substrate available water.

Table 2.3. Physical and Chemical Properties of Selected Substrates, Kansas BuildEx and Rooflite® Extensive MC.

Property	Lab	BX	stdev	RL	stdev	p-value
Dry density (g/cm^3)	A	1.47	0.01	0.98	0.01	0.0002*
Saturated density (g/cm^3)	A	1.77	0.01	1.33	0.00	0.0073*
Maximum water retention (%)	A	29.50	0.71	35.00	0.00	0.0577*
Total pore space (%)	A	42.50	0.71	58.00	0.00	0.0205*
Air-filled porosity (%)[2]	A	13.00	0.00	23.00	0.00	-
Water permeability (mm/min)	A	0.20	0.00	30.90	0.64	0.0093*
pH[1]	B	7.00	-	7.60	-	-
EC (mmhos/cm)[2]	A	0.10	0.00	0.20	0.00	-
OM (%)	B	2.10	0.14	1.95	0.05	0.3118
Total N (%)	B	0.73	0.04	2.30	0.71	0.0615
Total C (%)	B	3.64	0.20	6.00	0.94	0.0130*
Ca (mg/L)	B	1464.7	293.94	1346.3	221.96	0.8268
Cu (mg/L)	B	0.27	0.06	0.63	0.06	0.0015*
Zn (mg/L)	B	0.87	0.31	3.17	0.60	0.0041*
Mg (mg/L)	B	97.87	38.10	88.93	17.81	0.7316
Mn (mg/L)	B	2.07	0.12	3.27	0.40	0.0078*
Na (mg/L)	B	18.10	15.55	18.07	9.80	0.9976
NO3 (mg/L)	B	3.63	1.16	1.97	0.15	0.1282
P (mg/L)	B	56.3	40.66	54.6	7.50	0.6844
K (mg/L)	B	107.00	26.37	83.47	5.67	0.2053
Fe (mg/L)	B	14.43	1.40	19.90	2.82	0.0395*

Note: BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC substrate. Stdev is standard deviation. P-values with an asterisk (*) denote a significant difference among the means ($\alpha = 0.05$). Lab analyses denoted with an A were conducted by Turf and Soil Diagnostics Lab and analyses denoted with a B were conducted by KSU Soil Testing Lab. Two replications for all Turf and Soils Diagnostics Lab analyses, except pH (no replication). There were three replicates for all KSU Soil Testing Lab analyses. For analyses with a standard deviation of 0.00 the replication results were the same and statistical analyses were not conducted[2]. Analysis for pH was not conducted due to only having one replication.[1]

The physical and chemical properties of the two substrates shown in Table 2.3 and discussed in this dissertation are based upon the conditions of the substrates when they were collected from the APD-EGR in March 2018 or gathered from stored substrate materials and then taken to each respective soil testing lab. Changes in substrates through time were not examined. Detectable chemicals in the Humic Balance remaining in the substrates when APD-EGR samples were collected in March 2018 would have been accounted for in the KSU-STL tests.

Tests for particle size distribution (Table 2.4) show that Kansas BuildEx contained a greater proportion of sand particles and more clay than Rooflite® Extensive MC substrate. Kansas BuildEx may have a greater effect on plant performance (cover and biomass) because fine particles can increase nutrient uptake and translocation (Zhao et al., 2012). Additionally, water retention is greater for substrates consisting or more particle of smaller sized due to having greater inner particle pore space (Young et al., 2014). It is expected that water will rapidly flow through Rooflite® Extensive MC substrate due to it being composed primarily of large particles, resulting in greater pore space (Handreck and Black, 2002).

Table 2.4. Particle Size Distribution for Selected Substrates.

Particle Size (mm)	BX	RL
Clay < 0.002	2.9	1.3
Silt 0.002 - 0.0063	4.5	5.8
Sand 0.063 – 2.0	67.6	52.4
Particles[1] > 2.0	25	40.5

Note: BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC substrate. Includes both mineral and organic components[1].

Conclusions

As stated in Chapter 1, the goal of this dissertation was to understand the relationships between micro-meteorological variables, substrate type and depth, and mixed-species performance on green roof systems. The first part of understanding these relationships was to pinpoint key differences between the two substrates used for this study. Substrate chemical and physical properties can greatly influence plant health, plant growth, and the water characteristic of a substrate. There are significant differences between Kansas BuildEx and Rooflite® Extensive MC for several substrate physical properties (dry density, saturated density, maximum water retention, total pore space and water permeability). Kansas BuildEx had a greater dry density and saturated density than Rooflite® Extensive MC. However, Rooflite® Extensive MC had greater maximum water retention, total porosity, air-filled porosity, and water permeability than Kansas BuildEx. There are also significant differences between Kansas BuildEx and Rooflite® Extensive MC for several chemical properties (Total C, Cu, Zn, Mn, and Fe), with Rooflite® Extensive MC having greater chemical contents. It is unclear how the differences in substrate chemical and physical properties between Kansas BuildEx and Rooflite® Extensive MC substrate will affect how water is stored and dispensed (Chapter 3) over the long-term and plant performance (Chapter 4), but the differences identified during this 2018-2019 study are discussed in related chapters.

Future Recommendations

Substrate nutrient levels change temporally, and plants can influence the rate at which these levels are depleted (Mitchell, 2017). It would be beneficial to repeat substrate chemical analysis on this green roof in the future to see how these nutrient levels have changed. Also, many of the substrate tests were done with only two replicates. Replication should be increased for future substrate tests to allow for statistical analyses and to increase the statistical power of each analysis conducted. Lekhon Alam (KSU Ph.D. student who is also studying the APD-EGR) has done initial substrate analyses that should provide further insights as the two substrates and plant mixes on the APD-EGR have matured. Studies five years and ten years after implementation of the APD-EGR (in 2023 and 2028) should be very instructive.

References

Alpkem, 1986. RFA Methodology for Nitrate and Nitrite Nitrogen. A303–S170 (Alpkem Corporation, Clackamas, OR, US).

Ampim, P.A.Y., Sloan, J.J., Cabrera, R.I., Harp, D.A., Jaber, F.H., 2010. "Green roof growing substrates: types, ingredients, composition and properties." Journal of Environmental Horticulture 28 (4), 244–252. https://www.hrijournal.org/doi/pdf/10.24266/0738-2898-28.4.244

ASTM International, 2018a. ASTM D4972-18, Standard Test Methods for pH of Soils. (West Conshohocken, PA, US). https://doi.org/10.1520/D4972-18

ASTM International, 2018b. ASTM F1632-03, Standard Test Method for Particle Size Analysis and Sand Shape Grading of Golf Course Putting Green and Sports Field Rootzone Mixes. (West Conshohocken, PA, US). https://doi.org/10.1520/F1632-03R18

ASTM International, 2019. ASTME2399/E2399M-19, Standard Test Method for Maximum Media Density for Dead Load Analysis of Vegetative (Green) Roof Systems. (West Conshohocken, PA, US). https://doi.org/10.1520/E2399_E2399M-19

ASTM International, 2020. ASTM E277-20, Standard Guide for Vegetative (Green) Roof Systems. (West Conshohocken, PA, US).

Best, Brooke Byerley, Rebecca K. Swadek, and Tony L. Burgess. 2015. "Chapter 6- Soil-Based Green Roofs." In Green Roof Ecosystems (Ed. by R. Sutton). London: Springer Science, 139–74. https://doi.org/10.1007/978-3-319-14983-7_6

Bousselot, J., V. Russel, L. Tolderlund, S. Celik, B. Retzlaff, S. Morgan, I. Buffam, R. Coffman, J. Williams, M. E. Mitchell, J. Backer, J. DeSpain. 2020. "Green Roof Research in North America: A Recent History and Future Strategies." Journal of Living Architecture 7: 27-64.

Brenneisen, S., 2006. "Space for urban wildlife: designing green roofs as habitats in Switzerland." Urban Habitats 4: 27-36.

BuildEx. 2020. "Green Roofs and Horticulture." Retrieved from: https://buildex.com/green-roofs-and-horticulture/

Buist R. 2008. "Going for organics." Living Architecture Monitor 10(1):16–21.

Coffman, R.R., and G. Davis. 2005. "Insect and avian fauna presence on the Ford assembly plant ecoroof." Paper presented at the Third Annual Greening Rooftops for Sustainable Communities Conference, Awards and Trade Show: Washington, D.C., 4-6 May.

Colla, S.R., E. Willis, and L. Packer. 2009. "Can green roofs provide habitat for urban bees (Hymenoptera: Apidae)?" Cites and the Urban Environment 2 (1): 1-12.

Dakin, Karla., Lisa Lee. Benjamin, and Mindy. Pantiel. 2013. The Professional Design Guide to Green Roofs. 1st ed. Portland, Or. Timber Press.

Dunnett, N., and N. Kingsburry. 2004. Planting Green Roofs and Living Walls. Portland, Oregon: Timber Press.

Emilsson, Tobias. "Vegetation Development on Extensive Vegetated Green Roofs: Influence of Substrate Composition, Establishment Method and Species Mix." Ecological Engineering 33, no. 3–4 (July 2008): 265–77. https://doi.org/10.1016/j.ecoleng.2008.05.005

FLL. 2008. Guideline for the Planning, Execution and Upkeep of Green Roof Sites. Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e. V. Colmantstr. 32, 53115 Bonn.

Friedrich, C. 2008. "Don't call it dirt!" Living Architecture Monitor 10(1):16–21.

Griffin, K. 2014. Extensive Green Roof Substrate Composition: Effects of Physical Properties on Matric Potential, Hydraulic Conductivity, Plant Growth, and Stormwater Retention in the Mid-Atlantic. PhD Dissertation. University of Maryland.

Green Roof Technology (GRT). 2020. "German FLL Guideline for Green Roofs introduced in 2002 at ASTM: Subcommittee E06.71." Jörg Breuning. Accessed May 2020. http://www.greenrooftechnology.com/fll-green-roof-guideline

Handreck, K. and N. Black. 2002. Growing media for ornamental plants and turf. Second Edition. University of New South Wales Press, Sydney, Australia. 483 pp.

Hillel, D. 2003. Introduction to Environmental Soil Physics. San Diego, CA. Elsevier Science.

Kadas, G. 2006. "Rare invertebrates colonizing green roofs in London." Urban Habitats 4: 66-86.

Kirkham, M. B. 2014a. "Chapter 4 - Soil–Water Terminology and Applications." In Principles of Soil and Plant Water Relations (Second Edition), 41–52. Boston: Academic Press. https://doi.org/10.1016/B978-0-12-420022-7.00004-5

Kirkham, M. B. 2014b. "Chapter 10 - Field Capacity, Wilting Point, Available Water, and the Nonlimiting Water Range." In Principles of Soil and Plant Water Relations (Second Edition), 153–70. Boston: Academic Press. https://doi.org/10.1016/B978-0-12-420022-7.00010-0

Lambrinos, J. 2015. "Chapter 4 - Water Through Green Roofs," In Green roof Ecosystems ." (Ed. by R. Sutton). London: Springer Science. 81–105. https://doi.org/10.1007/978-3-319-14983-7_4.

Lata, J. -C., Y. Dusza, L. Abbadie, S. Barot, D. Carmignac, E. Gendreau, Y. Kraepiel, J. Mériguet, E. Motard, and X. Raynaud. 2018. "Role of Substrate Properties in the Provision of Multifunctional Green Roof Ecosystem Services." Applied Soil Ecology: 464–69. https://doi.org/10.1016/j.apsoil.2017.09.012

MacIvor, J.S., and K. Ksiazek. 2015. "Chapter 14 - Invertebrates on Green Roofs," In Green Roof Ecosystems (Ed. by R. Sutton). London: Springer Science. 333-355.

Mentens, J., D. Raes, M. Hermy. 2006. "Green roofs as a tool or solving the rainwater runoff problem in the urbanized 21st century." Landscape and Urban Planning 77: 217-226.

Mehlich, A., 1984. "Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant." Communication in Soil Science and Plant Analysis 15 (12), 1409–1416. https://doi.org/10.1080/00103628409367568

Millennium Ecosystem Assessment (MEA) (Program). 2005. Ecosystems and human well-being. Washington, D.C: Island Press.

Mitchell, Mark Edwin. 2017. "Nutrient Cycling Dynamics and Succession in Green Roof Ecosystems." Ph.D., United States -- Ohio: University of Cincinnati. https://search.proquest.com/docview/2124444033/abstract/E4AA6731BEB94BFEPQ/1

Nagase, A. and N. Dunnett. 2010. "Drought tolerance in different vegetation types for extensive green roofs: Effects of watering and diversity." Landscape Urban Planning 97: 318–327.

Nagase, Ayako, and Nigel Dunnett. 2011 "The Relationship between Percentage of Organic Matter in Substrate and Plant Growth in Extensive Green Roofs." Landscape and Urban Planning 103 (2): 230–36. https://doi.org/10.1016/j.landurbplan.2011.07.012

Nektarios, P.A., I. Amountzias, I. Kokkinou, and N. Ntoulas. 2011. "Green roof substrate type and depth affect the growth of the native species Dianthus fruticosus under reduced irrigation regimens." HortScience 46: 1208–1216.

Nippert, J.B., R.A. Wieme, T.W. Ocheltree, and J.M. Craine. 2012. "Root characteristics of C-4 grasses limit reliance on deep soil water in tallgrass prairie." Plant and Soil 355: 385 - 394. https://doi.org/10.1007/s11104-011-1112-4

Ntoulas, Nikolaos, Panayiotis A. Nektarios, Eleutherios Charalambous, and Achilleas Psaroulis. 2013. "Zoysia Matrella Cover Rate and Drought Tolerance in Adaptive Extensive Green Roof Systems." Urban Forestry & Urban Greening 12 (4): 522–31. https://doi.org/10.1016/j.ufug.2013.07.006

O'Green, A. T., R.A., Dahlgren, A. Swarowsky, K.W. Tate, D.J. Lewis, and M.J. Singer. 2010. "Research connects soil hydrology and stream water chemistry in California oak woodlands." California Agriculture 64, 78-84.

Oberndorfer, E., J. Lundholm, B. Bass, R. Coffman, H. Doshi, N. Dunnett, S. Gaffin, M. Kohler, K. Liu, and B. Rowe. 2007. "Green roofs as urban ecosystems: ecological structures, functions, and services." Bioscience 57: 823-833.

Olszewski, M. and C. Young. 2011. Physical and chemical properties of green roof media and their effect on plant establishment. Journal of Environmental Horticulture 29(2): 81-86. https://doi.org/10.24266/0738-2898-29.2.81

Quyum, A. 2000. “Water Migration Through Hydrophobic Soils. Dissertation.” University of Calgary. 157 pages.

Richards, L. A. 1931. “Capillary conduction of liquids through porous mediums.” Physics 1:, 318-333.

Rooflite. 2020. “Certified Green Roof Media. Retrieved” from: https://www.roofliteoil.com/

Rousseva, S. M. KerchevaT. ShishkovG.J. LairN.P. NikolaidisD. MoraetisP. KrámS.M. BernasconiW.E.H. BlumM. MenonS.A. Banwart. 2017. “Soil Water Characteristics of European SoilTrEC Critical Zone Observatories” Advances in Agronomy: 142 https://doi.org/10.1016/bs.agron.2016.10.004.

Rowe, DB. 2017. “Green roofs: plant production and installation methods.” In Proceedings of the 2017 Annual Meeting of the International Plant Propagators' Society 97-100.

Sailor, D.J., and M. Hagos. 2011. “An updated and expanded set of thermal property data for green roof growing media.” Energy and Buildings 43(9): 2298-2303.

Santamouris, M. 2014. “Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments.” Solar Energy 103 (5): 682-703.

Schrader, S., and M. Böning. 2006. “Soil formation on green roofs and its contribution to urban biodiversity with emphasis on Collembolans.” Pedobiologia 50:347–356.

Schroll E, J. Lambrinos, and D. Sandrock. 2009. “Irrigation requirements and plant survival on northwest green roofs.” Atlanta, GA: The Cardinal Group; Seventh Annual Greening Rooftops for Sustainable Communities Conference, Awards and Trade Show. Toronto.

Silvola, J. 1985. “Photosynthesis measurements on a CAM plant, Sedum telephium (Crassulaceae).” Annales Botanici Fennici 22(3): 195-200.

Skabelund, L.R., C. Blocksome, D. Brokesh, J.H. Kim, M. Knapp, and M. Hamehkasi. 2014. “Semi-arid green roof research 2009–2014: resilience of native species.” Paper Presented at the 12th Annual Green Roof & Wall Conference, Nashville, TN.

Skabelund, L.R. K. DiGiovanni and O. Starry. 2015. “Chapter 2 - Monitoring Abiotic Inputs and Outputs.” In Green Roof Ecosystems (Ed. by R. Sutton). London: Springer Science. 27-62.

Skabelund, L., A. Decker, T. Moore, P. Shrestha, and J. L. Bruce. 2017. “Monitoring two large-scale prairie-like green roofs in Manhattan, Kansas.” Cities Alive 15th Annual Green Roof and Wall Conference Proceedings. 30 pp. Paper presented at Cities Alive 15th Annual Green Roof and Wall Conference

Snodgrass, E.C., and L.L. Snodgrass. 2006. Green Roof Plants: A Resource and Planting Guide. Timber Press.

Sutton, R.K. 2015. “Introduction to Green Roof Ecosystems.” In Green Roof Ecosystems (Ed. by R. Sutton). London: Springer Science, 1-22.

Sutton, R.K., J.A. Harrington, L.R. Skabelund, P. MacDonagh, R.R. Coffman, and G. Koch. 2012. “Prairie-Based Green Roofs: Literature, Templates, and Analogs.” Journal of Green Building 7 (1): 143–72. https://doi.org/10.3992/jgb.7.1.143

Sutton, Richard. 2008 “Media Modifications for Native Plant Assemblages on Extensive Green Roofs.” Conference Proceedings, 13.

USDA NRCS National Plant Materials Center, 2019. Plant guide and fact sheet (Bouteloua curtipendula, Bouteloua dactyloides, Bouteloua gracilis, Schizachyrium scoparium). Plants Database https://plants.sc.egov.usda.gov/java/, Accessed date: May 2020

VanWoert, N.D., D.B. Rowe, J.A. Andersen, C.L. Rugh, and L. Xioa. 2005. “Watering regime and green roof substrate design impact Sedum plant growth.” Hortscience 40(3): 659-664.

Wolf, D., and J.T. Lundholm. 2008. “Water uptake in green roof microcosms: effects of plant species and water availability.” Ecological Engineering 33:179-186.

Young, T., D.D. Cameron, J. Sorrill, T. Edwards, and G.K. 2013. “Importance of Different Components of Green Roof Substrate on Plant Growth and Physiological Performance.” Urban Forestry & Urban Greening 13(3): 507–16. https://doi.org/10.1016/j.ufug.2014.04.007

Zhao, L.J., Peralta-Videa, J.R., Ren, M.H., Varela-Ramirez, A., Li, C.Q., Hernandez-Viezcas, J.A., Aguilerad, R.J., Gardea-Torresdeya, J.L., 2012. “Transport of Zn in a sandy loam soil treated with ZnO NPs and uptake by corn plants: electron microprobe and confocal microscopy studies.” Journal of Chemical Engineering 184, 1–8. https://doi.org/10.1016/j.cej.2012.01.041

Chapter 3 - Investigating Plant-Substrate-Water Relations for Three Green Roof Depths at Kansas State University, Manhattan, Kansas

Synopsis

Water availability is one of the most critical factors in a green roof system. Understanding soil-plant water relations in green roofs is key for understanding plant success and failures on the green roof. Three experimental research green roof beds were designed for the Kansas State University (KSU) College of Architecture, Planning and Design (APD) building and were initially planted in October 2017. The three green roof beds consist of three different depths (4, 6, and 8 inches [10.2, 15.3, and 20.4 cm]). The experimental design is a strip plot design within a randomized complete block design for each green roof depth. Each green roof depth contains two substrates (Rooflite® Extensive MC and Kansas BuildEx), and three different plant mixes (all-*Sedums*, *Sedums* and native grasses, and all-natives). Water holding capacities of the roof and soil moisture release curves were estimated to provide insight on how water is stored and the energy status of this water within the two selected green roof substrates. Soil moisture dynamics in each of the substrate types was investigated by analyzing the recession curve slopes for each of the green roof substrates to provide insight as to how green roof substrate properties can cause variations between the two substrates in soil moisture retention and recession. The outcomes of this study have enhanced the knowledge of soil-water relations of green roof ecosystems and understanding of the soil moisture characteristics of green roof substrates, which can aid in the improvement of irrigation and management practices to make green roofs more sustainable.

Introduction

Current trends in urbanization and climate change concerns have made green roofs an increasingly common approach in the effort to create more sustainable, resilient cities. Human development has caused disruptions to natural habitat, soil, and vegetation. These disruptions have greatly affected ecohydrological processes near and in urban areas. There is an urgent need innovative and practical tools achieve sustainable management of water resources, and this management must improve “the coexistence of man and nature” (Zaleski, 2002).

In contrast to conventional rooftops, water that lands on green roofs enters a complex ecohydrological system. The first process is water capture and storage. Water inputs, either through precipitation or irrigation, can be intercepted by vegetation and stored within the substrate and drainage layers. Typically, water entering a green roof system has a short residence time (Lambrinos, 2015). The water entering the system will be stored, but once the green roof reaches storage capacity, subsurface drainage and subsequent runoff from a green roof system will start to occur. Water exits the system either by (1) infiltrating through the substrate and drainage layers and exiting the roof via drainage pipes, (2) evaporating from the soil surface, or (3) being pulled from the substrate to the plant roots, to shoots, to leaves, and exiting the plant stomata during transpiration (Lambrinos, 2015).

Green roof substrates are typically designed to have a coarse texture to ensure good infiltration, especially during intense rainfall events, to limit the possibility of ponding (unless wetland-like conditions are desired). These substrates also require a high porosity to provide sufficient aeration and limit weight loading of the green roof system on the structure supporting the roof. The caveat of creating a substrate with high air-filled porosity is that it will result in lower water retention (Spomer, 1980). Water in a green roof system departs via rapid infiltration and runoff or ET, which can quickly deplete the water reservoir. Therefore, plant survival in green roof systems is often limited by substrate moisture (Dvorak and Volder, 2010) and water availability is frequently limited due to shallow substrate depths (Nagase and Dunnett, 2010).

As explained by Farrell et al (2013), the porous nature of green roof substrates can cause detrimental fluctuations in substrate moisture availability and frequent droughts in green roof systems. If a substrate does not supply what is required for plant survival and growth, green roof designs will fail (Bousselot et al., 2020). Many substrate characteristics directly impact green roof substrate water retention performance (FLL, 2008), and storage capacity varies considerably with substrate composition (Lambrinos, 2015). There have been few peer-reviewed publications on green roof substrate research (Bousselot et al., 2020). However, understanding green roof substrate-water relations can help guide future green roof implementation and management practices, especially irrigation practices. In the future, sustainable management of urban areas may need to focus on moisture stress management (Nouri et al, 2012) including on green roof ecosystems.

Roof Capacity

Regardless of the design, every green roof system has a maximum water retention capacity (Bousselot et al., 2020). The Forschungsgesellschaft Landschaftsentwicklung Landschaftbau (FLL) guidelines state that the main cause for variation in water storage capacity of green roof systems is substrate depth (FLL, 2008). Graceson et al (2013) investigated the effect of green roof substrate composition on water retention capabilities and found a significant effect of substrate type on retention. This study shows there is a need to further investigate the effects of substrate characteristics on water retention and expanding this to investigate a depth effect as well.

In green roof systems, the volume of water held in the substrate profile can be increased by increasing substrate volume and depth, however, specifying for deeper depths can be problematic because it also increases structural weight loading, reducing the number of buildings that can support these deeper profiles (Farrell et al, 2013). Water retention properties of green roof substrates can be increased by altering water holding characteristics of the substrate. For example, decreasing substrate particle size can increase the amount of water held in the substrate profile because of increased pore space (Young et al, 2014, Graceson et al., 2013, Olzewski and Young, 2011).

To understand how the selected green roof substrate depths influence water retention of these profiles, the "roof capacity" of each substrate for the specified green roof depths needs to be determined. Field capacity is defined as "an empirical measurement supposed to represent the soil profile's ability to retain water after the process of internal drainage has ceased" (Hillel, 2003, p 432), but this term only refers to field conditions and free-draining soils (Kirkham, 2014) and green roof systems do not have underlying soils using capillary forces to pull water deeper into the soil profile. Because of this characteristic of green roofs, determining roof capacity builds upon previous horticultural work to determine "container capacity." Kirkham (2014, p. 155) defines container capacity as "the amount of water remaining in a pot after irrigation and visible drainage has ceased." Soil containers can be used as experimental tools for investigating soil water relations in systems that differ from "ground bed soils" (Spomer, 1975, p. 21). When investigating soil water relations, pots, cans, flats, benches, and planters can be looked at as containers (Spomer, 1975; Kirkham, 2014). I define "roof capacity" as the amount of water remaining after the green roof profile has been saturated and visible drainage has ceased.

The previously mentioned studies outline the effects of substrate properties on water retention, but these studies do not investigate the relationship between substrate, plant type, and water retention. The APD-EGR is a great experimental setting for assessing the effect of substrate type on plant performance (coverage and survival). An extremely important determinant of plant performance in these different substrate-depth settings is how water is stored in the selected substrates and how water storage varies by green roof profile (substrate) depth. Research conducted at the APD-EGR assesses the difference in roof capacity for green roof substrates with different characteristics and how water storage varies for each of these substrates at three different depths.

Soil Moisture Monitoring

There can be a large difference in green roof water retention between green roof systems with different properties. Green roof design has been motivated by the need for good stormwater retention to aid with stormwater management in highly developed areas. One of the challenges for designing green roofs with good stormwater retention is that these designed systems also require good drainage to stay within the structural limitation for maximum weight capacities (FLL 2008). Some green roofs can have very limited water retention, even when manufacture specifications claim otherwise (Simmons et al. 2008). Many green roof characteristics affect green roof water storage capacity. Some of these characteristics include drainage and retention layers (Simmons et al., 2008), substrate composition and depth (Monterusso et al., 2005), along with the physiology and functional forms of the vegetative communities growing on a particular green roof (Dunnett and Kingsbury 2004).

Plant available water can decrease quickly after precipitation and irrigation events, especially in shallow media (VanWoert et al. 2005). For example, research has generally been in support of increased organic matter (greater than FLL recommendations) to aid both plant establishment and improving plant available water (Molineux et al. 2009). Methods of manipulating aggregate particle size distribution and adding organic matter can be used to modify the green roof substrate's water retention properties. Organic matter retains moisture and provides nutrients (Kirkham, 2014). However, high organic matter content is not recommended on green roofs because organic matter will decompose, resulting in substrate depth reduction and leaching of nutrients such as nitrogen and phosphorus through runoff (Rowe, 2011). High percentages of organic matter can also be problematic because under dry conditions (which can be very common on green roofs) they can cause water repellency (Kirkham, 2014). ASTM 2777 (2020) recommends organic matter content percentages ranging from 3 to 15%.

Nagase and Dunnett (2012) simulated rain events in greenhouses to quantify rainwater capture by plant communities consisting of either monocultures or species mixes. Sedum spp. showed the greatest amount of water runoff and grasses were the most effective at water capture. Rainwater interception is optimized by certain plant structural properties (Nagase and Dunnett, 2012). For example, in this study the taller plants with a larger diameter had greater interception and water retention than the shorter plants with smaller diameters (Nagase and Dunnett, 2012). Previous studies found that lower-growing and mat-forming plants like Sedum spp. have less rainfall interception than taller plants due to having a smaller surface area (Clark, 1940; Park and Cameron, 2008). Also, plant root structure plays a role in water retention. Grasses and forbs have more root growth than Sedum spp. allowing for greater water capture by the sponge-like system in the substrate created by grasses and forbs. This study by Nagase and Dunnett (2012) questions whether water capture correlates to water use of plants. In response to this question, Lundholm et al. (2010), found that water loss to evapotranspiration (ET) followed a similar pattern to water capture, where both water capture and loss had a positive correlation with the number of species planted, showing that planting with more species capture more water and release more moisture back into the atmosphere through ET than plantings with fewer species.

Soulis et al (2017) analyzed the relationship between runoff reduction, initial substrate moisture conditions, and total rainfall depth with conceptual and physically based models. It was concluded that substrates without vegetation had higher subsurface drainage rates. Also, if initial soil moisture was lower, retention was higher. Soulis et al (2017) found that vegetation type had a great effect on initial substrate moisture. Differences in initial substrate moisture for vegetation types are likely due to the different ET rates. Succulents provided minimal advantages compared to non-vegetated green roofs because of low ET rates that result in high soil moisture content between consecutive rainfall events were similar for the two green roof types (Soulis et al., 2017). Dunnett and Nolan (2004) found that the main limiting factor for green roof systems is water availability rather than depth on its own, although deeper substrates usually allow for greater water holding capacities (VanWoert et al, 2005).

Soil Moisture Characteristics

Many substrate composition modifications have been suggested and implemented to increase the amount of plant available water and/or to lessen the variation in water availability. Some of these suggestions include increasing the amount of organic matter or by incorporating other additives to aid in water retention (Lambrinos, 2015). Because plants survive off available water and not just the water content it is important to know the energy status of the soil water. Water potential in the soil is a measure of the energy status of the soil-water relative to the status of pure water at atmospheric pressure and a standard elevation (Hillel, 2003). Matric potential can be described as the "tenacity with which soil water is held by the soil matrix" (Hillel, 2003, p

93). Water moves within the soil and plants because of the gradient in water potential (Hillel, 2003). To help us better understand water availability through time, soil moisture characteristic curves are used to display the relationship between soil moisture and tension (negative matric potential).

Soil structure and pore size distribution affect water storage at low tensions (less than 1 bar) (Hillel, 2003). Therefore, the soil structure and pore size distribution will also affect the roof capacity of green roof substrates. To be sure that green roof plants are getting enough water we must equate volumetric water content to water potential via soil water release testing. Of the studies that describe water holding capacities of green roof substrates, few assess the soil moisture characteristics of the substrates used (Berndtsson, 2010). To better understand the relationship, more research is needed to evaluate the effects of soil moisture levels on vegetative coverage in a green roof system. There is a need to study the green roof soil-plant-atmosphere-continuum (SPAC) to understand what affects water availability, water uptake, coverage, and growth on the green roof.

Green roofs frequently experience prolonged dry periods (Wolfe and Lundholm, 2008), and these periods create a growing environment characterized by frequent water stress. The development of sustainable green roof management practices requires careful consideration of the regional context (climatic conditions) and an understanding of the soil-plant-water relations occurring within the green roof system. This dissertation work has sought to shed some light on these important aspects.

This chapter investigates soil-plant-water relations of green roofs in Manhattan, Kansas and a key part of this process is understanding how water is stored and dispensed by the green roof substrates and determining if water retained is available for plant use. This study investigates the way green roof substrates store and dispense water and how green roof plant mixes play a role in this process.

Research Objectives

1. Understand how the two substrates, Kansas BuildEx and Rooflite® Extensive MC, vary in the way they store and dispense water.
2. Understand how plant mix affects the way water is stored and dispensed within Kansas BuildEx and Rooflite® Extensive MC substrate.
3. Understand how the two substrates vary in terms of water potential to provide insight on plant available water.

Research Questions

1. How does substrate type and depth impact roof capacity?
2. How does water recession vary for Kansas BuildEx and Rooflite® Extensive MC following precipitation events?
3. How does the energy status of the soil water vary for Kansas BuildEx and Rooflite® Extensive MC?

Hypotheses

1. Kansas BuildEx and Rooflite® Extensive MC will vary in roof capacity due to differences in substrate composition.
2. Kansas BuildEx and Rooflite® Extensive MC will differ in the rate at which they dry following precipitation events due differing substrate physical properties.
3. Because of Rooflite® Extensive MC substrate's higher percent air space, when comparing water content values Rooflite® Extensive MC substrate will have a higher tension (negative matric potential) than Kansas BuildEx.

Methods

Determining Roof Capacity

As stated above, for this study "roof capacity" is defined as the amount of water remaining after the green roof profile has been saturated and visible drainage has ceased. Roof capacity was measured by modifying the protocol described by Gessert (1976). PVC cylinders were used instead of pots to allow for simpler dimensions to work with when calculating volume. This protocol was followed for profile depths of 4, 6, and 8 inches. First, the volume of a PVC cylinder of a specified depth was measured (using inside diameter). Mesh screening was attached to the bottom of each cylinder to allow for drainage while holding in the substrate particles. Plastic wrap was applied over the mesh to keep the water in the cylindrical column. The cylinder was filled with Rooflite® Extensive MC substrate and packed to a known density. The cylinder was then placed above a larger container to collect water drained from the cylinder. Next, the substrate was slowly saturated, and the amount of water added was documented. Once the substrate was saturated the cylinder was lifted and the plastic wrap was removed so that water drained from the cylinder until drainage has ceased. The following equations were then used to calculate roof capacity for the substrate within each specified depth for the Rooflite® Extensive MC substrate. This same process was then repeated for the Kansas BuildEx substrate at the three different APD-EGR depths.

(1) Porosity % = volume of water required for saturation ÷ total volume of the cylinder

(2) Air Space % = volume of drained water ÷ total volume of the cylinder

(3) Roof Capacity = porosity % – air space %

Figure 3.1. Pictures (from left to right) Show the PVC Setup with Rack and Bucket Beneath, Thin Layer of Water at Surface of Substrate after Saturating, and a PVC Column Draining.

Water Release Testing

Samples of both Rooflite® Extensive MC and Kansas BuildEx substrates were sent to the Turf and Soil Diagnostic (TSD) lab in Linwood, Kansas for water release testing. TSD followed ASTM D6835 protocol for green roof water release testing. TSD followed Method C (using a pressure chamber) for determining tension points up to 4 bars and Method D (using a Decagon Dewpoint Potentiometer) for determining tension points at 15 bars. Samples used in ASTM D6836 Method C were saturated from bottom up. Water release testing (up to 4 bars) used three replicates of Rooflite® Extensive MC substrate and two replicates of Kansas BuildEx substrate. The 15-bar data point was generated from multiple test specimens around the 15-bar soil tension.

Sensor Characterization

METER Group (METER, previously Decagon Devices) 5TM soil moisture and temperature sensors deliver temperature readings measured by an onboard thermistor while soil moisture values are measured using the dielectric constant of the media (utilizing capacitance/frequency domain technology). The volume of influence for each sensor is 715 mL as shown in Figure 3.8. Em50G and ZL6 data loggers provided plug-and-read access to the 24 5TM sensors placed on the APD-EGR in March 2018 (buried in the center of each of “C” plant mix plots), and the additional 24 5TM sensors placed on the APD-EGR in July 2019 (buried in the center of each of “A” plant mix plots), with immediate access to sensor data through ZENTRA Cloud.

To calibrate the Meter 5TM sensors used on this green roof, actual (measured) and observed (sensor reading) soil moisture values were compared. To do this, three three-L containers were filled halfway with oven-dried Rooflite® Extensive MC substrate and three more three-L containers were filled halfway with dried Kansas BuildEx substrate. Next, sensors were placed flat on the substrate and the containers were filled the rest of the way with dried substrate. Next, water was added in 30mL increments until a volumetric water content (VWC) of 0.05 was reached. Next, water was added in 75 mL increments until a volumetric water content of 0.25 was reached. Finally, 150 mL of water was added to reach 0.30 volumetric water content. The sensor readings for VWC were recorded with each incremental addition of water to the container. After Round 1 was completed, the containers were emptied and dried and the process was repeated for all six containers. Plots of actual VWC versus sensor VWC readings are presented in Figure 3.2 for both rounds of volumetric water additions.

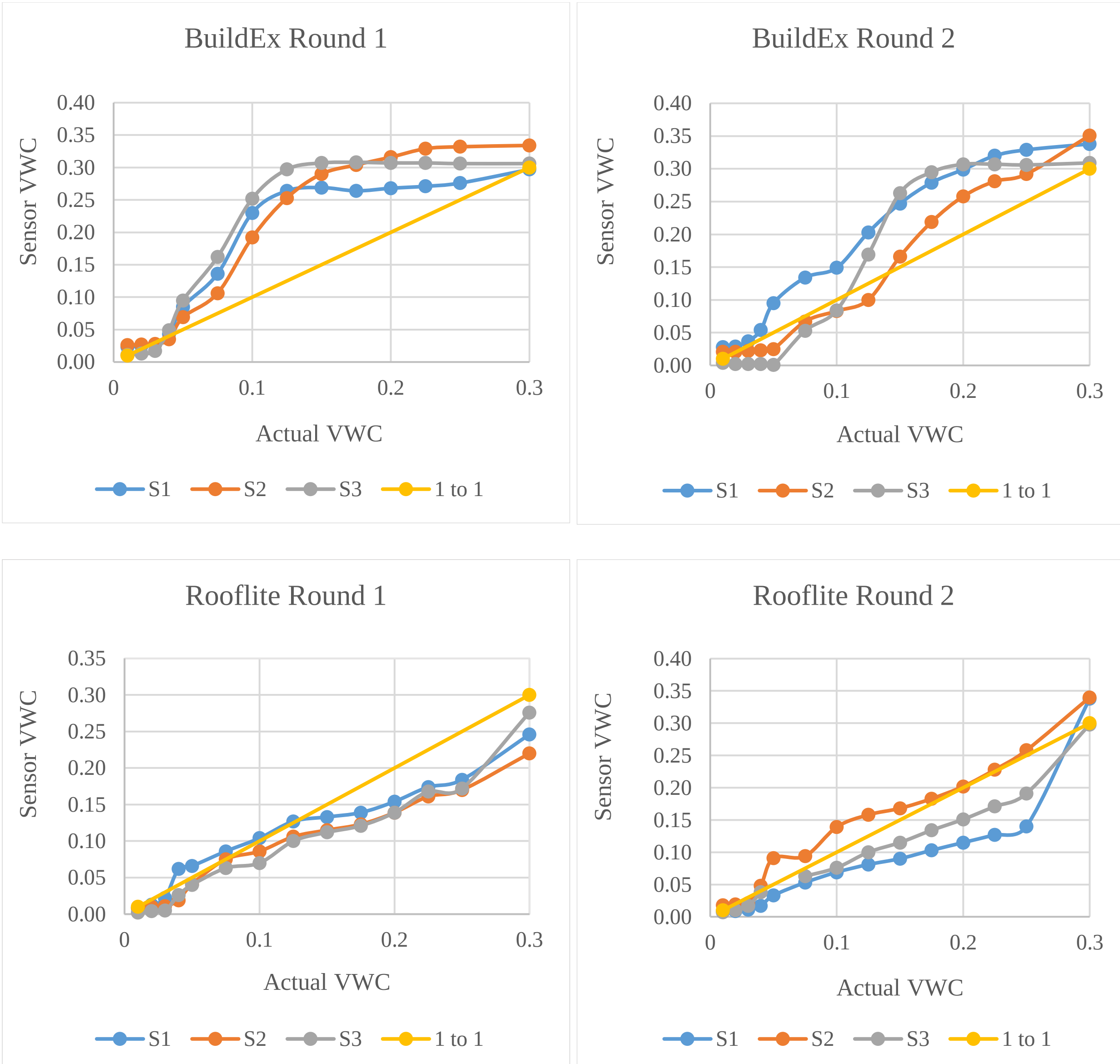


Figure 3.2. Sensor Characterization Plots for Round 1 and Round 2. S1, S2, and S3 indicate plotted lines for volumetric water content (VWC) readings of sensors 1, 2, and 3 respectively plotted against actual (measured) volumetric water content (VWC) (m3/m3).

Due to the variation in the in the calibration trials, there was not enough consistency in the calibration curves to create substrate specific calibration curves. As demonstrated by the quartiles calculated in Table 3.1, over 75% of the sensor readings are within the 0.05 to 0.2 m^3/m^3 range. This corresponds to the range of sensor readings for which calibration curves tended to be closer to the 1:1 line. Thus, it was decided to not use substrate-specific calibration curves.

Table 3.1. Volumetric Water Content (m3/m3) Sensor Quartiles (Q1, Q2 and Q3) for Each Substrate Depth.

	8 in	6 in	4 in
min	0.029	0.046	0.049
Q1	0.103	0.112	0.134
Q2	0.129	0.134	0.154
Q3	0.151	0.171	0.183
max	0.379	0.285	0.371

Soil Moisture Monitoring

This research took place on the APD-EGR. These green roofs were constructed June to October 2017 and all live plants were installed (planted) on each of the three green roof beds by June 2018. This research-focused green roof system consists of three different planting areas (beds), distinguished by depth (4 inches, 6 inches, and 8 inches) as illustrated in Figure 3.3. Due to observed variation between green roof cells, the green roof depths were physically measured in June 2018. Actual depths ranged from 2.4-5.2 inches for the 4-inch bed; 4.5-7.5 inches for the 6-inch bed; and 6.5-10.1 inches for the 8-inch bed. Each planting area or bed contains four blocks, consisting of six (approximately 4’ x 4’) experimental cells for a total of 72 experimental cells (Figure 3.3). The experimental design is a strip plot design within a randomized complete block design for each green roof depth. Each green roof depth contains two substrates (Rooflite® Extensive MC and Kansas BuildEx), and three different plant mixes (all-*Sedums*, *Sedums* and native grasses, and all-natives).

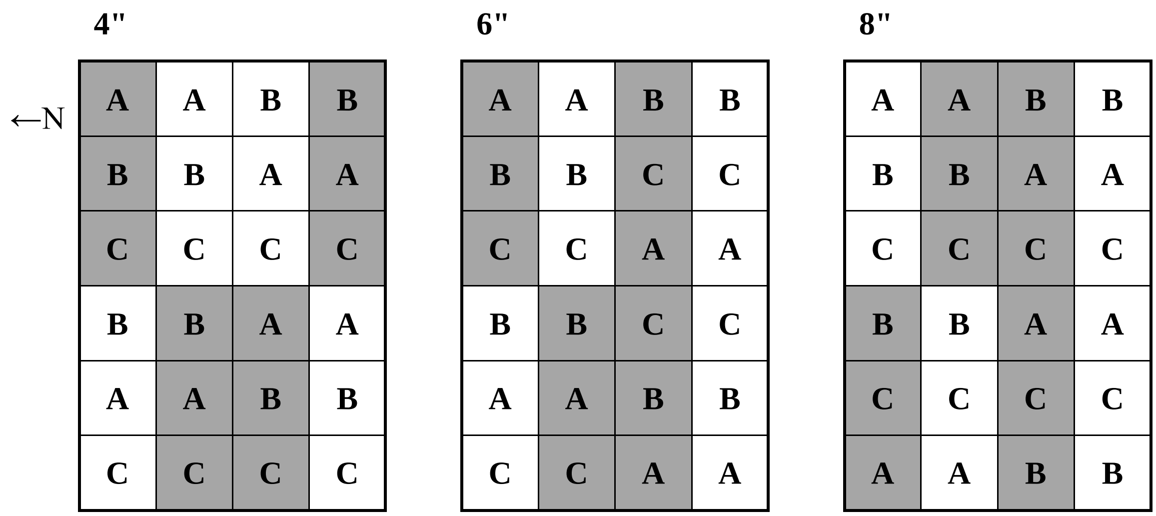


Figure 3.3. Randomized Species Mix Layout for Each Substrate Depth. Shaded boxes represent experimental plots that consist of Kansas BuildEx substrate and non-shaded areas represent experimental plots that will of Rooflite® Extensive MC substrate. A, B, and C represent the plant mixes: all-Sedum (A); Sedum & grasses (B); all-native graminoids and forbs (C). The 4”, 6”, and 8” noted above each planting area shows the substrate depth (in inches) of each planting.

Due to limited funding, only a certain number of data loggers and sensors were able to be purchased and installed on the APD-EGR. Our research team decided that it was most important to place soil moisture sensors in the plots containing the all-native grasses and forbs mix so that we could document soil moisture and temperature dynamics across each of the three experimental beds or depths for this selected native plant mix. In March 2018, 24 METER 5TM temperature and soil moisture sensors were installed in all-native cells (labeled “C” in Figure 3.3), to monitor subsurface soil moisture and temperature levels. A METER 5TM sensor was buried in the center of the substrate profile for each of the native grass and forb plots labelled

“C” (one 5TM sensor in each of the substrates within each experimental block as shown in Figure 3.4). Thus, a total of eight METER 5TM sensors were deployed in each bed (depth).

In 2019 our research team was able to secure additional data loggers and 5TM sensors and we decided to deploy these in the plots containing the all-*Sedum* mix so that we could examine if there were meaningful differences between the all-natives and all-*Sedum* plots regarding soil moisture and soil temperature. In July of 2019 24 METER 5TM temperature and soil moisture sensors were installed in all-natives cells (labeled “A” in Figure 3.3). Sensor layout after July 2019 is referred to as “configuration 2.” Figure 3.5 shows the first APD-EGR sensor configuration March 2018 to July 22, 2019, and Figure 3.6 shows the second sensor configuration for July 23, 2019, to present. There were issues with prolonged periods of missing data in the 6-inch bed, requiring the 6-inch bed to be excluded from data analysis for configuration 2.

SA		SG		SSe		WG
	WG		SI		SE	
SE		SA	**X**	SG		SSe
	SSe		WG		SI	
SI		SE		SA		SG

Mix A

CB		SH		SSc		PO
	PO		KP		DP	
DP		CB	**X**	SH		SSc
	SSc		PO		KP	
KP		DP		CB		SH

Mix C

Figure 3.4. Sedums only (A) and All-Natives Mix (C) Plant and Sensor Layout for the APD-RGR. Plant species names are abbreviated in each box to show planting layout for one experimental cell. The "X" represents METER 5TM sensor location. Sensors in Mix C were installed in March 2018. Mix A sensors were installed July 2019. Plant abbreviations for Mix A and C are as follows: *Sedum album var. murale* (SA), *Sedum ellacombeanum* (SE), *Sedum hybridum* (SI), *Sedum kamtschaticum var. floriferum* (WG), *Sedum sexangulare* (SSe), *Sedum spurium* (SS), *Carex brevoir* (CB), *Dalea purpurea* (DP), *Koeleria pyramidata* (KP), *Packera obovata* (PO), *Schizachyrium scoparium* (SSc), *Sporobolus heterolepis* (SH).

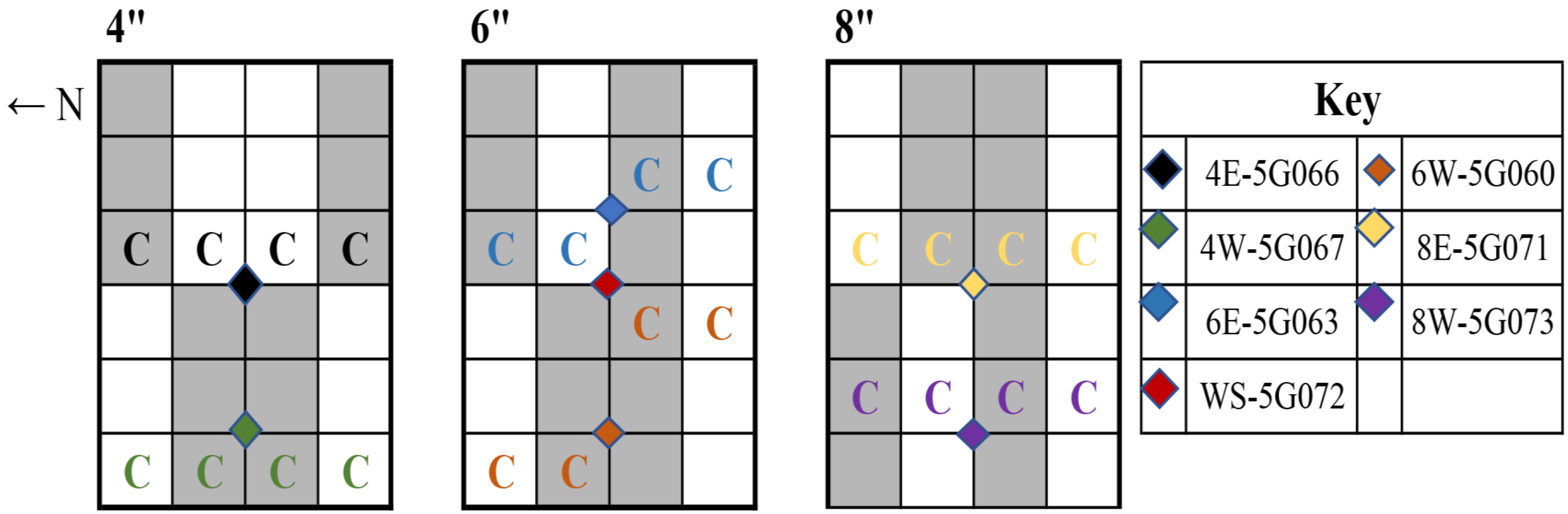


Figure 3.5. Configuration 1 Sensor and Data Logger Layout from March 2018 to July 22, 2019. A "C" indicates a sensor placed in the Mix C (native graminoids and forbs) cell. Diamonds in the key indicate data logger identification numbers and placement on the APD-EGR.

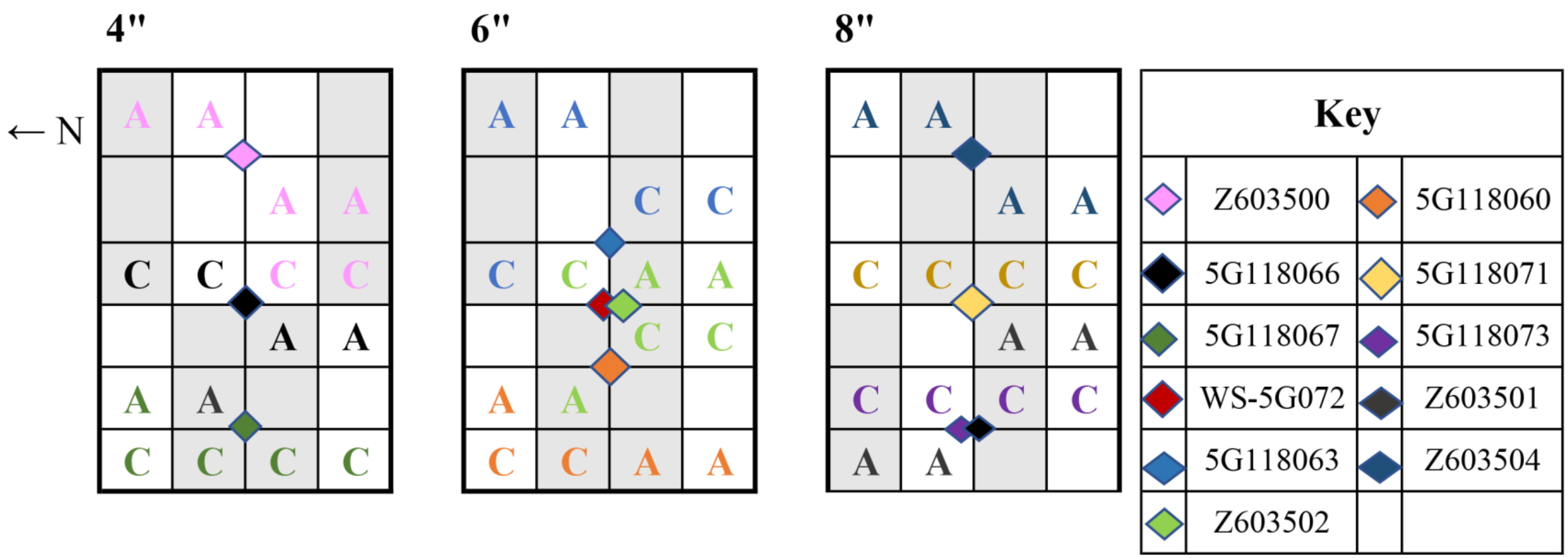


Figure 3.6. Configuration 2 Sensor and Data Logger Layout after July 23, 2019. An "A" indicates a sensor placed in the Mix A (all-Sedum) cell and "C" indicates a sensor placed in the Mix C (all-native graminoids and forbs) cell. Diamonds in the key indicate data logger identification numbers and placement on the APD-EGR.

METER 5TM soil moisture and temperature sensors (Figure 3.7) deliver temperature readings measured by an onboard thermistor. Soil moisture values are given by measuring the dielectric constant of the media by utilizing capacitance/frequency domain technology. Each sensor has a 715-mL measurement volume as shown in Figure 3.8 and measurements are recorded every 15 minutes. Em50G data loggers allow for plug and read use of sensors with immediate access to data through DataTrac 3 software. All available soil moisture data was downloaded, backed up, and saved. Data following significant precipitation events of one inch (25.4 mm) or greater was analyzed.

Figure 3.7. METER 5TM Soil Moisture and Temperature Sensor. (Source: METER Group, Inc. 2019).

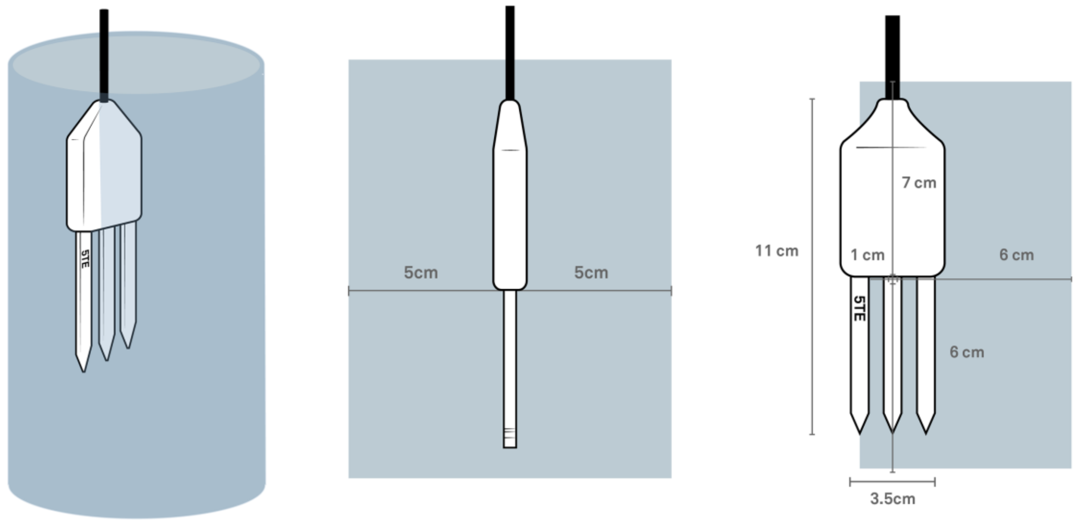


Figure 3.8. METER 5TM Soil Moisture and Temperature Sensor Measurement Volume (Source: METER Group, Inc. 2019).

Data Analysis

Roof Capacity

First, the studentized residuals and QQ (Quantile Quantile) plots were checked to ensure the data meets the required assumptions for the MIXED procedure. Data was then analyzed in SAS Studio using the MIXED procedure to test for Type III tests of fixed effects for the effects of type and depth and the interaction between the two effects. A tukey post-hoc test was used to rank the differences between roof capacities for each substrate depth combination at an alpha level of 0.05 for each analysis (Proc MIXED, SAS version 9.3).

Soil Moisture

Soil moisture dynamics in each of the substrate types were analyzed by conducting a differential analysis of the soil moisture sensor data for each green roof depth. Rate of recession was determined by calculating the change in volumetric water content per unit time (1-hour and

24-hour) after each peak in soil moisture following heavy rainfall events (greater than 1-inch). A generalized linear mixed model was fit to the soil moisture recession rates for each bed (4, 6, and 8 inches) using a lognormal transformation. Lognormal transformation allows for the mean and variance to be estimated on the logarithmic scale, assuming a normal distribution. The GLIMMIX and LSMEANS (least square means) procedures in SAS version 9.4 were used to fit the model and compute the least square means of fixed effects ($\alpha = 0.05$). Data was then analyzed in SAS 9.4 using the GLIMMIX procedure to test fixed effects for the effects of substrate on recession rate in the 4-, 6-, and 8-inch beds for the first sensor configuration. For the second sensor configuration, the GLIMMIX procedure was used to test for fixed effects for the effects of substrate and mix and the interaction between substrate and mix on recession rate in the 4-inch and 8-inch beds.

Results

Roof Capacity

Table 3.2 shows the average volume of water held in each profile depth for both substrates (Table 3.2). The interaction between substrate type and depth was not significant. There is evidence for both a main effect of substrate and a main effect of depth on roof capacity (α=0.05). Overall, Kansas BuildEx had a greater roof capacity than Rooflite® Extensive MC. There was no evidence for a significant difference in roof capacity between 6- and 8-inch depths. There is evidence for a significant difference in roof capacities (α=0.05) for 4- and 6-inch depths and 4-and 8-inch depths, with 4-inch having the greatest roof capacity on a per unit container volume basis (see Table 3.3).

Table 3.2. Average Volume of Water (mL) Held in the Column for Kansas BuildEx (BX) and Rooflite® Extensive MC (RL) for all Three Depths (4-, 6-, and 8-inch).

Depth	RL (mL)	BX (mL)
4	215 (SD=12.49 n=3)	334 (SD=10.54 n=3)
6	241 (SD=72.13 n=3)	373 (SD=31.78 n=3)
8	352 (SD=25.53 n=3)	559 (SD=16.07 n=3)

Table 3.3. Average Roof Capacity (percent volume water held in substrate per volume of substrate) for Kansas BuildEx (BX) and Rooflite® Extensive MC (RL) for all Three Depths (4-, 6-, and 8-inch).

Substrate	Depth	Roof Capacity (%)	Grouping
RL	4	26	DC
BX	4	42	A
RL	6	19	D
BX	6	30	BC
RL	8	21	D
BX	8	34	AB

Note: KB denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC substrate. There were three replications of each substrate type-depth combination. Means that do not share a letter a significantly different (α=0.05).

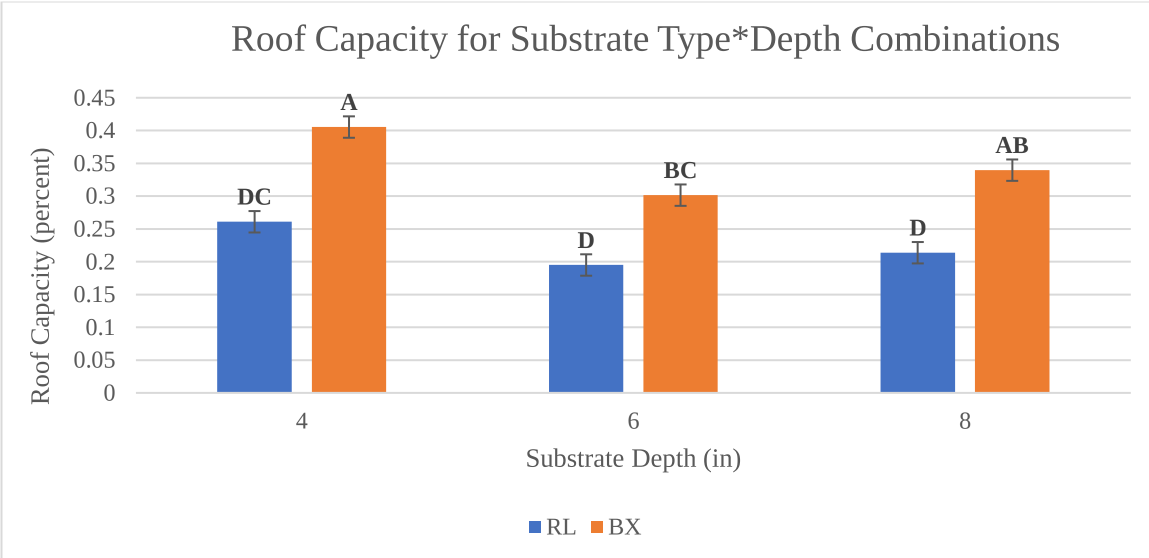


Figure 3.9. Roof Capacity Tukey Grouping for DEPTH*TYPE Least Squares Means (α=0.05). LS-means with the same letter are not significantly different.

Water Release Testing

The results of the water release testing are displayed in Table 3.4. The water release curves (Figure 3.10), show that for majority of the range of tension Rooflite® Extensive MC has a higher VWC than Kansas BuildEx.

Table 3.4. Volumetric Water Content (θ_V% v/v) of Kansas BuildEx (BX) and Rooflite® Extensive MC (RL) for Specified Tension Values.

Tension (-bars)	**BX θ_V**	**RL θ_V**
0	33.872	43.747
0.1	16.936	39.867
0.4	11.68	15.811
1	8.176	13.968
4	7.008	12.416
15	3.942	2.328

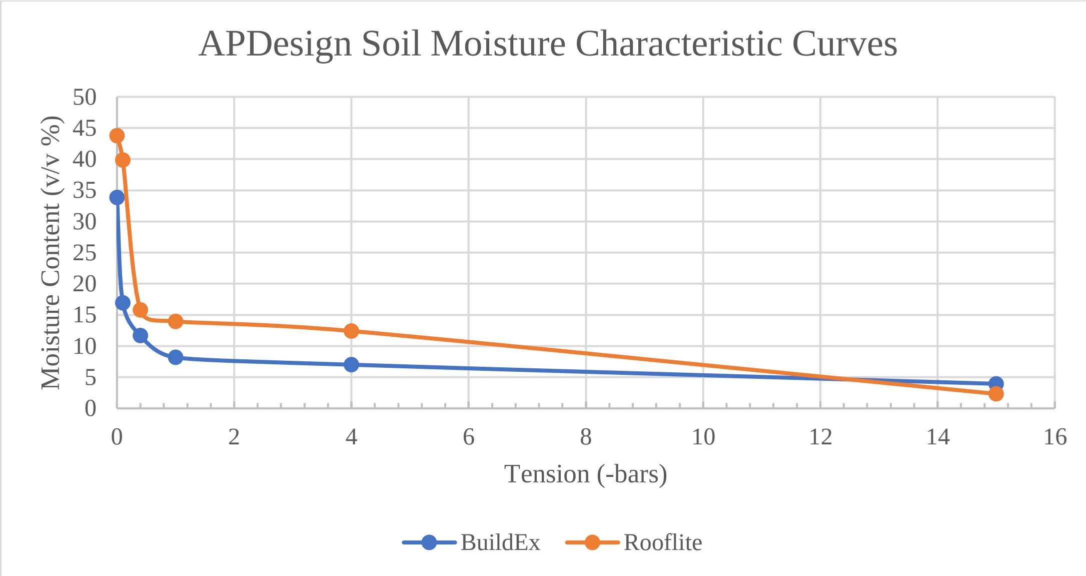


Figure 3.10. Water Release Curves for the Kansas BuildEx and Rooflite® Extensive MC Substrates. Testing completed by Turf and Soil Diagnostics Lab in Linwood, Kansas. Testing was conducted with three replicates for each substrate.

Soil Moisture Recession Analysis

For the first sensor configuration (with 5TM sensors buried in the middle of the all-native graminoids and forbs mix) there was strong evidence for a significant effect of substrate type on rate of recession for the 1-hour recission period ($p < 0.001$), but there was not an effect of substrate type on rate of recession for the 24-hour recession period in the 4-inch bed ($\alpha = 0.05$) (Table 3.5). In the 1-hour recession period, Rooflite® Extensive MC had a greater rate of recession than Kansas BuildEx (Table 3.6). In both the 6- and 8-inch beds there was no evidence for an effect of substrate type on rate of recession for both recession periods ($\alpha = 0.05$) (Tables 3.7 and 3.8).

Table 3.5. Recession Analysis Configuration 1 Summary Table. BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC.

Depth	Substrate	Mix	Recession Period (hr)	Estimate ($\Delta\theta_V$/hr)	SE
4	BX	C	1	0.0059	0.0014
4	RL	C	1	0.014	0.0015
4	BX	C	24	0.0045	0.0014
4	RL	C	24	0.0046	0.0014
6	BX	C	1	0.0063	0.0014
6	RL	C	1	0.0047	0.0013
6	BX	C	24	0.0010	0.0002
6	RL	C	24	0.0010	0.0002
8	BX	C	1	0.011	0.0029
8	RL	C	1	0.011	0.0029
8	BX	C	24	0.0010	0.0002
8	RL	C	24	0.0013	0.0002

Table 3.6. Sensor Configuration 1 Type III Test of Fixed Effects for the 1-Hour (left) and 24-Hour (right) Recession Periods for the 4-Inch Bed.

4-inch 1-hour Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Subs	1	176	37.41	**<.0001**

4-inch 24-hour Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Subs	1	190	0.00	0.9502

Note: Bold text indicates a significant p-value (α=0.05)

Table 3.7. Differences of Substrate Least Squares Means for 1-Hour Recession Period.

Differences of Substrate Least Squares Means						
Subs	_Subs	Estimate	SE	DF	T Value	Pr > |t|
KB	RL	-0.8984	0.1469	176	-6.12	**<.001**

Note: Bold text indicates a significant p-value (α=0.05)

Table 3.8. Sensor Configuration 1 Type III Test of Fixed Effects for the 1-Hour (left) and 24-Hour (right) Recession Periods for the 6-Inch Bed.

6-inch 1-hour Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Subs	1	6.068	0.77	0.4148

6-inch 24-hour Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Subs	1	3.07	0.37	0.5861

Table 3.9. Sensor Configuration 1 Type III Test of Fixed Effects for the 1-Hour (left) and 24-Hour (right) Recession Periods for the 8-Inch Bed.

8-inch 1-hour Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Subs	1	6.072	0.62	0.4592

8-inch 24-hour Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Subs	1	6.035	0.00	0.9709

For the first sensor configuration (with 5TM sensors buried in the middle of the *Sedums*-only and the all-native graminoids and forbs mix), there was not an effect of substrate type or mix on rate of recession for both recession periods in the 4-inch bed (Table 3.9). For the 8-inch bed there was a slight effect of mix ($p=0.0584$) on rate of recession for the 1-hour recession period ($\alpha = 0.05$) (Table 3.10). The difference of Least Squared Means for mix for the 1-hour recession period in the 8-inch bed (Table 3.11), showed that the *Sedums* only mix (A) had a greater rate of recession than the all-native graminoids and forbs mix (C).

Table 3.10. Recession Analysis Configuration 2 Summary Table. BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC.

Depth	Substrate	Mix	Recession period	Estimate ($\Delta\theta_V$/hr)	SE
4	BX	A	1	0.019	0.005554
4	RL	A	1	0.022	0.005554
4	BX	C	1	0.015	0.005269
4	RL	C	1	0.021	0.005269
4	BX	A	24	0.0030	0.000661
4	RL	A	24	0.0029	0.000661
4	BX	C	24	0.0027	0.000627
4	RL	C	24	0.0023	0.000627
8	BX	A	1	0.032	0.005740
8	RL	A	1	0.021	0.005772
8	BX	C	1	0.026	0.005740
8	RL	C	1	0.015	0.005772
8	BX	A	24	0.0075	0.001657
8	RL	A	24	0.0046	0.001680
8	BX	C	24	0.0041	0.001657
8	RL	C	24	0.0030	0.001680

Table 3.11. Sensor Configuration 2 Type III Test of Fixed Effects for the 1-Hour (left) and 24-Hour (right) Recession Periods for the 8-Inch Bed.

4-inch 1-hour Type III Test of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Subs	1	5.666	2.08	0.2021
Mix	1	4.91	0.04	0.8589
Subs*Mix	1	5.666	0.00	0.9535

4-inch 24-hour Type III Test of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Subs	1	64.62	0.26	0.6112
Mix	1	5.536	0.51	0.5044
Subs*Mix	1	64.62	0.29	0.5917

Table 3.12. Sensor Configuration 2 Type III Test of Fixed Effects for the 1-Hour (left) and 24-Hour (right) Recession Periods for the 8-Inch Bed.

8-inch 1-hour Type III Test of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Subs	1	11.97	2.48	0.1414
Mix	1	11.97	4.38	**0.0584**
Subs*Mix	1	11.97	0.60	0.4550

8-inch 24-hour Type III Test of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Subs	1	4.922	0.24	0.6461
Mix	1	5.37	1.51	0.2705
Subs*Mix	1	119.7	0.27	0.6063

Note: Bold text indicates a significant p-value (α=0.05)

Table 3.13. Sensor Configuration 2 Difference of Least Square Means for Mix for the 1-Hour Recession Period in the 8-Inch Bed.

Differences of Mix Least Squares Means						
Mix	_Mix	Estimate	SE	DF	T Value	Pr > |t|
A	C	0.8349	0.3991	11.97	2.09	**0.0584**

Note: Bold text indicates a significant p-value (α=0.05)

Discussion

Roof capacities (the amount of water remaining after the green roof profile has been saturated and visible drainage has ceased) ranged from 19% (6-inch) to 26% (4-inch) for Rooflite® Extensive MC and from 30% (6-inch) to 41% (4-inch) for Kansas BuildEx. A study by DeNardo et al. (2005) found a substrate field capacity of 34%. A study by Hilten et al. (2008) modeled green roof runoff and found the substrate field capacity to be 11%. In comparison to these studies the substrates used on the APD-EGR have good water retention capabilities, but Kansas BuildEx has a higher roof capacity than Rooflite® Extensive MC for all three of the depths. The roof capacity experiments show that increasing the depth of the substrate does not increase the volume of water held in the profile by that same factor. This may be due to the force of gravity pulling water down in the soil profile. For example, when doubling the substrate (4 to 8 inches) depth it only increases the relative volume of water held in the substrate by 1.64% for Rooflite® Extensive MC and 1.67% for Kansas BuildEx (Table 3.14). This is important for the green roof design process. Green roof designers may want to increase the substrate depth by a few inches to increase water availability for the plants, but it must be decided if increasing the depth to provide an additional small volume of water for the plants is worth it.

Table 3.14. Roof Capacity (RC) Factor Increases for Rooflite® Extensive MC (RL) and Kansas BuildEx (BX) for the 4- 6-, and 8-Inch Depths.

Depth	Depth factor increase	RL RC factor increase	BX RC factor increase
4	1	1	1
6	1.5	1.12	1.12
8	2	1.64	1.67

The results of the water release testing showed Rooflite® Extensive MC substrate having greater water retention than Kansas BuildEx. The water release testing results are not in line with the roof capacity results. The inconsistency in the results of these two tests can be due to the nature of how substrates were packed for analysis. For the roof capacity tests, substrates were packed in the PVC columns to be as close to the observed bulk density for each substrate on the APD-EGR. For the water release testing the substrates were packed. Turf and Soil Diagnostics lab reported substrate bulk densities of 1.47 g/cm^3 and 0.98 g/cm^3 for Kansas BuildEx and Rooflite® Extensive MC respectively. Substrate samples taken from the APD-EGR found that average bulk density for Kansas BuildEx and Rooflite® Extensive MC substrate was 1.03 g/cm^3 and 1.35 g/cm^3 respectively.

The Rooflite® Extensive MC substrate has a lower roof capacity for than Kansas BuildEx for all three substrate depths. This is important when considering the soil moisture characteristic curve for both substrates. For most soil moisture values Rooflite® Extensive MC has a greater tension than Kansas BuildEx, meaning that at many of the soil moisture values it is harder for the plants to withdraw and thus use the water in the substrate profile when planted in Rooflite® Extensive MC than when planted in Kansas BuildEx.

Even though differences in roof capacities were found, the soil moisture analysis showed that there is no statistical difference in the “rate of drying out after precipitation events” between the two substrates. For the first configuration there was only an effect of substrate on the rate of soil moisture recession in the 4-inch bed for the 1-hour recession period ($p < 0.0001$), with Rooflite® Extensive MC drying out faster than Kansas BuildEx. The rate of recession for Rooflite® Extensive MC was 0.013 $\Delta\theta_V$/hr and the rate of recession for BuildEx was 0.0060 $\Delta\theta_V$/hr. For the second configuration there was only a significant effect of mix on the rate of recession in the 8-inch bed for 1-hour recession period. In the 8-inch bed there was slight evidence of mix on soil moisture recession ($p =0.0584$) with the Sedums mix (mix A) drying out at a faster rate than the all-natives mix (mix C) for the 1-hour recession period. The rate of recession for the Sedums only mix was 0.0061 $\Delta\theta_V$/hr and the rate of recession for the all-natives mic was 0.0035 $\Delta\theta_V$/hr. Also, a study conducted by Ntoulas et al. (2013) investigated soil moisture decline (water deficit cycles) in 7.5 and 15 cm (approximately 3 and 6 inches) substrate depths for 4 different substrate types. This study found that substrate moisture recession rates following an irrigation event were not dependent on substrate type or depth. VanWoert et al. (2005) investigated the effect of vegetation and media type on water retention and found that vegetation did not influence water retention as much as the substrate component for sloped greens roofs with depths of 2 to 6 cm (approximately 0.8 to 2.4 inches). This finding can help explain why there was only an effect of mix on soil moisture recession in the 8-inch bed. For an intensive green roof like the 8-inch bed of the APD-EGR, there is more water available in the soil profile for plant use, and the difference in plant water use strategies can explain the effect of mix on soil moisture recession.

Conclusions

In conclusion both substrates have good retention capacities, but Kansas BuildEx has a higher roof capacity than the commercial green roof substrate provided by Rooflite® Extensive MC. The effect of this higher roof capacity on plant performance is discussed in Chapter 4. Increasing substrate profile depth does not increase roof capacity by the same factor. Green roof designers and researchers will have to make critical decisions on whether increasing the substrate depth and to increase water availability to the plants is worth further increasing structural load to the building to provide a small additional amount of water. In terms of roof capacity, soil moisture recession, and soil moisture characteristics, locally blended green roof substrates are a promising choice for green roof designs, but more research is needed to understand the differences in soil moisture for the two substrates over longer periods of time.

Limitations and Future Considerations

One limitation of this study is the many failed sensor calibration attempts. There was too much variation between calibration trials to develop substrate specific calibration curves. Another limitation of this study is it only utilized the first 1-hour or 24-hour periods after peak soil moisture levels due to rainfall. Because green roofs are frequently experiencing conditions much drier than the moisture content in the 24-hour window following precipitation events, it would be beneficial to analyze soil moisture levels for a longer duration of time in the future.

References

Berndtsson, J.C. 2010. “Green roof performance towards management of runoff water quantity and quality: A review.” Ecological Engineering 36:351-360.

Bonoli, A., et al., 2013. “Green roofs for sustainable water management in urban areas.” Journal of Environmental Engineering and Management 1, 153–156.

Bousselot, J., V. Russel, L. Tolderlund, S. Celik, B. Retzlaff, S. Morgan, I. Buffam, R. Coffman, J. Williams, M. E. Mitchell, J. Backer, J. DeSpain. 2020. “Green Roof Research in North America: A Recent History and Future Strategies.” Journal of Living Architecture 7: 27-64.

Clark, O.R. 1940. “Interception of Rainfall by prairie grasses, weeds, and certain crop plants.” Ecological Monographs. 10(2):243-277.

Cobos, Douglas R., and Chambers, Chris. "Calibrating ECH2O Soil Moisture Sensors." Decagon Devices. Decagon Devices, Inc., 17 Nov. 2010. <http://manuals.decagon.com/Application%20Notes/13393_Calibrating%20ECH2O%20Probes_Print.pdf>.

DeNardo, J.C., A. R. Jarrett, H.B. Manbeck, D.J. Beattie, and R.D. Berghage. 2005. “Stormwater mitigation and surface temperature reduction by green roofs.” Transactions of the ASAE 48(4): 1491-1496.

Dunnett, N., and N. Kingsburry. 2004. Planting Green Roofs and Living Walls. Portland, Oregon: Timber Press.

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., X. Q. Ang, and J.P. Rayner. 2013. “Water-retention additives increase plant available water in green roof substrates.” Journal of Ecological Engineering 52:112-118.

FLL. 2008. Guideline for the planning, execution and upkeep of green-roof sites. English edition. Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau, Bonn.

Gessert, G. 1976. “Measuring a mediums airspace and water holding capacity.” Ornamentals Northwest 1(8):11-12.

Graceson, A., J. Monaghan, N. Hall, M. Hare. 2013. “Plant growth responses to different growing media for green roofs.“ Journal of Ecological Engineering 69: 196-200.

Hillel, D. 2003. Introduction to Environmental Soil Physics. Elsevir Science & Technology. pg 432.

Kirkham, M.B. 2014. Principles of soil and plant water relations. 2nd Ed. Elsevier Science & Technology.

Lambrinos, J.G. 2015. "Chapter 4 - Water Through Green Roofs." In Green Roof Ecosystems (Ed. by R. Sutton). London: Springer Science. 81-105.

Li, Y., and R.W. Babcock Jr. 2014. "Green roof hydrologic performance and modeling: a review." Water Science & Technology 69 (4), 727–738.

Lundholm, J.T., J.S. MacIvor, Z. Macdougall, and M. Ranalli. 2010. "Plant species and functional group combinations affect green roof ecosystem functions." PLoS One 5 (3): 1-11.

METER Group Inc, 2019. 5TM Manual. Retrieved from: http://publications.metergroup.com/Manuals/20424_5TM_Manual_Web.pdf

Molineux C., C. Fentiman, and A. Gange. 2009. "Characterising alternative recycled waste materials for use as green roof growing media in the UK." Journal of Ecological Engineering. 35(10):1507–1513.

Monterusso, M., B. Rowe, and C. Rugh. 2005. "Establishment and persistence of Sedum spp. And native taxa for green roof applications." HortScience 40(2): 391-396.

Nagase, Ayako, and Nigel Dunnett. 2012. "Amount of water runoff from different vegetation types on extensive green roofs: Effects of plant species, diversity and plant structure." Landscape and Urban Planning 104 (3–4) (3/15): 356-63.

Nouri H, S. Beecham, F. Kazemi, and A.M. Hassanli. 2012. "A review of ET measurement techniques for estimating the water requirements of urban landscape vegetation." Urban Water 10(4):247–259

Ntoulas, Nikolaos, Panayiotis A. Nektarios, Eleutherios Charalambous, and Achilleas Psaroulis. 2013. "Zoysia Matrella Cover Rate and Drought Tolerance in Adaptive Extensive Green Roof Systems." Urban Forestry & Urban Greening 12 (4): 522–31. https://doi.org/10.1016/j.ufug.2013.07.006

Olszewski, M. and C. Young. 2011. "Physical and chemical properties of green roof media and their effect on plant establishment." Journal of Environmental Horticulture 29(2): 81-86. https://doi.org/10.24266/0738-2898-29.2.81

Park, A., and J.L. Cameron. 2008. "The influence of canopy traits on throughfall and stemflow in five tropical trees growing in a Panamanian plantation." Forest Ecology and Management 255: 1915-1925.

Rowe DB. 2011. "Green roofs as a means of pollution abatement." Environmental Pollution 159(8–9):2100–2110.

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.

Soulis, K.X., N. Ntoulas, P.A. Nektarios, and G. Kargas. 2017. "Runoff reduction from extensive green roofs having different substrate depth and plant cover." Journal of Ecological Engineering. 102, 80–89.

Spomer, L.A. 1975. "Small soil containers as experimental tools: soil water relations." Communications in Soil Science and Plant Analysis. 6(1): 21-26.

Spomer, L.A. 1980. "Container soil water relations: Production, maintenance, and transplanting." Journal of Arboriculture. 6:315–320.

VanWoert, N.D., D.B. Rowe, J.A. Andersen, C.L. Rugh, R.T. Fernandez, and L. Xioa. 2005. "Green roof stormwater retention: effects of roof surface, slope, and media depth." Journal of Environmental Quality 34(3): 1036-1044.

Wolfe, D., and J. Lundholm. 2008. "Water uptake in green roof microcosms: effects of species and water availability." Ecological Engineering. 33: 179-186.

Young, Thomas, Duncan D. Cameron, Jeff Sorrill, Tim Edwards, and Gareth K. Phoenix. 2013. "Importance of Different Components of Green Roof Substrate on Plant Growth and Physiological Performance." Urban Forestry & Urban Greening 13(3): 507–16. https://doi.org/10.1016/j.ufug.2014.04.007

Zalewski, M. 2002. "Ecohydrology – the use of ecological and hydrological processes for sustainable management of water resources." Hydrological Sciences. 47(5): 823-832.

Chapter 4 - Assessing the Effect of Green Roof Species Mixes and Substrate Type on Plant Coverage and Above-Ground Biomass for Three Green Roof Depths

Synopsis

Green roofs are increasingly common as cities seek environmentally sustainable approaches to mitigate climate change impacts while providing urban amenities. To provide insight on green roof plant selection for green roofs in the Flint Hills Ecoregion (Kansas, USA) and similar climates, three experimental research green roof beds were designed for the Kansas State University (KSU) College of Architecture, Planning and Design (APD) building and were initially planted in October 2017. The three green roof beds consist of three different depths (4, 6, and 8 inches [approximately 10.2, 15.3, and 20.4 cm]). The experimental design is a strip plot design within a randomized complete block design for each green roof depth. Each green roof depth contains two substrates (Rooflite® Extensive MC and Kansas BuildEx), and three different plant mixes (all-*Sedums*, *Sedums* and native grasses, and all-natives). The main objective for the APD Experimental Green Roof research is to observe how mixed-species vegetation performs within two green roof substrates to improve the design, implementation, and management of green roofs. To realize this objective, our interdisciplinary team has been investigating the relationships between micro-meteorological and subsurface variables, two different substrates of three different depths, and vegetative coverage associated with three distinct species mixes. To assess growth, a linear mixed model has been fit to vegetative growth response measured at the end of each growing season ($\alpha = 0.05$). The model includes fixed effects of substrate type, species mix, and their two-way interaction, along with the random

effect of block. To assess above-ground biomass, a linear mixed model was fit to each species biomass measured at the end of each growing season. For each bed (4, 6, and 8 inches) the MIXED and LSMEANS procedures in SAS version 9.4 were used to fit the model and compute the least square means of fixed effects ($\alpha = 0.05$). When looking at species mix performance in these beds, by the end of the second growing season there was a significant effect of mix type on amount of cover (or vegetative coverage with each plot), with the all-natives and *Sedum* and native grass mixes having the greatest cover in the 4-inch and 8-inch beds. In the 6-inch bed there was a significant effect between mix and substrate types, with Rooflite® Extensive MC having greater cover in the *Sedums*-only mix, the *Sedum* and native grass mix having the greatest cover in Rooflite® Extensive MC, and the *Sedum* and native grass mix, and the all-natives mix having the greatest cover in Kansas BuildEx. Regarding individual species performance, by the end of 2019, little bluestem had greater biomass in the Rooflite® Extensive MC substrate than in the Buildex substrate for the 4-, 6-, and 8-inch beds. In the 6-inch bed, sideoats grama had greater biomass in the Rooflite® Extensive MC substrate than in BuildEx, while purple prairie clover had greater biomass in Kansas BuildEx substrate than in Rooflite® Extensive MC. Buffalograss was one of the species planted in the *Sedum* and native grass mix and based on personal observations it performed exceptionally well throughout this study.

Introduction

Plant selection is one of the most important areas to understand when designing green roofs and ensuring their success (Dvorak and Volder, 2010). When selecting green roof species, one must consider its microclimate (Metselaar 2012), which is defined by Merriam-Webster as "the essentially uniform local climate of a … small site or habitat." Green roof microclimates often consist of shallow substrates that experience periodic drought and rapid fluctuations in soil moisture, which make drought tolerance a critical component of plant selection (Wolf and Lundholm, 2008). To achieve success on shallow green roofs, beneficial adaptations exhibited by selected plants may include CAM photosynthesis pathways, drought avoidance and tolerance, woody growth, water storage organs, and other traits that that reduce water loss and heat gain (MacIvor and Lundholm, 2011). Vegetation types selected for green roof plantings are more likely to be successful if the plant species is easily propagated, establishes rapidly, and achieves high ground cover density (Getter and Rowe, 2006). *Sedums*, stress-tolerant grasses, and herbaceous dicots that are adapted to the conditions of a shallow green roof are preferred for planting (VanWoert et al., 2005; Köhler, 2006; Durham et al., 2007; Emilsson et al., 2007; Wolf and Lundholm, 2008). Nevertheless, each region needs to be studied regarding the most appropriate substrate types and species mixes if we are to create regenerative living green roofs.

Since the 1800's, about 97% of tallgrass prairies and more than 60% of mixed and shortgrass prairies of North America have been converted to agricultural or urban areas (MEA, 2005). One way to help conserve the biodiversity of these threatened prairie ecosystems is to find supplemental areas for planting of prairie grassland species, including on rooftops where this is possible and wise. Native plants are viewed as perfect for at-grade landscapes because they are adapted to local climates and frequently do not require supplemental irrigation (Oberndorfer et al., 2007). Nature conservation and biodiversity policies also often favor the use of locally distinctive plant species, but rooftop conditions may make some native species unsuitable. Providing diverse, living vegetative coverage is also vital to capture and conserve rainfall and optimize other ecosystem services on green roofs.

North American green roof research has increased dramatically during the past decade. There have been numerous studies utilizing one or a few plant species to assess green roof suitability, testing the effects of growth media, measuring stormwater retention, and evaluating the environmental benefits provided by *Sedum* green roofs. However, less than ten studies that focus on green roof diversity as a primary variable were found in this review of the published literature (Kolb and Schwarz, 1986; Dunnett et al., 2008; Lundholm et al., 2010, Nagase and Dunnett, 2010; Butler and Orians, 2011; MacIvor and Lundholm, 2011; Nagase and Dunnett, 2013; Heim and Lundholm, 2014). Finding a native plant regime capable of thriving on Kansas green roofs roof may provide many of the ecological benefits outlined in the introduction.

***Sedum* Green Roofs**

Potential green roof species must be able to thrive in difficult growing conditions because the shallow rooftop substrate and full exposure to the environment permits periodic drought and rapid fluctuations in soil moisture (Wolfe and Lundholm, 2008), thus making *Sedums* a common plant species used on green roof installations. *Sedum* species are a common genus selected for green roof plantings because of their growth habits and physiological characteristics, along with their ease of establishment through plugs, cuttings, and seeds. *Sedum* species utilize the crassulacean acid metabolism (CAM) photosynthesis pathway. CAM photosynthesis is an adaptation that allows plant species to switch between C3 and C4 photosynthesis. When moisture conditions are high enough, these plants can fix CO_2 during the day. However, under drought conditions these plants will fix CO_2 during the night, allowing the stomata to remain closed during the day resulting in more efficient use of soil moisture (Silvola, 1985). These adaptations make many *Sedum* species very well adapted to thrive under the harsh conditions that green roof environments can create. The evergreen nature of *Sedums* also allows green roof vegetative cover to persist year-round (Nagase, 2010). *Sedum* species also can thrive in very shallow substrate profiles, which is beneficial for buildings that may have structural weight limitations for green roof systems. A major limiting factor for green roof establishment and growth is substrate thickness (Getter and Rowe, 2008).

There is evidence of positive plant responses to substrate depth in the literature, even for *Sedum* species. Getter and Rowe (2008) compared *Sedum* cover and growth at depths of 4-, 7- and 10-cm (1.57, 2.76, and 3.93 inches) and found that seven (7) cm is the shallowest substrate required for *Sedums* to achieve the greatest growth and cover. Different plant forms have different root structures, requiring different substrate depth. Plant performance and growth on green roofs are directly affected by substrate depth (Vijayaraghavan, 2016). Nevertheless, there are many very hardy *Sedum* species (Cook-Patton and Bauerle, 2012; Rowe, 2017; Snodgrass and Snodgrass, 2006), and some of these have persisted with and without irrigation on different green roofs in Manhattan, Kansas (Skabelund et al., 2014, and Lee R. Skabelund, pers. comm., June 2019). Although it is well known that *Sedums* are successful at thriving on a green roof, there has been growing interest in assessing native species performance in these unique environments.

Use of Native Plant Species

When considering the use of native plant species for green roof designs, the question of "will native species thrive in a harsh green roof environment?" is of great importance. There have been several studies assessing native plant survival on green roofs and these studies have differing results. Monterusso et al. (2005) examined native plant suitability for extensive green roofs in Michigan using a 10 cm substrate. The study concluded that native plant species are not ideal for green roof plantings, after finding that only four of the 18 native plant species survived at the end of the study. However, Sutton et al. (2012) emphasized that the survival of native plant species could be enhanced by deeper substrates and some provision of irrigation. In a green roof system, solely looking at survival is not enough. Green roofs are often advocated for because of the many benefits they can provide (outlined in Chapter 1), and green roof plant diversity plays an important role in providing intended benefits.

Use of native prairie plant mixes will also provide a supplemental habitat for insect and avian species (Cook-Patton, 2015). Green roofs are viewed as a promising technology for reintroducing lost native species in urban environments, but more research is necessary for native plant green roof applications in semi-arid regions (Nektarios et al., 2011).

A 2012 survey of ecological literature on prairie plant species and a survey of 21 existing green roofs with native species indicated that many, but not all, prairie and grassland species will survive and thrive on green roofs (Sutton et al., 2012). Based on this review, grasslands appear to be a great source for potential native plant species for use on green roofs. Blanusa et al., (2013) suggests that choices of plant species should not be solely made on what survives, plant choices should also include species that will provide the greatest ecosystem services. Use of native species for green roof plantings at Kansas State University is an important next step in understanding some of the potential ecological and environmental benefits provided by green roofs in the region.

Use of Diverse Species Mixes

Some researchers suggest using diverse species mixes to improve green roof function and resilience (Lundholm et al., 2010; Bousselot et al., 2020). An extensive review of ecological literature conducted by Cook-Patton and Bauerle (2012) concluded that diverse green roof plantings will maximize the number of environmental services provided by the green roof. However, they also emphasized that "empirical research linking plant biodiversity with green roof performance is limited" (Cook-Patton and Bauerle, 2012, pg 85). Therefore, diversity experiments are required for to determine what type of diversity (namely functional group, functional plant trait, phylogenetic, structural diversity) improve green roof functions and to determine how successful mixed-species plant communities improve the ecosystem services provided (Cook-Patton, 2015). Functional group diversity is defined as "distinguishes species by broad morphological or physiological characteristics (Ex: C3, C4, succulents, legumes), whereas functional plant trait diversity is defined as directly quantifies differences in trait means among species" (Cook-Patton and Bauerle, 2012, pg 86).

Lundholm and Williams (2015) express that there is much more to discover about how diverse green roof plant species mixes function and how diverse plant communities influence green roof sustainability and ecosystem functions. Studying the relationships between biotic and abiotic factors, and their shared effects on delivery of green roof ecosystem services, is vital for understanding how green roof ecosystems are likely to function and change over time (Lundholm and Williams, 2015).

Functional group diversities and structural complexities are important to consider when designing green roofs because they impact insulation, stormwater retention, and plant survival (Dunnett and Nagase, 2008). Verheyen et al. (2008) found that more diverse grassland plots had higher evapotranspiration rates than in monocultures and this trend was reversed during periods of severe water stress. However, more research is needed to understand how diversity will affect water uptake and evapotranspiration on green roofs. According to Nagase and Dunnett (2010), diverse plant mixes (consisting of species with different functional diversities and structural complexity) are more advantageous than monocultures in terms of survivability and visual rating under dry conditions. Functional diversity distinguishes species by broad morphological or physiological characteristics (ex: C3, C4, CAM, legumes) (Cook-Patton and Bauerle, 2012) and examples of structural complexity are plant height, branching, and leafiness (Dunnett and Nagase, 2008). Typically, when forbs and grasses are used in the mix, irrigation is required to maintain aesthetic quality, but this depends on microclimatic variables, substrate depth, and substrate material/composition (Nagase and Dunnett, 2010). Plant diversity may also aid in the preservation of green roof function over longer time frames through compensatory dynamics. For example, if the green roof experiences a pest invasion or abiotic conditions where one plant species is unable to survive, the other plant species that are less impacted can maintain the green roof function (Cook-Patton, 2015).

Evaluation of Substrate Type and Depth

Green roofs possess several challenges in relation to substrate. As stated in Chapter 2, substrate type (chemical and physical properties) can influence plant performance in green roof systems. Substrate depth also affects green roof plant survival and growth (Getter and Rowe, 2008). Green roof substrates need to be lightweight and provide adequate drainage, while also retaining enough moisture to support plant life (Ampim et al., 2010). Due to building structural load constraints, green roof substrates are often kept shallow (Lata et al, 2018). This shallow nature creates a growing environment that quickly dries out and is extremely susceptible to variations in local temperatures causing stunted growth in some plant species (ASTM, 2019).

For shallower substrates it is possible organic matter is the limiting factor for plant growth (Graceson et al. 2014). This study by Graceson et al. (2014) also found that growing media with higher water holding capacities had a beneficial effect on plant growth and by increasing organic matter content, substrate bulk density will be reduced allowing for a greater number of buildings to be retrofitted with a green roof system. In a short-term greenhouse experiment, Nagase and Dunnett (2011) investigated the effect of organic matter content on the growth of four grasses and forbs. All the species had a different response to organic matter content (Nagase and Dunnett, 2011). Under the dry condition scenario organic matter content did not have any effect on the growth of the four species, but under a well-watered irrigation regime a few of the species had much more growth when planted in substrates with high organic matter content (Nagase and Dunnett, 2011). Nagase and Dunnett have expressed criticism for this study because green roof conditions experience periodic droughts and lush growth is not realistic under more realistic rooftop conditions. Gabrych et al. (2016) surveyed 51 green roofs in Helenski, Finland from July to August 2011 and documented 203 plant species. Among the vascular plants 106 were native and 34 were non-native. Substrate depth strongly influenced plant community structure. For all the general linear models (GLMs) tested substrate depth was the most important explanatory variable. In many cases plant growth is optimized by deeper substrate depths, which usually provide greater water holding capacities (VanWoert et al., 2005b).

Evaluation of the variables that influence what species performance on green roofs can provide insight on how to manage a green roof. The four physical factors of soil that affect plant growth are mechanical impedance, water, aeration, and temperature, with water being the most important factor (Kirkham, 2014). To maintain optimum provision of services and efficiently manage a green roof, knowledge of the relationships between plant species performance in terms of cover and biomass—in relation to soil depth and moisture—is required. Sutton et al. (2012) also stated that additional research is needed to understand and eventually improve the success of native green roof species. Additional costs for deeper substrates or supplementary irrigation from a sustainable source may be worth it when one considers the ecosystem services that can be provided (Blanusa et al., 2013). However, glade and rock outcrop communities are mentioned as models for shallower substrates by Lundholm and Richardson (2010), Cook-Patton and Bauerle

(2012), and Sutton at al. (2012). As discussed in Chapter 1, glade and rock outcrop communities are found in various prairie-like ecosystems such as those found in parts of the Flint Hills Ecoregion.

Above-Ground Biomass and Vegetative Coverage as an Indicator of Green Roof Performance

Some benefits of green roofs can be directly related to the vegetative cover and biomass of the plants. The amount of plant biomass reflects a site's relative productivity and ability to support ecosystem services, such as water management, carbon sequestration, nutrient cycling and pollination (Calkins, 2012). The measurement of biomass on a site therefore can be a key component in assessment of environmental performance. Above-ground biomass measurements can be compared over time to determine the increase of ecosystem services and can be an indicator of the health of the vegetation in terms of growth and disease (McCoy et al., 2018).

Vegetative coverage plays a key role in protecting green roofs from the harsh surrounding microclimate. For example, green roofs species can shield the substrate from direct sunlight and wind (Cascone, 2019). Green roof plants can contribute significantly to the green roof's runoff reduction capabilities (Vijayaraghavan, 2016). The extent to which plant cover reduces runoff depends highly on plant height, diameter, and root and shoot biomass. Nagase and Dunnett (2012) found that grasses were more effective at reducing green roof runoff than forbs and *Sedums*.

Research Objectives

1. Understand how vegetative coverage and species above-ground biomass of three mixed-species plantings change over time, using two different substrate types (Kansas BuildEx and

Rooflite® Extensive MC), and three different substrate depths (4 inches, 6 inches, and 8 inches).

2. Test the effects of substrate type on vegetative coverage and species above-ground biomass of three mixed-species within three specified substrate depths of 4, 6, and 8 inches.

Research Questions

1. How does the performance of the three plant mixes (A: all-Sedums, B: Sedums and native grasses, and C: all-native graminoids and forbs) on the APD-EGR differ in each substrate in terms of vegetative coverage?
2. How does the performance of the native species on the APD-EGR differ in each substrate in terms of above-ground biomass?

Hypotheses

1. Coverage will be greater for the Sedum mix due to Sedum species adaptations to survive extreme stress.
2. Coverage will be greater in the Rooflite® Extensive MC substrate due it being a commercially available green roof product.
3. Above-ground biomass will be greater in the Rooflite® Extensive MC substrate due being a commercially developed green roof product.

Methods

Study Site

The Architecture, Planning and Design Experimental Green Roof (APD-EGR) is located atop Seaton Hall at Kansas State University in Manhattan, Kansas. The Koppen-Geiger Climate Classification for this city is Cfa (Humid Subtropical Climate), characterized by a warm temperate main climate, with fully humid precipitation and hot summers (Weatherbase, 2021). July is the warmest month of the year with an average temperature of 80F (26.7C) and the coolest month is January with an average temperature of 27F (-2.8C). Manhattan, Kansas receives an average of 34.3 inches (871.2 mm) of precipitation per year. June receives the most rainfall (averaging 5.4 inches/137.2mm) (Weatherbase, 2021).

Experimental Design

The APD-EGR was constructed during the summer of 2017. The APD-EGR consists of three different planting areas, distinguished by depth (4, 6, and 8 inches). Each planting area contains four blocks, that consist of six (approximately 4' x 4') experimental cells. The three different planting areas provide a total of 72 4' x 4' experimental cells on the green roof. Each 4' x 4' experimental cell is separated by metal (aluminum) dividers. The only portion of the experimental cells within each depth that are not separated is the expanded shale leveling and drainage layer which lies at the lowest level of each planting area.

Figure 4.1. Photo of the APDesign Experimental Green Roof. Photo by Allyssa Decker, taken on July 12, 2019, facing southeast with the 4-inch bed left/center.

This research study utilizes a strip plot design within a randomized complete block design which allows the research team to isolate sources of variation so treatments can be examined and statistically analyzed. To understand mixed species growth and dynamics, the horizontal strips of the design are the three different multi-species mixes (mix A, an all-*Sedums* mix composed of six species; mix B, a *Sedums* and native grasses mix composed of two *Sedum* species and four species of graminoids; and mix C, an all-native graminoids and forbs mix composed of four species of grasses and two species of native wildflowers), while the vertical strips of the design are the two different substrate types (Kansas BuildEx and Rooflite® Extensive MC substrate) for each of the three different substrate depths (4”, 6”, 8”) being used for this study. The three depths were selected because most green roofs range from 4 to 8 inches in depth and the variety in plant types was selected because many green roofs are planted with *Sedum spp.* and/or native species. Kansas BuildEx and Rooflite® Extensive MC substrates were selected by the designers of the APD-EGR because they were specified for other green roofs at Kansas State University. The Kansas BuildEx substrate was used on the East Memorial Stadium Green Roof, while Rooflite® Extensive MC substrates were specified and installed on the APD green roofs north of the APD-EGR. The locations of substrate types and paired species mixes within each block were randomized by KSU-Plant Pathology Statistician Tim Todd. Figure 4.2 depicts the experimental layout of the APD-EGR.

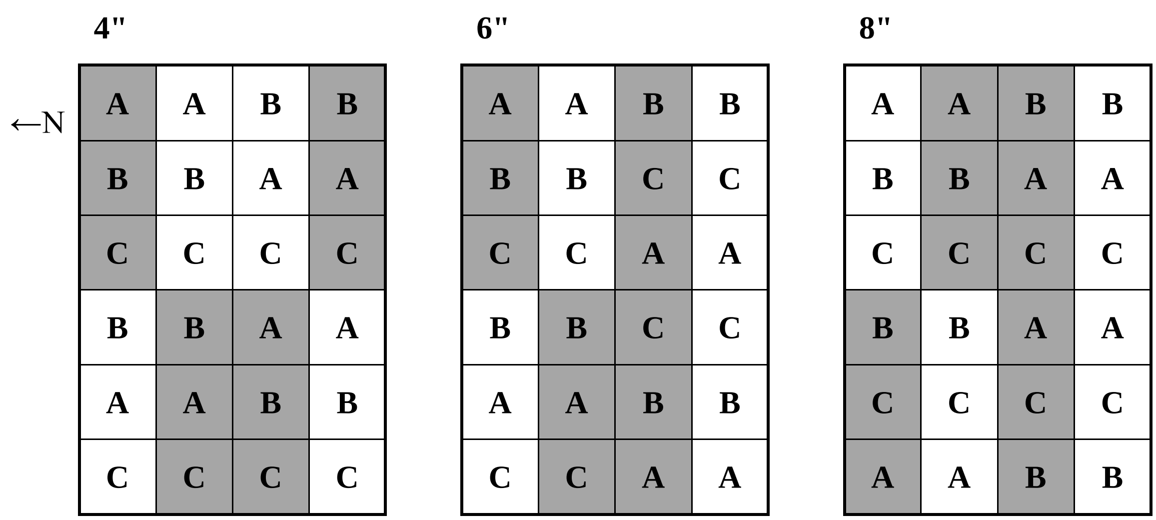


Figure 4.2. Randomized Species Mix and Substrate Type Layout for Each Planting Area. Shaded boxes represent experimental cells that consist of Kansas BuildEx substrate while non-shaded areas represent experimental cells that consist of Rooflite® Extensive MC substrate. A, B, and C represent the plant mixes: All-Sedum, Sedum and grasses, and all-native graminoids and forbs. The 4”, 6”, and 8” above each planting area shows the substrate depth of each planting bed.

Species Selection and Layout

Professor Lee R. Skabelund selected species in Spring-Summer 2015, after considering species that had seen success on other U.S. Central Plains and Midwest green roofs and a review of the green roof literature. The all-Sedum mix (A) contains the following species: *Sedum album var. murale, Sedum ellacombeanum, Sedum hybridum, Sedum kamtschaticum var. floriferum, Sedum sexangulare,* and *Sedum spurium*. The *Sedum* and native grasses (B) mix contains the following species: *Bouteloua curtipendula, Bouteloua dactyloides, Bouteloua gracilis, Schizachyrium scoparium, Sedum reflexum,* and *Sedum ruprestre.* The native grasses and forbs mix (C) contains the following species: *Carex brevoir*, *Dalea purpurea, Koeleria pyramidata, Packera obovata, Schizachyrium scoparium,* and *Sporobolus heterolepis* (Table 4.1). Most of the *Sedum* species were selected based on their use elsewhere and through consulting sources such as Emory Knoll Farms, Chicago Botanical Garden green roof studies, and the USDA Plants Database. The two *Sedum* species specified for mix B, the *Sedum* and native grasses mix, were not available and so substitutes were made by Blueville Nursery in consultation with the building design team.

Table 4.1. Species Used for Each of the APDesign Research Green Roof Plant Mixes.

Mix A: All-*sedums*	**Mix B: *Sedum* and native grasses**	**Mix C: All-natives**
1. *Sedum album var. murale* (SA)	1. *Bouteloua curtipendula* (BC)	1. *Carex brevoir* (CB)
2. *Sedum ellacombeanum* (SE)	2. *Bouteloua dactyloides* (BD)	2. *Dalea purpurea* (DP)
3. *Sedum hybridum* (SI)	3. *Bouteloua gracilis* (BG)	3. *Koeleria pyramidata* (KP)
4. *Sedum kamtschaticum var. floriferum* (WG)	4. *Schizachyrium scoparium* (SSc)	4. *Packera obovata* (PO)
5. *Sedum sexangulare* (SSe)	5. *Sedum reflexum* (SRe)	5. *Schizachyrium scoparium* (SSc)
6. *Sedum spurium* (SS)	6. *Sedum ruprestre* (SRu)	6. *Sporobolus heterolepis* (SH)

To create a planting layout, the selected plant species were numbered in alphabetical order (using Scientific [Latin] nomenclature) starting from the top of the list (#1) to the bottom of the list (#6) for each mix (A, B, and C). Note that randomization of plant layout was attempted, however, clustering of the same species proved problematic in some instances. Thus, a systematic numbering system was selected. The systematic ordering shown in Table 4.1 and Figure 4.3 avoided clustering any of the same species in the same cell. Figure 4.4 shows the proposed layouts for each plant mix (A, B, and C) for the APD-EGR. The plant species names are abbreviated in each box to show planting layout. The three different multi-species mixes (all-*Sedums* mix, native *Sedums* and grasses mix, and all-native graminoids and forbs mix) have been randomized and were planted in the same layouts of equal numbers (three plants of each species within a cell for a total of 18 plants per cell) within the two different substrates for each of the three planting areas (Figure 4.3).

1		**2**		**3**
	5		**6**	
2		**3**		**4**
	6		**1**	
3		**4**		**5**
	1		**2**	
4		**5**		**6**

Figure 4.3. Systematic Plant Layout for APDesign Experimental Green Roof Cell. The numbers represent each species listed in in Table 4.1.

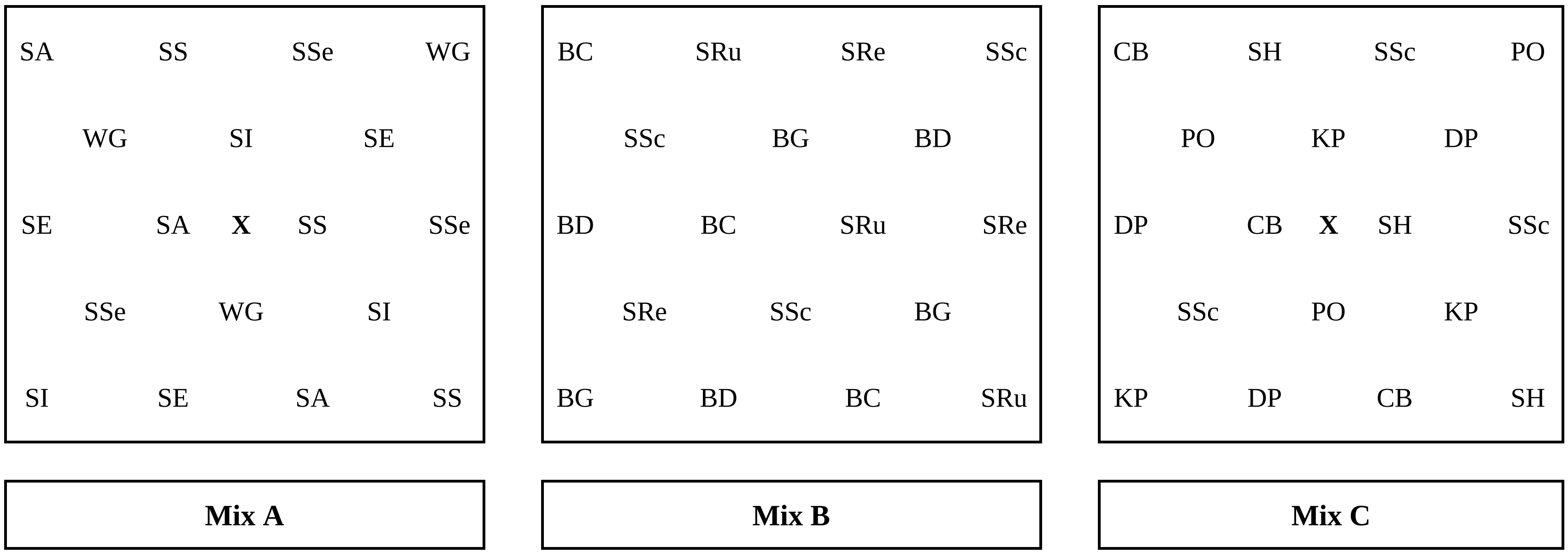


Figure 4.4. Plant Mix Layouts for the APDesign Experimental Green Roofs. Plant species names are abbreviated in each box to show planting layout. See Table 4.1 for plant abbreviations. The “X” represents METER 5TM sensor locations.

Species Replacements

After the experimental green roofs were planted, the APD-EGR was audited by the research team to be sure that the contractors had created the green roofs proposed by the designers (including planting the mixed-species vegetation as shown above in the Proposed Plant Mix Layouts). Several green roof species were out of place and needed to be replanted. During spring 2018, it was observed that many green roof species did not survive the winter. Before beginning the research study, all dead APD-EGR plants had to be replaced. The research team would have liked to replace the dead species in April or May 2018, but the plugs were not available until June. Figure 4.5 shows green roof plants that were replaced in June 2018.

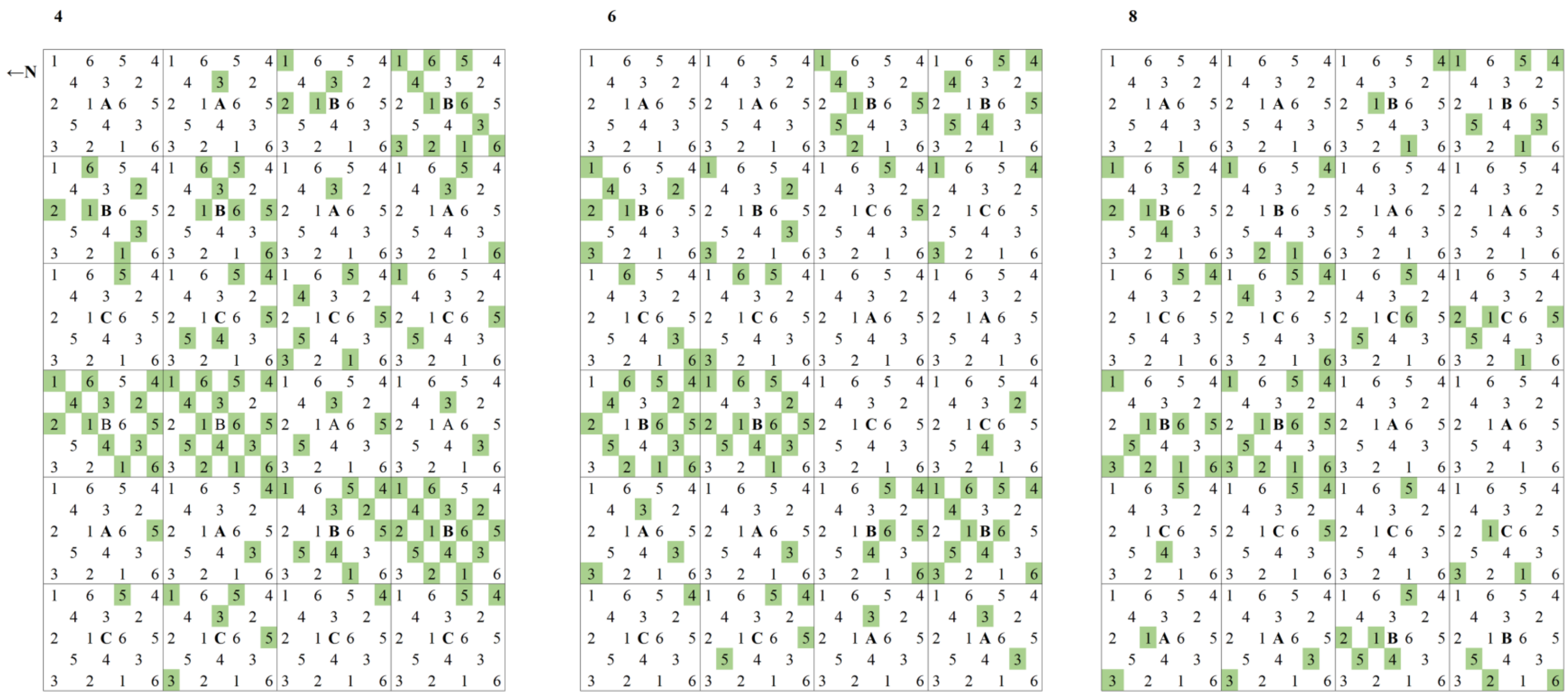


Figure 4.5. Spring Replacement Plant Map. Each number represents an individual green roof plant. The numbers highlighted in green show the green roof plants that were considered dead after the spring 2018 green roof audit. The 4, 6, and 8 above each planting area indicates the substrate depth of each planting bed in inches.

Irrigation Protocol

Plants on the APD-EGR were watered on an as-needed basis. The goal was to ensure that planting areas received at least one inch (25.4 mm) of water each week via rainfall or supplemental irrigation. After rainfall events, irrigation was not provided until soil moisture levels reached the critical value of 0.05 cm^3/cm^3 (as set by the research team following more than a year of observing soil moisture sensors deployed on other Kansas State University green roofs). Irrigation was provided by either a nearby spigot (potable water) or from the collected rainfall in a cistern nearby (Figure 4.6). A hand wand was used for watering paired with a flow meter to allow for accurate documentation of water applied. Each green roof cell was water individually for a set period (ranging from 20 to 60 seconds depending on the amount of water needed).

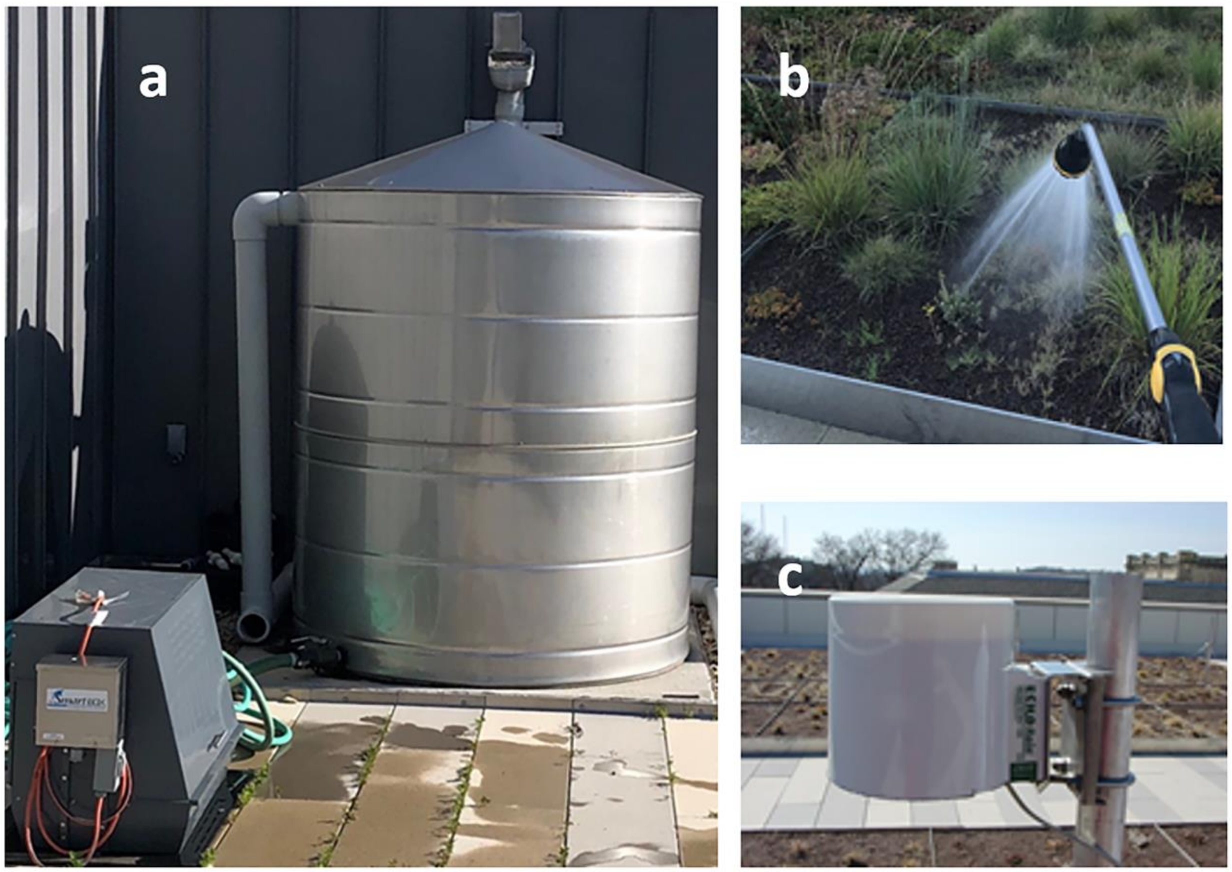


Figure 4.6. Irrigation Equipment Photos. Image a) 800-gallon cistern and pump. Image b) Hand watering wand. Image c) ECRN-100 High Resolution Rain Gauge.

Vegetative Coverage Measurements

For the purposes of this research, vegetative coverage is used to describe the percentage of ground surface covered by living plant material (Cook-Patton and Bauerle, 2012). Vegetative coverage was measured monthly throughout the growing season. For this study, growing season is defined as the time between last spring frost (typically in mid-April) and first autumn frost (typically in late-October).

Overhead photography was used to capture vegetative coverage of each of the green roof cells (Figure 4.7). Photos were cropped to contain only what is inside each individual cell and then pulled into ImageJ, a Java-based image processing program developed at the National Institutes of Health and the Laboratory for Optical and Computational Instrumentation (Rashband, 2018). Once photos were uploaded to ImageJ, coverage could be measured following the protocol developed by Colleen Butler (2012). To measure cover in ImageJ, the image was broken into hue, saturation, and brightness (HSB stack). From here, the image threshold was changed to black and white, and the threshold bars were adjusted so that plants were shown as black with everything else shown in white. Once the threshold of the image was adjusted, the "analyze" and "measure" features were used to measure percent cover.

Figure 4.8 shows examples of cropped vegetative coverage photos from each of the species mix and substrate type factor combinations taken during the first growing season. Vegetative coverage was determined by assessing the plants covering the soil surface when looking directly down at each plot, as recorded in the photographs taken. In other words, this was a visual assessment of coverage rather than physically measuring vegetative cover.

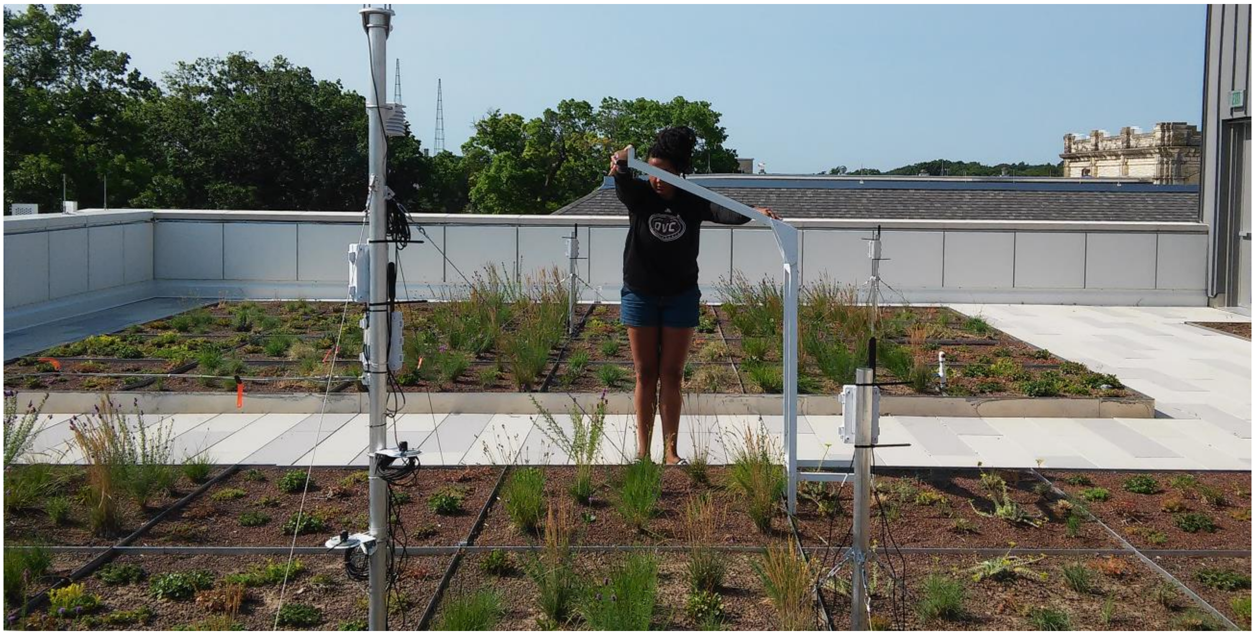


Figure 4.7. Taking Overhead Coverage Photos. Photo by Lee Skabelund on June 15, 2018.

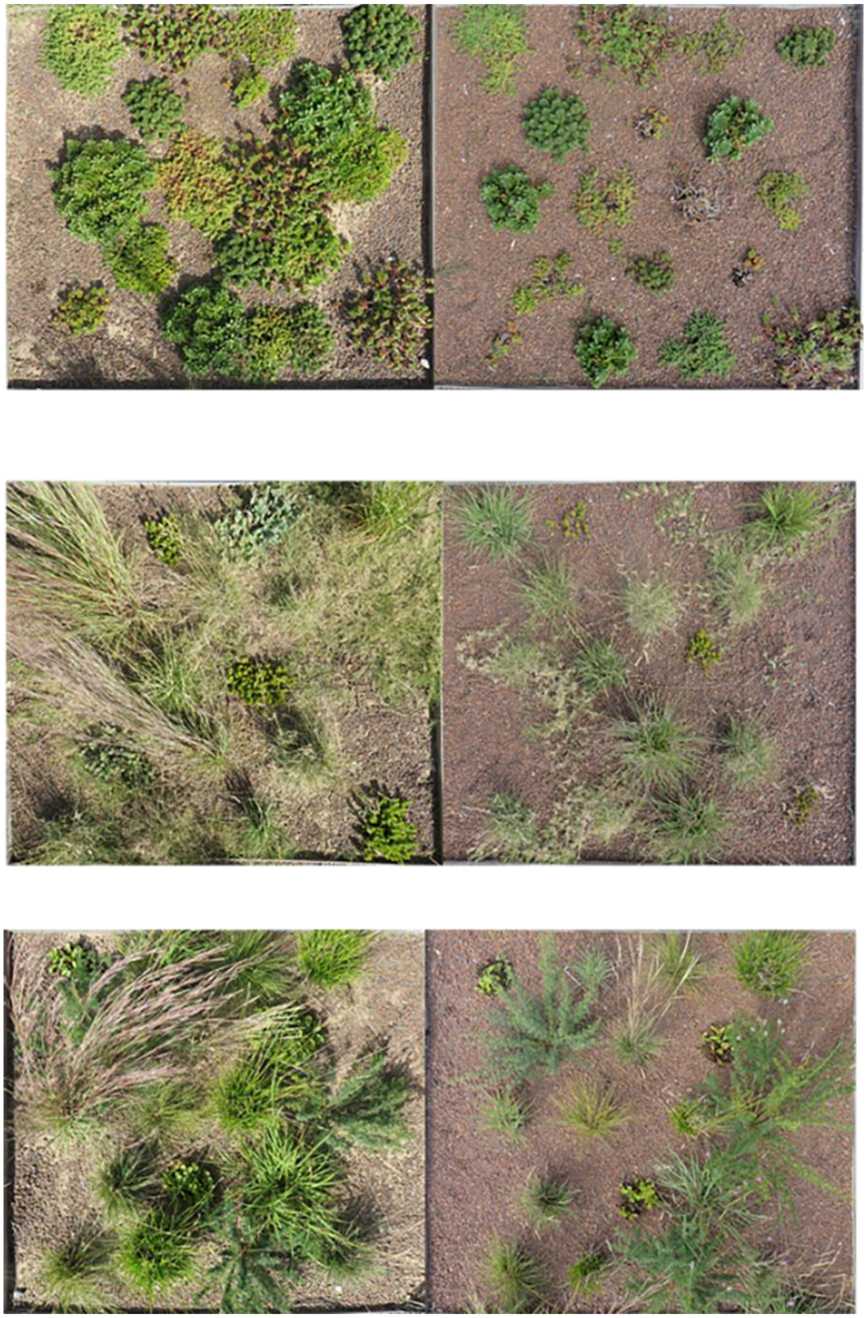


Figure 4.8. Overhead Photos of Example Species Mixes. Images were taken each month during the first two growing seasons (2018 and 2019). The side-by-side images of the three six-species plant mixes were taken September 12, 2018, within the 8-inch bed. The photos on the left are of species planted in the Kansas BuildEx substrate, while photos on the right are of species planted in the Rooflite® Extensive MC substrate. The two photos on the top are of cells planted with six *Sedum* species (mix A), the two photos in the middle are of cells planted with two *Sedum* species and four native grass species (mix B), and the two photos on the bottom are of cells planted with all native species—four graminoids and two forbs (mix C). These images are representative of the greater vegetation coverage typically found in the BuildEx cells during the first two growing seasons.

Above-Ground Biomass Measurements

At the end of the growing season in 2018 and 2019 all the native species were clipped for above-ground biomass measurements. For each green roof cell, all native species were clipped in the native and *Sedum* mix B (except *Bouteloua dactyloides* "buffalograss") and the all-natives mix C. Plants were clipped at approximately two inches above the substrate surface. *Bouteloua dactyloides* was excluded due it its low-growing sod nature (with a majority of *Bouteloua dactyloides* plants aboveground biomass being below the 2-inch [approximately 5 cm] mark for clipping). *Bouteloua dactyloides* produces stolons (runners) that grow horizontally and take root at the node. The three individual plants of each species planted within a cell were collected in an individual paper bag (labeled with the species name and cell location). Bags were weighed and then dried at 60C for three days. After drying, bags were weighed again. Above-ground biomass was calculated as wet bag weight minus dry bag weight.

Data Analysis

To assess growth, a linear mixed model was fit to the vegetative cover measured at the end of each growing season (2018 and 2019) for each bed (4, 6, and 8 inches). The MIXED and LSMEANS (least square means) procedures in SAS version 9.4 were used to fit the model and compute the least square means of fixed effects ($\alpha = 0.05$).

To assess above-ground biomass, a linear mixed model was fit to each species biomass measured at the end of each growing season (2018 and 2019). For each bed (4, 6, and 8 inches) the MIXED and LSMEANS procedures in SAS version 9.4 were used to fit the model and compute the least square means of fixed effects ($\alpha = 0.05$).

Forb Reproduction Observations

At the end of the 2018 growing season, many native forb seedlings were observed. At this time, it was decided that forb reproduction on the APD-EGR should be recorded. Thus, at the end of the 2018 and 2019 growing seasons, each native forb that was not one of the six originally planted live plugs in each cell was counted for each of the “all-natives” cells. The number of offspring was recorded for *Dalea purpurea* and *Packera obovata*, the two native forb species in the all-natives mix.

Results

Plant Cover

2018 Growing Season

For the 2018 growing season there was a significant effect for both main effects, species mix and substrate, on plant cover for both the 4-inch and 8-inch beds (Tables 4.2 and 4.4). The main effects of mix and substrate both had p-values less than α=0.05. For the 6-inch bed there was a significant effect of mix on plant cover with a p-value less than α=0.05 (Table 4.3).

Table 4.2. Type III Test of Fixed Effects for 4-inch End of Season Cover in 2018.

Type III Test of Fixed Effects				
Effect	**Num df**	**Den df**	**F value**	**Pr>F**
Mix	2	6	19.85	**0.0023***
Substrate	1	3	14.48	**0.0319***
Mix*Substrate	2	6	0.84	0.4765

Note: An asterisk (*) shows a significant effect on plant cover (α=0.05).

Table 4.3. Type III Test of Fixed Effects for 6-inch End of Season Cover in 2018.

Type III Test of Fixed Effects				
Effect	**Num df**	**Den df**	**F value**	**Pr>F**
Mix	2	6	10.41	**0.0112***
Substrate	1	3	2.37	0.2210
Mix*Substrate	2	6	0.93	0.4446

Note: An asterisk (*) shows a significant effect on plant cover (α=0.05).

Table 4.4. Type 3 Test of Fixed Effects for 8-inch End of Season Cover in 2018.

Type III Test of Fixed Effects				
Effect	**Num df**	**Den df**	**F value**	**Pr>F**
Mix	2	6	17.44	**0.0032***
Substrate	1	3	34.29	**0.0099***
Mix*Substrate	2	6	2.87	0.1332

Note: An asterisk (*) shows a significant effect on plant cover (α=0.05).

In the first growing season (2018), the differences of least squared means showed that the all-natives mix (C) and the *Sedum* and native grass (B) had the highest average cover. Average cover for mix C was approximately 44.8, 56.9, and 58.8 percent for the 4-, 6-, and 8-inch depths respectively. Average cover for the *Sedum* and native mix (B) was approximately 45.3, 65.23, and 70.12 percent for the 4-, 6-, and 8-inch depths respectively. The all-*Sedum* mix (A) had the lowest coverage (Figures 4.9, 4.10, and 4.11) of within each of the three beds (4-inch, 6-inch, and 8-inch). Average cover for mix A was approximately 28.0, 43.7, and 44.3 percent for the 4-, 6-, and 8-inch depths respectively. The differences of least squared means also showed that Kansas BuildEx yielded a higher average coverage than Rooflite® Extensive MC substrate for the 4- and 8-inch depths (see Figures and 4.11). Average cover for Kansas BuildEx was approximately 44.2, 58.0, and 66.5 percent for the 4-, 6-, and 8-inch depths respectively. Average cover for Rooflite® Extensive MC was approximately 34.4, 53.5, and 49.0 percent for the 4-, 6-, and 8-inch depths respectively.

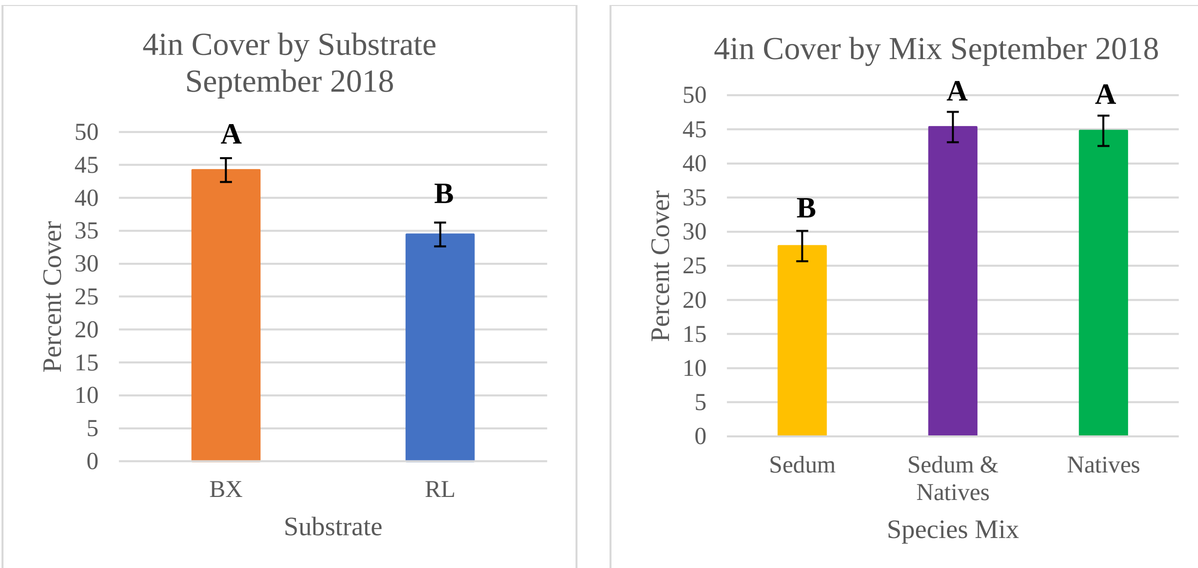


Figure 4.9. 4-inch Cover by Substrate (left) and by Mix (right) for 2018. BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC. n = 24, α > 0.05 Error bars represent ± one SE. Means that do not share a letter are significantly different.

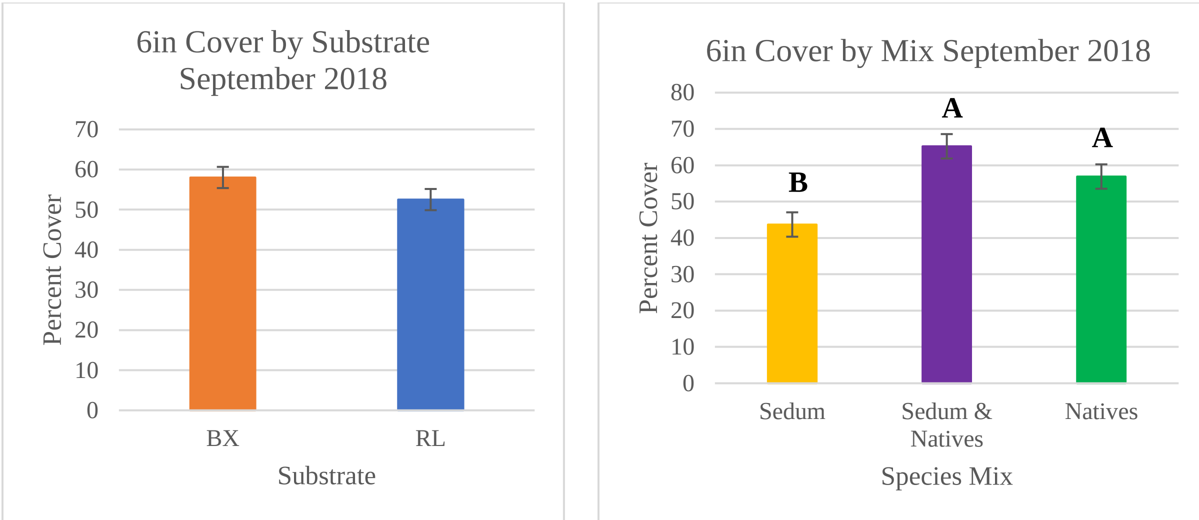


Figure 4.10. 6-inch Cover by Substrate (left) and by Mix (right) for 2018. BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC. n = 24, $\alpha > 0.05$ Error bars represent ± one SE. Means that do not share a letter are significantly different.

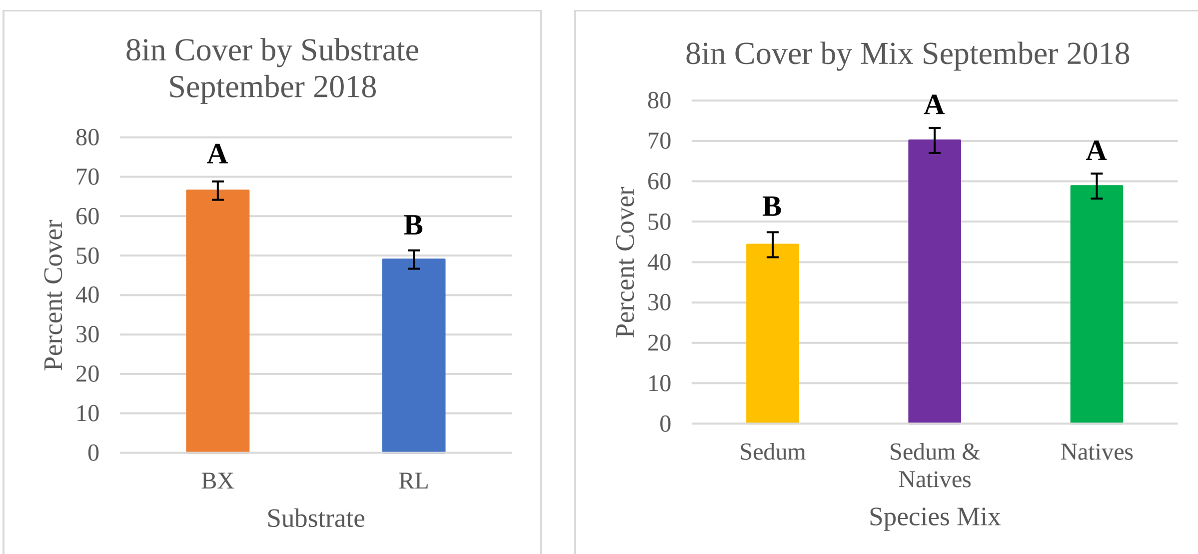


Figure 4.11. 8-inch Cover by Substrate (left) and by Mix (right) for 2018. BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC. n = 24, $\alpha > 0.05$ Error bars represent ± one SE. Means that do not share a letter are significantly different.

2019 Growing Season

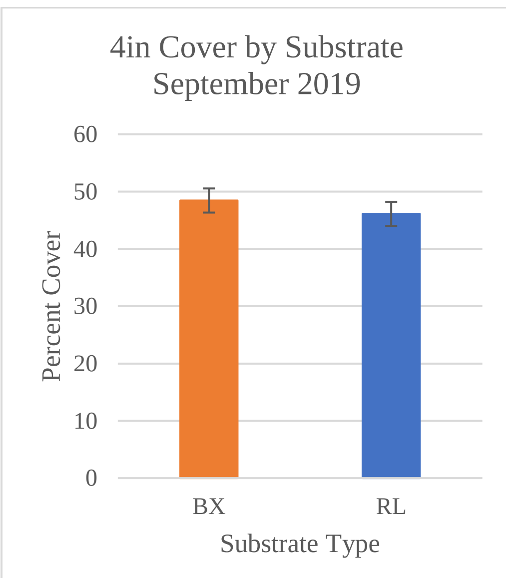
Vegetative cover trends were similar to the findings in 2018 for the 2019 growing season for the 4-inch and 8-inch beds (tables 4.5 and 4.7). For both beds there was evidence of a main effect of mix on cover. However, for the 4-inch bed there was not a significant main effect of substrate on cover, but there was evidence for a main effect of substrate on cover for the 8-inch bed. For the 6-inch bed there was evidence for an interaction of the main effects of mix and substrate on cover (Table 4. 6). Due to the significant interaction the difference of LSMeans for each substrate mix, differences in cover by substrate for the mixes and differences in cover by mix across the substrates were found (Figure 4.13). In the 6-inch depth Rooflite® Extensive MC substrate had a greater overall coverage than Kansas BuildEx substrate.

By the end of the 2019 growing season, there was no effect of substrate on cover for the 4-inch bed. At the 4-inch depth, average percent cover for Kansas BuildEx and Rooflite® Extensive MC was 48.5 and 46.1 percent across all species mixes, respectively (Figure 4.12). After finding evidence for a main effect of mix on cover, assessing the differences of least squared means showed where these differences occurred. There were significant differences in cover between the *Sedum* and native grass and the *Sedum*-only mix and between the all-natives and the *Sedum*-only mix. However, there was no difference between the percent cover for the all-natives mix and the *Sedum* and native grass mix. The average percent cover for the all-native, *Sedum* and native grass, and the *Sedum*-only mixes across both media types was 52.43, 57.53, and 31.89 percent, respectively (Figure 4.12).

Table 4.5. Type III Test of Fixed Effects for 4-inch End of Season Cover 2019.

Type III Test of Fixed Effects				
Effect	**Num df**	**Den df**	**F value**	**Pr>F**
Mix	2	6	51.49	**0.0002***
Substrate	1	3	0.64	0.4836
Mix*Substrate	2	6	0.28	0.7680

Note: An asterisk (*) shows a significant effect on plant cover (α=0.05).



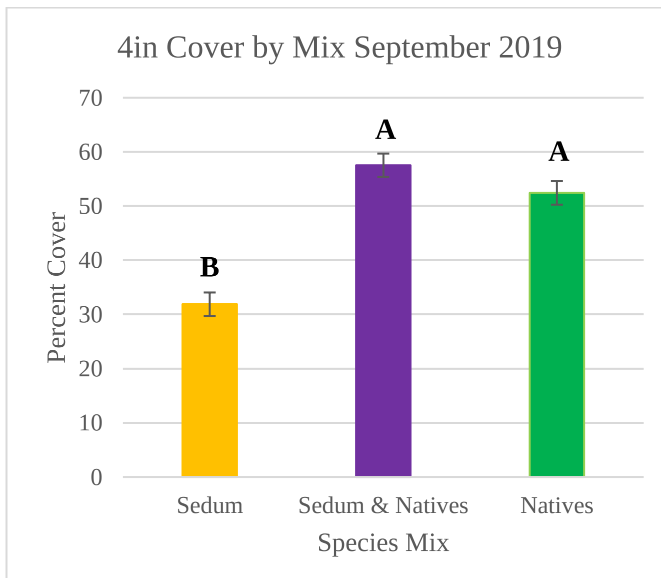


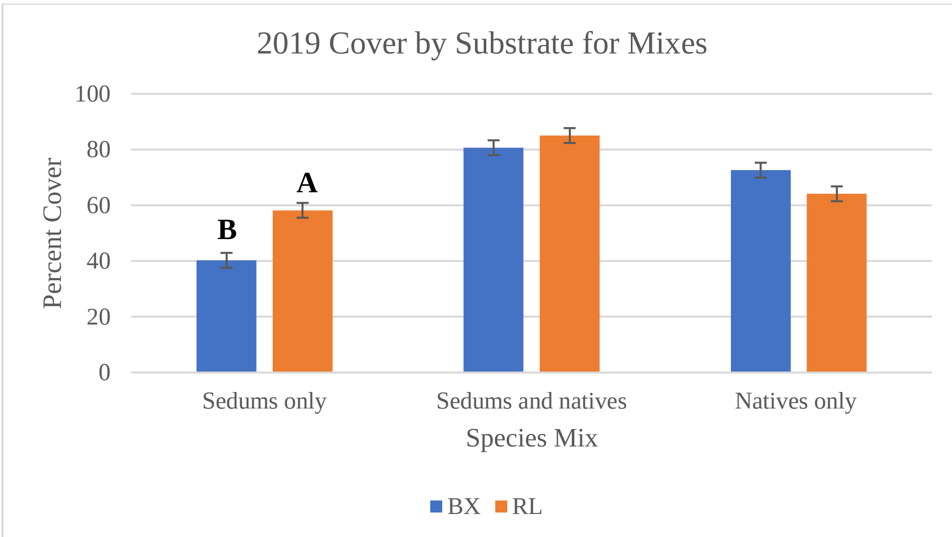
Figure 4.12. 4-inch Cover by Substrate (left) and by Mix (right) for 2019. BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC. n = 24, α > 0.05 Error bars represent ± one SE. Means that do not share a letter a significantly different.

Due to the evidence for a significant interaction between the main effects, cover cannot be evaluated at the main effect level in the 6-inch bed. Differences of least squared means for all the treatment combinations were compared within substrates and within mixes. At the end of the 2019 growing season, there was no difference in cover between Kansas BuildEx and Rooflite® Extensive MC for both the *Sedum* and native grass mix (BX = 80.6% & and RL = 85.0%) and the all-natives mix (BX = 72.6% & and RL = 64.1%) (Figure 4.13). In the *Sedum*-only mix there was a significant difference in cover between Kansas BuildEx and Rooflite® Extensive MC, with average cover being 40.2% and 58.2% respectively in the two substrate types (Figure 4.13). When looking at the comparisons within substates, there were significant difference found between the mixes in both Kansas BuildEx and Rooflite® Extensive MC. Within the Kansas BuildEx cells the all-natives mix and *Sedum* and native grass mix had significantly higher percent cover than the *Sedum*-only mix. This is very likely due to the forms and growth patterns of the various species.

Table 4.6. Type III Test of Fixed Effects for 6-inch End of Season Cover 2019.

Type III Test of Fixed Effects				
Effect	**Num df**	**Den df**	**F value**	**Pr>F**
Mix	2	6	4.13	**0.0008***
Substrate	1	3	51.52	0.2135
Mix*Substrate	2	6	0.52	**0.0292***

Note: An asterisk (*) shows a significant effect on plant cover (α=0.05).



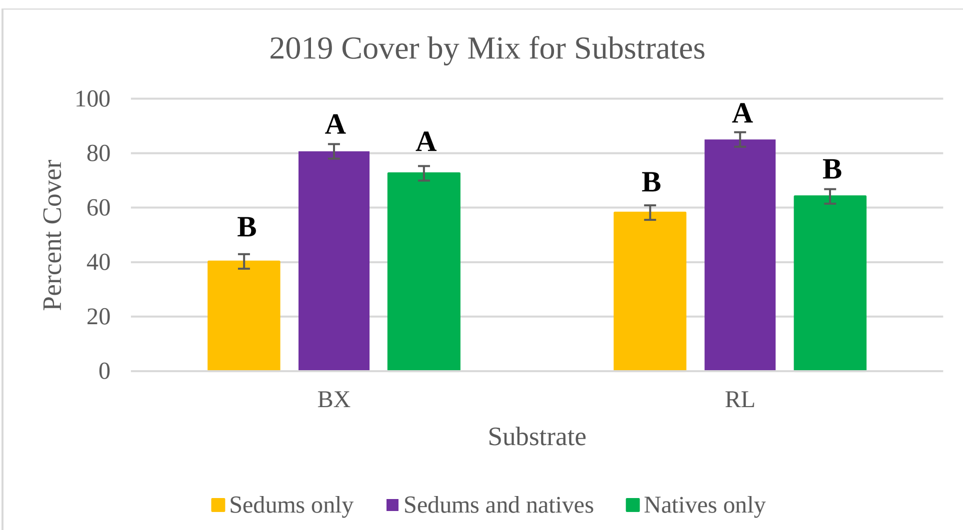


Figure 4.13. 6-inch Cover by Substrate for Each Species Mix (top) and 6-inch Cover by Species Mix for Each Substrate (bottom). BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC. n = 24, α > 0.05 Error bars represent ± one SE. Means that do not share a letter are significantly different.

In the 8-inch bed there were significant differences in average cover between the mixes. Differences of least squared means for cover were compared within substrates and within mixes. The all-natives and *Sedum* and native grasses mix (80.5% and 81.8% respectively) had significantly greater cover than the *Sedum*-only mix (64.58%) (Figure 4.14). There was marginal evidence for an effect of substrate on cover (p=0.0623). The average cover in the 8-inch bed for Kansas BuildEx was 81.1% and the average cover for Rooflite® Extensive MC was 70.1% (Figure 4.14).

Table 4.7. Type III Test of Fixed Effects for 8-inch End of Season Cover 2019.

Type III Test of Fixed Effects				
Effect	**Num df**	**Den df**	**F value**	**Pr>F**
Mix	2	6	8.64	**0.0171***
Substrate	1	3	8.43	**0.0623**
Mix*Substrate	2	6	2.42	0.1694

Note: An asterisk (*) shows a significant effect on plant cover (α=0.05).

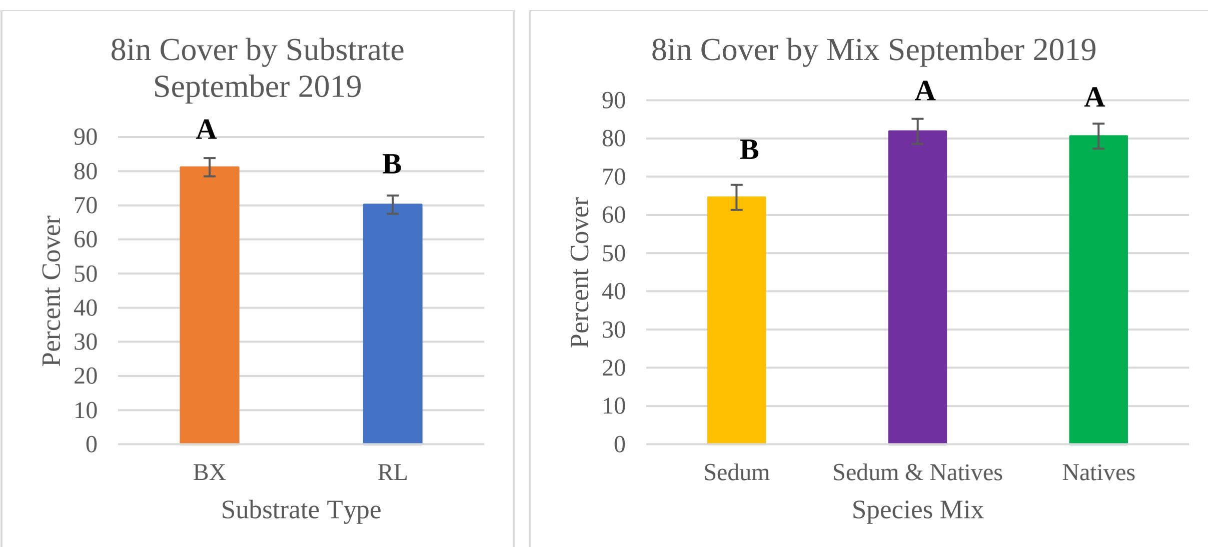


Figure 4.14. 8-inch Cover by Substrate (left) and by Mix (right) for 2019. BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC. n = 24, α > 0.05 Error bars represent ± one SE. Means that do not share a letter are significantly different.

Above-Ground Biomass

2018 Growing Season

In the 4-inch bed, differences in species above-ground biomass between the substrates were found (Table 4.8). The *Schizachyrium scoparium* (little bluestem) plants in the *Sedum* and native grass cells had greater above-ground biomass in the Kansas BuildEx (33.0g) substrate than in the Rooflite® Extensive MC substrate (20.1g). *Dalea purpurea* (purple prairie clover) within the all-natives cells had greater above-ground biomass in Rooflite® Extensive MC (33.6g) than in Kansas BuildEx (21.3g) (Figure 4.15).

Table 4.8. Type III Test of Fixed Effects for the 4-Inch Bed Above-Ground Biomass in 2018.

Type III Test of Fixed Effects				
Effect	**Num df**	**Den df**	**F Value**	**Pr>F**
Substrate	1	3	0.43	0.5567
Mix	1	3	2.10	0.2429
Substrate* mix	1	3	0.70	0.4629
Species (mix)	6	36	5.99	**0.0002***
Substrate* Species (mix)	6	36	1.52	0.2012

Note: An asterisk (*) shows a significant effect on plant cover (α=0.05).

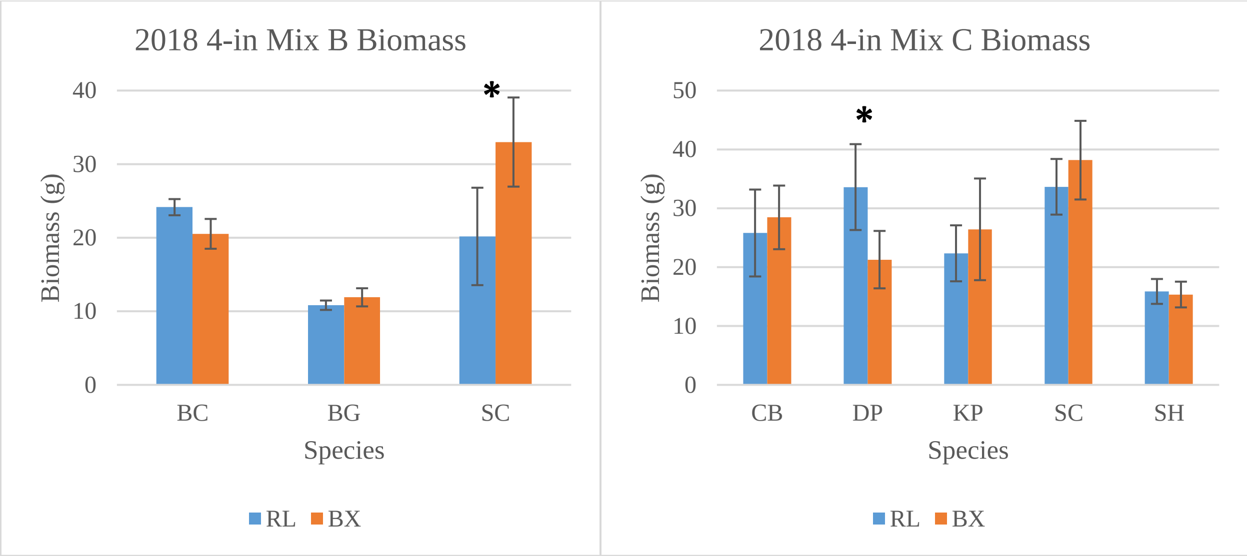


Figure 4.15. End of Season Above-Ground Biomass for Mix B (left) and Mix C (right) in the 4-Inch Bed in 2018. BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC. An asterisk (*) shows a significant difference in above-ground biomass (α=0.05). Plant abbreviations are as follows: *Bouteloua curtipendula* (BC), *Bouteloua dactyloides* (BD), *Bouteloua gracilis* (BG) *Carex brevoir* (CB), *Dalea purpurea* (DP), *Koeleria pyramidata* (KP), *Schizachyrium scoparium* (SC) and *Sporobolus heterolepis* (SH).

Differences in species above-ground biomass between the substrates were found in the 6-inch bed (Table 4.9). In the 6-inch bed *Bouteloua curtipendula* (sideoats grama) of the *Sedum* and native grass cells had greater coverage in the Rooflite® Extensive MC substrate (73.3g) than in Kansas BuildEx substrate (36.1g) (Figure 4.16).

Table 4.9. Type III Test of Fixed Effects for the 6-Inch Bed Above-Ground Biomass in 2018.

Type III Test of Fixed Effects				
Effect	**Num df**	**Den df**	**F Value**	**Pr>F**
Substrate	1	3	18.12	0.0238
Mix	1	3	0.01	0.9147
Substrate*mix	1	3	1.94	0.2575
Species(mix)	6	36	16.52	**<0.0001***
Substrate* Species(mix)	6	36	5.88	**0.0002***

Note: An asterisk (*) shows a significant effect on plant cover (α=0.05).

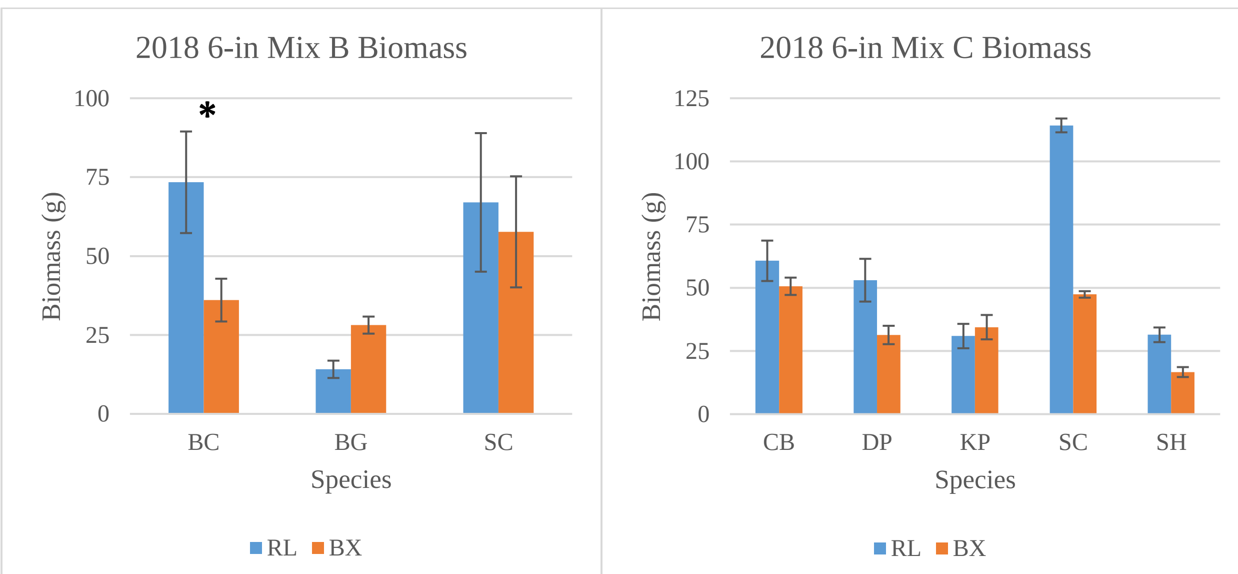


Figure 4.16. End of Season Above-Ground Biomass for Mix B (left) and Mix C (right) in the 6-Inch Bed in 2018. BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC. An asterisk (*) shows a significant difference in above-ground biomass (α=0.05). Plant abbreviations are as follows: *Bouteloua curtipendula* (BC), *Bouteloua dactyloides* (BD), *Bouteloua gracilis* (BG) *Carex brevoir* (CB), *Dalea purpurea* (DP), *Koeleria pyramidata* (KP), *Schizachyrium scoparium* (SC) and *Sporobolus heterolepis* (SH).

In the 8-inch bed, differences in species above-ground biomass between the substrates were found (Table 4.10). The *Schizachyrium scoparium* (little bluestem) plants in Kansas BuildEx (103.6g) had greater above-ground biomass than Rooflite® Extensive MC substrate (50.6g) in the all-natives cells (Figure 4.17).

Table 4.10. Type III Test of Fixed Effects for the 8-Inch Bed Above-Ground Biomass in 2018.

Type III Test of Fixed Effects				
Effect	**Num df**	**Den df**	**F Value**	**Pr>F**
Substrate	1	3	2.87	0.1888
Mix	1	3	6.97	0.0777
Substrate*mix	1	3	0.01	0.9190
Species(mix)	6	36	16.37	**<0.0001***
Substrate* Species(mix)	6	36	1.08	0.3943

Note: An asterisk (*) shows a significant effect on plant cover (α=0.05).

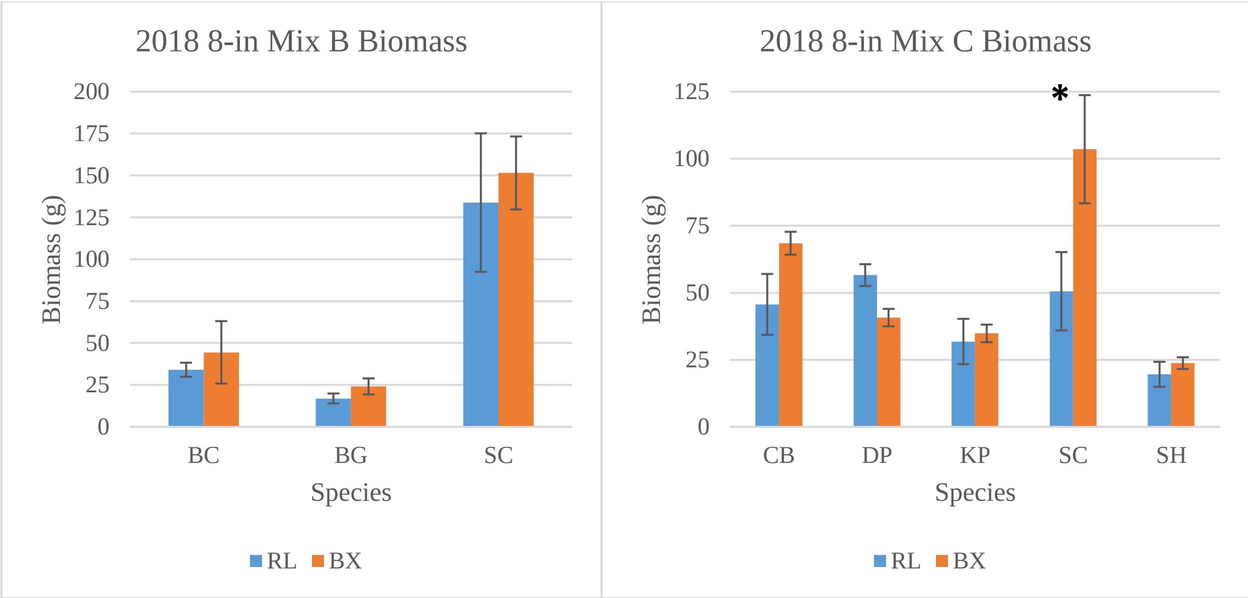


Figure 4.17. End of Season Above-Ground Biomass for Mix B (left) and Mix C (right) in the 8-Inch Bed in 2018. BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC. An asterisk (*) shows a significant difference in above-ground biomass (α=0.05). Plant abbreviations are as follows: *Bouteloua curtipendula* (BC), *Bouteloua dactyloides* (BD), *Bouteloua gracilis* (BG) *Carex brevoir* (CB), *Dalea purpurea* (DP), *Koeleria pyramidata* (KP), *Schizachyrium scoparium* (SC) and *Sporobolus heterolepis* (SH).

2019 Growing Season

For the *Schizachyrium scoparium* (little bluestem) plants in both the *Sedum* and native grass and all-natives mixes, above-ground biomass was greater in Rooflite® Extensive MC than Kansas BuildEx in the 4-inch bed (Figure 4.18). For the *Sedum* and native grass mix above-ground biomass of *Schizachyrium scoparium* was 91.6g for Rooflite® Extensive MC and 39.1g for Kansas BuildEx. Also, above-ground biomass of *Schizachyrium scoparium* in the all-natives mix was 165.0g for Rooflite® Extensive MC and 96.95g for Kansas BuildEx.

Table 4.11. Type III Test of Fixed Effects for the 4-Inch Bed Above-Ground Biomass in 2019.

Type III Test of Fixed Effects				
Effect	**Num df**	**Den df**	**F Value**	**Pr>F**
Substrate	1	3	9.89	0.0515
Mix	1	3	29.67	0.0122
Substrate*mix	1	3	0.06	0.8286
Species(mix)	6	36	38.48	**<0.0001***
Substrate* Species(mix)	6	36	1.90	0.1078

Note: An asterisk (*) shows a significant effect on plant cover (α=0.05).

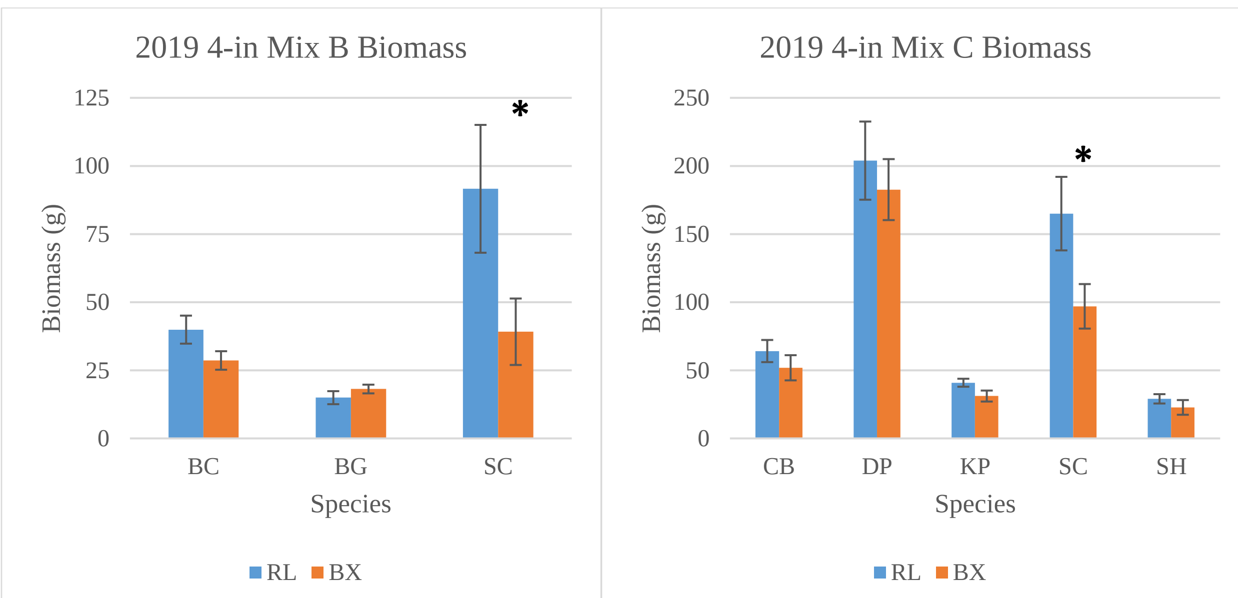


Figure 4.18. End of Season Above-Ground Biomass for Mix B (left) and Mix C (right) in the 4-Inch Bed in 2019. BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC. An asterisk (*) shows a significant difference in above-ground biomass (α=0.05). Plant abbreviations are as follows: *Bouteloua curtipendula* (BC), *Bouteloua dactyloides* (BD), *Bouteloua gracilis* (BG) *Carex brevoir* (CB), *Dalea purpurea* (DP), *Koeleria pyramidata* (KP), *Schizachyrium scoparium* (SC) and *Sporobolus heterolepis* (SH).

For the 6-inch bed, *Bouteloua curtipendula* (sideoats grama) of the *Sedum* and native grass mix had greater above-ground biomass in Rooflite® Extensive MC (99.65g) than Kansas BuildEx (39.0g) and *Dalea purpurea* (purple prairie clover) of the all-natives mix had greater above-ground biomass in Kansas BuildEx (310.6g) than Rooflite® Extensive MC (259.3g) (Figure 4.19). *Schizachyrium scoparium* (little bluestem) of both the *Sedum* and native grass mix and the all-natives mix had greater above-ground biomass in Rooflite® Extensive MC than in Kansas BuildEx (Figure 4.19). *Schizachyrium scoparium* above-ground biomass for the *Sedum* and native grass mix was 180.0g for Rooflite® Extensive MC and 70.6g for Kansas BuildEx. *Schizachyrium scoparium* above-ground biomass for the all- natives mix was 260.1g for Rooflite® Extensive MC and 97.3g for Kansas BuildEx.

Table 4.12. Type III Test of Fixed Effects for the 6-Inch Bed Above-Ground Biomass in 2019.

Type 3 Test of Fixed Effects				
Effect	**Num df**	**Den df**	**F Value**	**Pr>F**
Substrate	1	3	28.16	0.0131
Mix	1	3	24.48	0.0158
Substrate*mix	1	3	1.34	0.3311
Species(mix)	6	36	67.98	**<0.0001***
Substrate* Species(mix)	6	36	10.20	**<0.0001***

Note: An asterisk (*) shows a significant effect on plant cover (α=0.05).

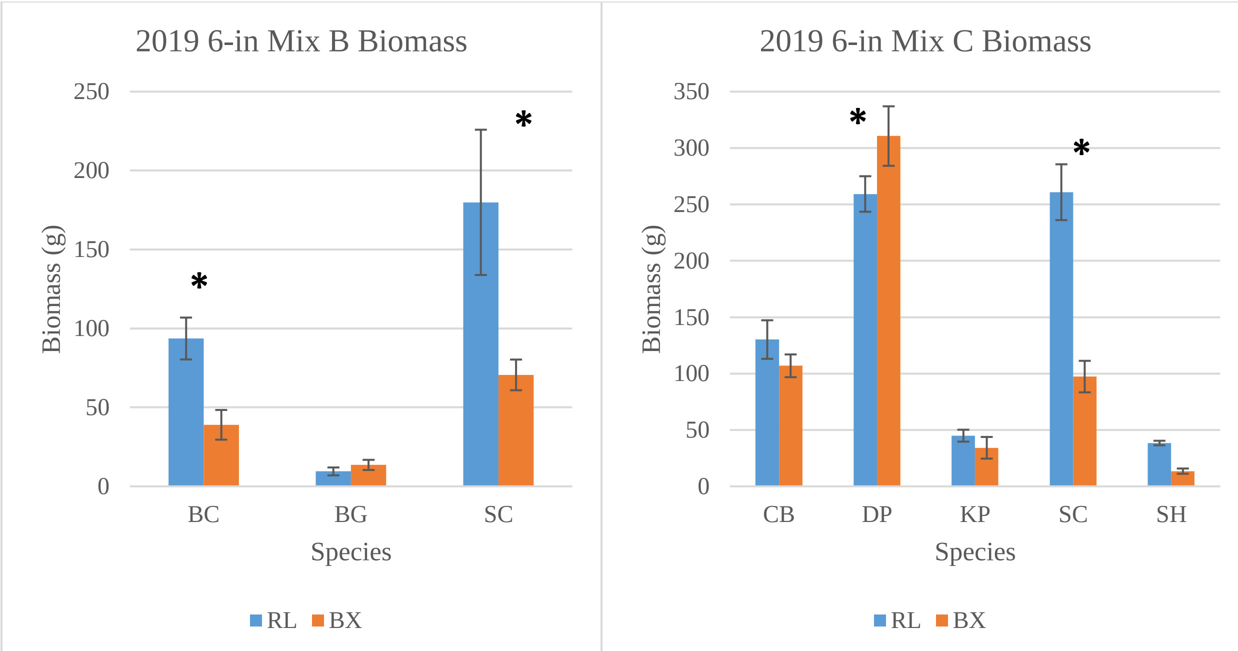


Figure 4.19. End of Season Above-Ground Biomass for Mix B (left) and Mix C (right) in the 6-Inch Bed in 2019. BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC. An asterisk (*) shows a significant difference in above-ground biomass (α=0.05). Plant abbreviations are as follows: *Bouteloua curtipendula* (BC), *Bouteloua dactyloides* (BD), *Bouteloua gracilis* (BG) *Carex brevoir* (CB), *Dalea purpurea* (DP), *Koeleria pyramidata* (KP), *Schizachyrium scoparium* (SC) and *Sporobolus heterolepis* (SH).

For the 8-inch bed the only significant different for above-ground biomass was found in the *Schizachyrium scoparium* (little bluestem) of the *Sedum* and native grass mix, where Rooflite® Extensive MC was greater than Kansas BuildEx (Figure 4.20). Above-ground biomass of *Schizachyrium scoparium* in the *Sedum* and native grass mix was 252.9g for Rooflite® Extensive MC and 141.4g for Kansas BuildEx.

Table 4.13. Type III Test of Fixed Effects for the 8-Inch Bed Above-Around Biomass in 2019.

Type 3 Test of Fixed Effects				
Effect	**Num df**	**Den df**	**F Value**	**Pr>F**
Substrate	1	3	1.53	0.3040
Mix	1	3	8.51	**0.0616**
Substrate*mix	1	3	5.25	0.1059
Species(mix)	6	36	52.98	**<0.0001***
Substrate* Species(mix)	6	36	2.02	0.0885

Note: An asterisk (*) shows a significant effect on plant cover (α=0.05).

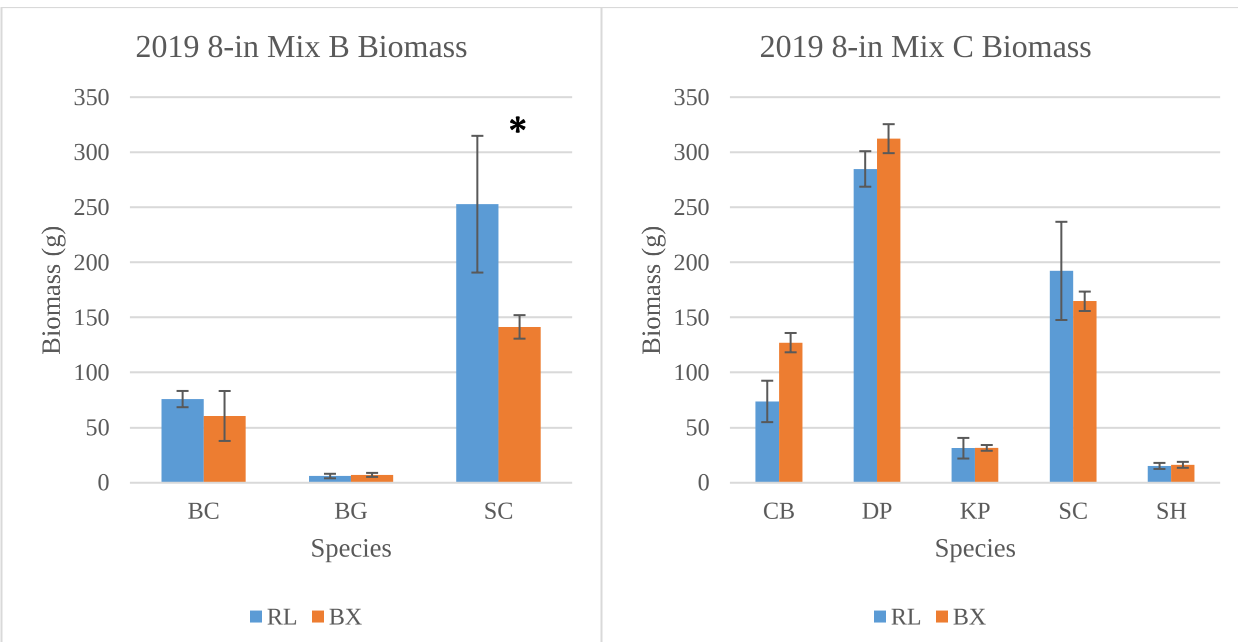


Figure 4.20. End of Season Above-Ground Biomass for Mix B (left) and Mix C (right) in the 8-Inch Bed in 2019. BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC. An asterisk (*) shows a significant difference in above-ground biomass (α=0.05). Plant abbreviations are as follows: *Bouteloua curtipendula* (BC), *Bouteloua dactyloides* (BD), *Bouteloua gracilis* (BG) *Carex brevoir* (CB), *Dalea purpurea* (DP), *Koeleria pyramidata* (KP), *Schizachyrium scoparium* (SC) and *Sporobolus heterolepis* (SH).

Schizachyrium Scoparium Mix Comparisons

Because Schizachyrium Scoparium (little bluestem) was planted in both the Sedum and native grass mix (B) and the all-natives mix (C), biomass comparisons for this grass could be made between the mixes (Figure 4.21). At the end of the 2018 growing season there was evidence for difference in biomass of little bluestem in the Rooflite® Extensive MC cells in the 4-inch bed and the 6-inch bed and in both the substrate types in the 8-inch bed. In the 4-inch bed there was little evidence for a difference between Mix B and Mix C at an α level of 0.05 (p=0.0633), with Mix C having greater biomass than Mix B in the Rooflite® Extensive MC cells by 13.48 grams. For the 6-inch bed there was strong evidence for a difference in little bluestem biomass for Mix B and Mix C in the Rooflite® Extensive MC cells at an α level of 0.05 (p=0.0011), with Mix C having greater little bluestem biomass than Mix B by 47.25 grams. In the 8-inch bed there was strong evidence for a difference between Mix B and Mix C at an α level of 0.05 (p=0.0261 for BuildEx and p=0.0003 for Rooflite® Extensive MC). In the Kansas BuildEx Substrate Mix B had a greater little bluestem biomass than Mix C by 47.98 grams. In the Rooflite® Extensive MC substrate Mix B has a greater little bluestem biomass than Mix C by 83.25 grams.

By the end of the 2019 growing season, there was statistically significant difference in little bluestem above ground biomass between Mix B and Mix C for both substrates in the 4-inch bed (BX p=0.007 and RL p=0.0009) and for Rooflite® Extensive MC for the 6-inch (p=0021) and 8-inch beds (p=0.0573). In the 4-inch bed little bluestem above ground biomass for Mix C was greater than Mix B by 57.8 grams in Kansas BuidEx and by 73.4 grams in Rooflite® Extensive MC. Also, in the 6-inch bed little bluestem above ground biomass for Mix C was greater than Mix B by 80.95 grams in Rooflite® Extensive MC. However, in the 8-inch bed little bluestem above ground biomass for Mix B was greater than Mix C by 60.45 grams in Rooflite® Extensive MC.

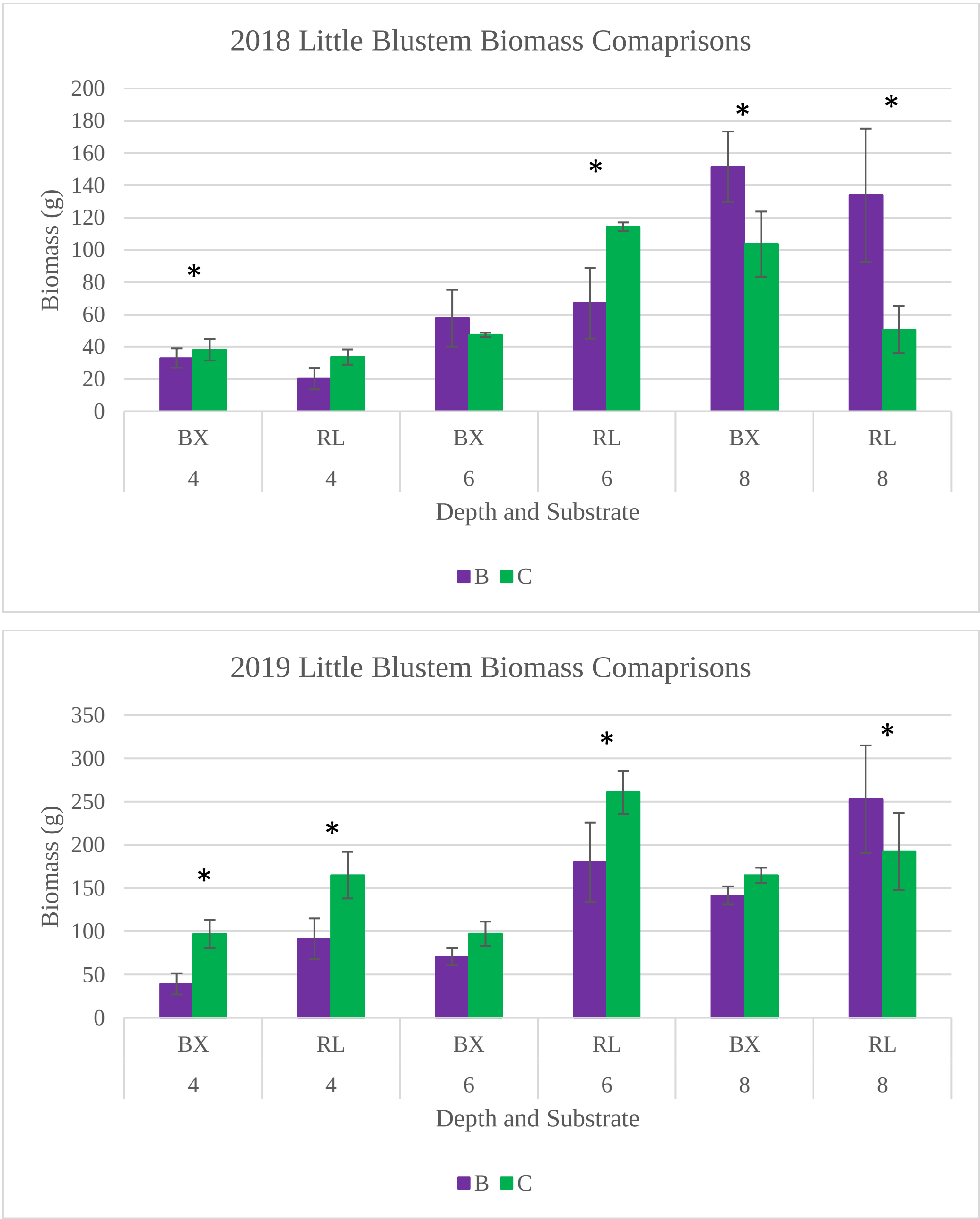


Figure 4.21. *Schizachyrium Scoparium* (Little Bluestem) Above-Ground Biomass Comparisons by Mix for Selected Substrates at Specified Depths for 2018 (top) and 2019 (bottom). BX denotes Kansas BuildEx and RL denotes Rooflite® Extensive MC. An asterisk (*) shows a significant difference in above-ground biomass (α=0.05).

Forb Reproduction

In all green roof beds and depths, *Dalea purpurea* exhibited higher reproduction numbers than *Packera obovata* (Table 4.14). This is due to the hardiness of *Dalea purpurea* (particularly its drought tolerance and adaptability on this exposed, full-sun green roof where air temperatures frequently exceeded 90F or 32.2C from June to August). For all the green roof depths, *Dalea purpurea* had greater reproduction numbers in Kansas BuildEx than in Rooflite® Extensive MC. For the 6-inch and 8-inch depths, *Packera obovata* had higher reproduction numbers in Rooflite® Extensive MC than Kansas BuildEx, while the opposite was observed in the 4-inch bed.

Table 4.14. Forb Reproduction Summary Data for *Dalea Purpurea* (DP) and *Packera Obovata* (PO) in Kansas BuildEx (BX) and Rooflite® Extensive MC (RL) for the 4-, 6-, and 8-Inch Depths on the APD-EGR.

Depth (inches)	**4**		**6**		**8**	
Species Code	**DP**	**PO**	**DP**	**PO**	**DP**	**PO**
RL average	34	1.75	28	2	47.25	1.25
BX average	37.25	3.25	50.75	0.25	68.25	0.25
Total	285	20	315	9	462	6

Discussion

Discussion of the Methods Selected

Due to the size of the experimental cells on the green roof it was decided that using overhead photography would be the best method for measuring above ground vegetative coverage. The plant camera stand created by Richard Thompson in the APDesign Fabrication Lab made it possible to photograph an entire experimental cell. The stand was designed to capture the entire experimental cell when the camera was positioned exactly in the center of each cell. The major challenge of the selected method was making sure the stand was in the right position to photograph the entire cell; all photos had to be checked after taking a photo of each cell, which slowed down the process.

Measuring vegetative coverage was especially difficult on windy days. High winds could cause sizable portions of the native plants to be blown outside of the boundaries of each experimental cell. To combat this issue photos were taken once winds died down. Another challenge of taking overhead photos to measure vegetative cover was that when measuring coverage of a mix does not provide any insight on what specific species are thriving better than others. Some of the selected native plants have grown outside of the bounds of the experimental cells, making above-ground biomass measurements a useful method of assessing plant performance on the APD-EGR. Above-ground biomass measurements were also used as a method of determining what substrate each individual native species performed better in. Additionally, above-ground biomass measurements allowed for performance (growth) comparisons of *Schizachyrium scoparium* in the *Sedum* and native grass mix and the all-natives mix for each substrate. These comparisons provide insight on what type of plant community and substrate a commonly used species such as *Schizachyrium scoparium* performs (or grows) better in.

Discussion of Results

Plant Cover for the Mixes

It was hypothesized that throughout the entire study the all-*Sedum* cells (mix A) would have greater cover than the *Sedum* and native grass cells (mix B) and all-natives cells (mix C) due to the low growing, mat forming nature of *Sedums* and because of their adaptation to survive extreme stress. However, by the end of the 2018 growing season the *Sedum* and native grass mix and the all-natives mix had significantly greater percentages of plant cover than the *Sedums-only* mix in all green roof substrate depths. At the end of the 2019 growing season the all-native cells and *Sedum* and native grass cells maintained significantly greater cover than the *Sedums*-only cells for the 4-inch and 8-inch beds. This suggests that with the employed irrigation protocol native plants can perform just as well or better than *Sedum* species, which is also supported in other green roof studies (Bousselot et al., 2009; Klein and Coffman, 2015; MacIvor and Lundholm, 2011; Schroll et al, 2009).

However, the 6-inch bed exhibited a significant interaction between the main effects of mix and substrate. In Kansas BuildEx, the native cells and the *Sedum* and native grasses cells had greater cover than the *Sedum* cells, with no difference in for cover for native cells and the *Sedum* and native grasses cells. In Rooflite® Extensive MC substrate the *Sedum* and native grass cells had significantly greater cover than all-*Sedum* cells and all-native cells, with no difference between all-*Sedum* cells and all-natives cells. These findings show that in an intermediate green roof depth plant performance in terms of cover depends on what substrate each species mix is planted in.

Despite the misconception that deep roots are a primary factor in plant water uptake for prairie grass species, research suggests otherwise. A grassland prairie study by Nippert and Knapp (2007), reported that when water was readily available most water uptake by prairie grass roots occurring in the 0-10 cm profile, and when water was less available C_3 grasses relied on deeper soil moisture and C_4 grasses still relied on the water near the soil surface. Also, the root distribution for C_4 grasses is greater in the surface soils (approx. 0-20 cm; approx. 0-8 in) (Nippert et al., 2012). This study by Nippert et al. (2012) also discusses that the deep roots of C_4

prairie grasses play a small role in water transport. Most grasses used on the APD-EGR are C_4 grasses (including *Bouteloa curtipendula, Bouteloua dactyloides, Bouteloua gracilis, Schizachyrium scoparium,* and *Sporobolus heterolepis*). *Keoleria pyramidata* and *Carex brevior* are C_3 grasses. The findings by Nippert and Knapp (2007) help explain why prairie grasses perform so well in all depths of the APD-EGR. In some ways, it seems the irrigated APD-EGR has provided a perfect habitat for some of these native grasses. For example, it has been discussed that many of the grasses selected in this study are known to thrive in thin, rocky soils of the nearby natural habitat at Konza Prairie. Also, on the green roof there is not much competition for sunlight with tall grasses.

Plant Cover for Substrates

It was hypothesized that cover would be greater in the Rooflite® Extensive MC cells (than in the Kansas BuildEx cells) due to Rooflite® Extensive MC substrate being a commercially developed and supplied product. In the 4-inch and 8-inch beds, there was a significant effect of substrate on cover for the 2018 growing season, with Kansas BuildEx yielding greater cover for all three plant mixes than Rooflite® Extensive MC (Figures 4.9 and 4.11). By the end of the 2019 growing season, the 8-inch bed was the only bed that exhibited a significant effect of substrate type on plant cover (Figure 4.14). These 2019 findings provide evidence that the effects of substrate composition may be more prevalent in deeper depths. The growing distinction in cover for the substrates as depths get deeper can be due to water availability in each of the substrate depths. The 4-inch bed has a smaller volume of substrate (and it was also observed that substrate depths ranged from 2.5 inches to 4 inches), therefore, the 4-inch depth has a smaller volume of water stored within the profile for plant use. At shallower depths, the limiting factor in green roof systems is often water availability and root space

(Dvorak and Volder, 2010; Nagase and Dunnett, 2010). However, in the deeper profile there is less overall plant water stress allowing for plant performance to be dictated by substrate characteristics. This is because available water is the difference between the profiles water holding capacity and wilting point, and water holding capacity is a function of the soils volume (a greater volume of soil holds a greater volume of water) (Kirkham, 2014).

For the 6-inch bed there was no effect of substrate type on cover for the 2018 growing season. For the 2019 growing season there was a significant interaction between substrate type and mix in the 6-inch bed. Rooflite® Extensive MC yielded significantly greater cover than BuildEx for the all-*Sedum* cells. However, for the *Sedum* and native grass cells and the all-native cells there was no meaningful difference between cover for Kansas BuildEx and Rooflite® Extensive MC. These findings suggest that in the intermediate green roof depths of 6-inches, substrate characteristics may have a greater effect on *Sedum* species performance than on native plant performance. When looking at cover by mix for both substrates, the *Sedum* and native grass and the all-natives mixes had greater cover than the *Sedums*-only mix when planted in Rooflite® Extensive MC; and the *Sedum* and native grass mix had greater cover than the all-natives and *Sedums*-only mixes when planted in Kansas BuildEx. Also, in Chapter 3 it was reported that Rooflite® Extensive MC held the smallest amount of water on a volume basis once drainage ceased (roof capacity). This previous finding can help explain why cover for the all-natives mix is less than the cover for the *Sedum* and native grass mix when planted in Rooflite® Extensive MC, but not when planted in Kansas BuildEx. It seems the *Sedum* and native grass mix is well equipped to handle green roof environmental stressors when planted at a semi-intensive depth of 6-inches.

Figure 4.22. Representative Photos of the Sedum and Native Grass Cells in Kansas BuildEx (left) and Rooflite® Extensive MC (right). Photos show extensive spread of *Bouteloua dactyloides* (Buffalograss) across the soil surface, with greater spread typical in BuildEx cells than in Rooflite® Extensive MC cells.

Above-Ground Biomass

In the 6-inch bed, *Bouteloua curtipendula* (sideoats grama) in the *Sedum* and native grass mix had a greater amount of above-ground biomass in Rooflite® Extensive MC than in Kansas BuildEx for both the 2018 (Figure 4.16) and 2019 (Figure 4.19) growing seasons. *Bouteloua curtipendula* is naturally found on rocky, open slopes and thrives in grassland prairies (USDA). The rocky nature of the Rooflite® Extensive MC substrate can in part explain why *Bouteloua curtipendula* exhibited greater above-ground biomass both years in the Rooflite® Extensive MC substrate. These findings suggest that in intermediate substrate depths soil characteristics must be considered when specifying *Bouteloua curtipendula* for green roof plantings while for extensive and intensive green roof depths the substrate characteristics seem to have less of an effect on *Bouteloua curtipendula* performance. Also, in Chapter 3 it was found that Rooflite® Extensive

MC in the 6-inch bed held the smallest amount of water by volume (roof capacity), this may be a characteristic preferred by *Bouteloua curtipendula.*

The *Dalea purpurea* (purple prairie clover) planted in the all-natives mix had a greater above-ground biomass in Rooflite® Extensive MC than in Kansas BuildEx for both the 4-inch and 6-inch beds in 2018 (Figures 4.15 and 4.16). In 2019, the only difference in above-ground biomass of *Dalea purpurea* for the two substrates was observed in the 6-inch bed with Kansas BuildEx having greater biomass than Rooflite® Extensive MC (Figure 4.19). Overall, *Dalea purpurea* performed very well on the green roof with above-ground biomass ranging from 21.28g to 40.75g for Kansas BuildEx and 33.6g to 56.6g for Rooflite® Extensive MC in 2018 (Figures 4.15, 4.16, and 4.17). In 2019, the above ground biomass ranged from 182.63g to 312.30g in Kansas BuildEx and from 203.9g to 284.83g for Rooflite® Extensive MC (see Figures 4.18, 4.19, and 4.20). In the second year of the study *Dalea purpurea* produced much more biomass than in the first year. *Dalea purpurea* is a warm season legume that naturally thrives in rocky open glades and gravel-hill prairies (USDA). The natural preferences of *Dalea purpurea* can explain why this species has performed so well on the APD-EGR throughout this study.

For the 2018 growing season, the *Schizachyrium scoparium* (little bluestem) planted in the *Sedum* and native grass mix had a greater above-ground biomass (at the 95% confidence level) in Kansas BuildEx than in Rooflite® Extensive MC in the 4-inch bed (Figure 4.15). Additionally, in 2018, the *Schizachyrium scoparium* planted in the all-natives mix had greater above-ground biomass in Kansas BuildEx than in Rooflite® Extensive MC for the 8-inch bed (Figure 4.17). For the 6-inch bed, above-ground biomass was greater in Rooflite® than Kansas BuildEx for the *Schizachyrium scoparium* planted in the all-natives cells (Figure 4.16). By the end of the 2019 growing season the above-ground biomass of *Schizachyrium scoparium* was significantly greater for Rooflite® Extensive MC than Kansas BuildEx in for both the *Sedum* and native grass cells and the all-natives cells of the 4-inch and 6-inch beds (Figures 4.18 and 4.19) and in the *Sedum* and native grass cells of the 8-inch bed (Figure 4.20). These findings suggest that BuildEx provides quick establishment and growth of *Schizachyrium scoparium* in the first year of establishment, but Rooflite® Extensive MC can maintain growth for the second year of establishment.

In the 4-inch bed all species planted had in increase in biomass produced in 2019 compared to 2018. In the 6-inch bed, three species planted in Kansas BuildEx and one species planted in Rooflite® Extensive MC saw a decline in above-ground biomass production. These species were *Bouteloua gracilis* (Mix B in BX and RL), *Koeleria pyramidata* (Mix C in BX) and *Sporobolus heterolepis* (Mix C in BX). In the 8-inch bed, seven species produced less biomass in 2019 than in 2018. These species were *Bouteloua gracilis* (Mix B in BX and RL), *Schizachyrium scoparium* (Mix B in BX), *Koeleria pyramidata* (Mix C in BX and RL), *Sporobolus heterolepis* (Mix C in BX and RL). *Koeleria pyramidata* is a cool season grass and a green roof environment might not be ideal for this species. In Mix B, the decreased production of *Bouteloua gracilis* may be due to increased competition with *Bouteloua dactyloides* (buffalograss). However, we cannot be exactly sure what is causing these declines in production. It will be important to track survival and above-ground biomass of these native species in the years to come to better understand how native species will perform on a green roof in the long-term.

Schizachyrium scoparium was the only species to be planted in both the *Sedum* and native grass mix and the all-natives mix. This similarity allowed for comparisons of plant performance of this species between mixes within one substrate. In the first year of the study, *Schizachyrium scoparium* had a greater above-ground biomass in the all-natives mix than in the *Sedum* and native grasses mix when planted in Rooflite® Extensive MC at 4- and 6-inch depths, however, there was no difference between the mixes for the *Schizachyrium scoparium* planted in Kansas BuildEx (Figure 4.21). Subsequently, the *Sedum* and native grass mix had a greater above-ground biomass for *Schizachyrium scoparium* than the all-natives mix in the 8-inch bed form both substrates and in the 8-inch bed (Figure 4.21). By the of the 2019 growing season *Schizachyrium scoparium* above-ground biomass was greater in the *Sedums* and native grass mix than in the all-natives mix for both substrates in a 4-inch depth and for Rooflite® Extensive MC in 6-inch depth cells (Figure 4.21).

These findings suggest for an extensive green roof and a semi-intensive green roof that *Schizachyrium scoparium* performs better within an all-native mix. Nevertheless, the lower above-ground biomass of *Schizachyrium scoparium* in the *Sedum* and native grass mix may be related to the extensive growth of *Bouteloua dactyloides* leading to more increased competition for nutrients and water. Conversely, the all-natives mix had greater *Schizachyrium scoparium* above-ground biomass than the *Sedum* and native grass mix in Rooflite® Extensive MC at the 8-inch depth (Figure 4.21). These findings suggest that substrate characteristics in combination with species mix play an important role in plant performance for *Schizachyrium scoparium.* Also, there may be less differences in above-ground biomass in the 8-inch bed because deeper depths make for less competition of resources, especially relation to water use (VanWoert et al. 2005).

Forb Reproduction

The number of offspring produced for *Dalea purpurea* only displayed a significant difference for the 6-inch bed, with the Kansas BuildEx substrate yielding a greater number of offspring than Rooflite® Extensive MC (Table 4.14). *Dalea purpurea* produced many offspring in all the substrate depths for both substrate types, ranging from 28 to 47 offspring for Rooflite® and 37 to 68 offspring for Kansas BuildEx (Table 4.14). These findings show that *Dalea purpurea* can thrive very well under a range of green roof depths.

Small numbers of offspring were observed for *Packera obovate* for all the depths. The 8-inch bed was the only depth that displayed a significant difference in the number of offspring, with Rooflite® Extensive MC yielding a greater number than Kansas BuildEx (Table 4.14). *Packera obovata* can survive on the green roof with supplemental irrigation. However, *Packera obovata* may not be a species for a full-sun green roof designed to be regenerative and self-sustaining.

For all three green roof depths (4, 6, and 8 inches), cover in Kansas BuildEx was always greater than or equal to cover in Rooflite® Extensive MC for 2018 and 2019, except for the 6-inch bed in 2019 having cover in Rooflite® Extensive MC substrate greater than Kansas BuildEx in the *Sedums*-only mix. However, above ground biomass was greater for several species planted in Rooflite® Extensive MC substrate than when planted in Kansas BuildEx. This difference in results may be due to seemingly greater cover in Kansas BuildEx for some of the species that were included in above-ground biomass sampling.

Personal Observations

In the *Sedum* and native grass mix it was observed that many of the *Sedums* planted in this mix died or diminished throughout all the depths. This poor performance may have been caused by the fast growth and spread of *Bouteloua dactyloides* (buffalo grass), which had created a low growing mat that covered most of the cells planted with the *Sedums* and natives mix.

It was observed that *Bouteloua dactyloides* had a greater spread in the Kansas BuildEx substrate in all substrates. This aggressive spread may have contributed to the death of many of the *S. reflexum* species planted in the *Sedum* and native grass mix, especially in the Kansas BuildEx substrate (Liu et al. 2019). These observations suggest it would be best to avoid specifying *Bouteloua dactyloides* with *S. reflexum* and similar *Sedum* species to be planted together in green roof plant mixes. Of note, the Kansas BuildEx substrate has a higher sand content and less pore space and larger particles that the *Bouteloua dactyloides* seem to prefer.

Seasonal Variability

The 2018 growing season was hotter and dryer than the 2019 growing season. Much less irrigation was required during 2019 due to a greater amount of precipitation than the previous year (Table 4.15). Because the APD-EGR is fully exposed to the surrounding environment, variability in weather trends between the two years can have a significant impact on survival and growth of the selected plant species. The *Sedum* species used in this study are known to favor well drained substrate conditions allowing the roots to completely dry (MBG, 2020). The 2019 growing season experienced more periods of prolonged soil moisture, which could have had a negative effect on *Sedum* growth on the APD-EGR. Hopman (2014) and Klein and Coffman (2015) found that *Sedum* species did not perform well under irrigated conditions (irrigated two to three times a week). There are many variables to consider.

Table 4.15. Total Precipitation and Irrigation by Month for 2018 and 2019.

	2018				2019			
	Precipitation		Irrigation		Precipitation		Irrigation	
Month	in	mm	in	mm	in	mm	in	mm
April	1.52	38.61	0	0	2.74	69.60	0	0
May	3.78	96.01	0	0	10.56	268.22	0	0
June	2.57	65.28	2.03	51.56	6.17	156.72	0.53	14.46
July	2.43	61.72	5.50	139.70	5.54	140.72	1.52	38.61
August	8.41	213.61	2.76	70.14	9.91	251.71	0	0
Total	**18.71**	**475.23**	**10.29**	**261.4**	**34.92**	**886.97**	**2.05**	**53.07**

As a visual comparison of what the APD-EGR looked like in early to mid-August of 2018 and 2019 and how the Experimental Green Roof looks like in early August 2021 see Figures 4.23, 4.24, and 4.25. In 2021 the research team intentionally introduced added stress to the APD-EGR by only irrigating after APD-EGR vegetation showed signs of stress and soil moisture readings were quite low. Thus, brownout of many native species (both native grasses and forbs) and poorer performance for many of the Sedums occurred on all three planting areas (Lee R. Skabelund, pers. comm., Aug 2021). Vegetative stress is clearly visible in Figure 4.25, although some areas of vegetation are much more stressed than others. Many different factors and variables are likely contributing.

Figure 4.23. APD-EGR in August 2018. Photo by Lee Skabelund on August 10, 2018.

Figure 4.24. APD-EGR in August 2019. Photo by Lee Skabelund on August 6, 2019.

Figure 4.25. APD-EGR in August 2021. Photo by Lee Skabelund on August 6, 2021.

One must also recognize that the APD-EGR is part of a larger set of dynamic systems, climatic, bio-physical, and management related. For instance, the sand placed beneath the pavers along the west side of the APD-EGR retains water along the west edge of the three APD-EGR beds, as evidenced by the abundance of plants growing on each side of the aluminum edging. Reflected sunlight, variable substrate depths within one cell and also cell-to-cell, slight changes in the amount of water available to cells or individual plants due to un-identified but certain sub-surface variations and differences in the amount of water applied to a particular part of a cell (inherent in any irrigation system, including hand-watering), and competition between the 18 planted APD-EGR plants (some of which have died or are being overtaken by other plants) and those plants coming up in abundance from seed—now create an even more dynamic ecosystem, with some plants and species benefiting from structural (designed and implemented) conditions and an ever-changing system of flows and fluxes on the APD-EGR.

Adjacent 4–5-inch APD green roofs (one of which is partially visible in Figure 4.26) were designed and created using only Rooflite® Extensive MC substrate and many similar plant species as the APD-EGR. These green roofs have not received any supplemental irrigation in 2020 and 2021, but despite this, they seem to be performing better in terms of plant health (except in a few places where plants have died out, perhaps due to the intensity of solar radiation reflected off specific parts of the building or its built components) than portions of the infrequently irrigated APD-EGR during the 2021 growing season (Lee R. Skabelund, pers. comm., Aug 2021). Why is this happening? A very close examination of many variables would be required to adequately answer this important question.

Figure 4.26. APD-EGR in August 2021. Photo by Lee Skabelund on August 12, 2021.

Conclusions and Practical Applications

This study shows that native planting palettes can perform exceptionally well in extensive, semi-intensive and intensive green roof systems with supplemental irrigation. It is especially important to note that cover of the native species mixes was still above 50% in the 4-inch bed, above 60% in the 6-inch bed, and above 75% in the 8-inch bed by the end of the second growing season. For the *Sedums*-only mix cover values were above approximately 30% in the 4-inch, 40% in the 6-inch, and 65% in the 8-inch bed. Cover remained higher in the all-natives mix than in the all-*Sedums* mix, further showing that native graminoids and forbs are great contenders for green roof plantings in the Flint Hills Ecoregion and areas with similar climates. Also, these findings show that locally blended substrates can yield high cover and above-ground biomass for native and *Sedum* green roof species. These findings also indicate that selected native species are still great candidates for extensive green roof plantings in full-sun settings with early evening shade in the summer months.

This study emphasizes the importance of understanding the relationship between substrate type and depth and plant performance. The results of Chapter 2 indicated there are differences in substrate chemical and physical properties between Kansas BuildEx and Rooflite® Extensive MC substrate with the potential to affect how water is stored and dispensed and the long-term and plant performance and Chapter 3 provided evidence for differences in how the two substrates store water and the energy status of the substrate water.

Limitations and Future Considerations

All species that were installed had been selected in 2015 by Lee R. Skabelund, except for the two Sedum species grown and provided by Blueville Nursery as replacements for the specified plants in the Sedum and native grass mix. Precisely how each species would do on the three full-sun APD-EGR planting areas or beds was uncertain, although they were thought to have a good chance of surviving and growing well with supplemental irrigation during establishment. Rigorous implementation oversight was not granted to the APD-EGR research team and thus not all desired design parameters were met. This was viewed by the research team as implementation variability common to many landscape architecture projects. Not having a perfectly implemented design (with all 72 green roof cells the same size, the two substrates precisely the same depth, and the 18 plants per cell grown and installed for optimum survival and health and spaced the same distance from one another within each cell) is a limitation that must simply be accepted; uncertainties related to feature variability are a given of nearly every constructed landscape and they are part of the APD-EGR.

Another major limitation of this study is that this was an irrigated study. Considering that not all green roof managers want to irrigate, it would be beneficial to continue monitoring plant cover and above-ground biomass under a little to no irrigation regime. Members of the APD-EGR research team have observed brownout of many native species (both grasses and forbs) as well as poorer performance for many of the Sedums during a somewhat dry 2021 growing season where supplemental irrigation has been applied to the APD-EGR in a much more limited way (Lee R. Skabelund, pers. comm., Aug 2021).

It is also important to note that plant cover was only recorded at the mix level, not the species level. The methods for analyzing plant cover only allowed for measuring cover at the mix level. Some of the species may have had greater growth in terms of cover throughout this two-year study and knowledge of species cover throughout the year could help guide species selection for future green roof designs in the Flint Hills Ecoregion or in regions with a similar climate. An assessment of individual species coverage could be completed, but the time required to do this may not be worth the time. These are the types of decisions any research team must make. What do we have the time and resources to evaluate, and how essential is the activity related to the larger research goals and the specific study objectives?

Finally, overhead photography can be a very time-consuming tool for measuring individual plant cover, but it can be a great method for measuring individual plant cover on smaller studies. Use of aerial photography using a sUAS (a small unmanned aerial system or drone with a mounted camera) is a possibility if technical expertise is available and permission to fly a sUAS is given for a project.

References

Ampim, P.A.Y., Sloan, J.J., Cabrera, R.I., Harp, D.A., Jaber, F.H., 2010. "Green roof growing substrates: types, ingredients, composition and properties." Journal of Environmental Horticulture. 28 (4), 244–252. https://www.hrijournal.org/doi/pdf/10.24266/0738-2898-28.4.244.

ASTM International. 2019. ASTM E2399/E2399M-19, Standard Test Method for Maximum Media Density for Dead Load Analysis of Vegetative (Green) Roof Systems. (West Conshohocken, PA, US). https://doi.org/10.1520/E2399_E2399M-19

Blanusa, Tijana, M. Madalena Vaz Monteiro, Federica Fantozzi, Eleni Vysini, Yu Li, and Ross W. F. Cameron. 2013. "Alternatives to Sedum on Green Roofs: Can Broad Leaf Perennial Plants Offer Better 'Cooling Service'?" Building and Environment 59: 99–107. https://doi.org/10.1016/j.buildenv.2012.08.011

Bousselot, J., V. Russel, L. Tolderlund, S. Celik, B. Retzlaff, S. Morgan, I. Buffam, R. Coffman, J. Williams, M. E. Mitchell, J. Backer, J. DeSpain. 2020. "Green Roof Research in North America: A Recent History and Future Strategies." Journal of Living Architecture. 7: 27-64.

Butler C, Butler E, Orians CM. 2012. "Native plant enthusiasm reaches new heights: perceptions, evidence, and the future of green roofs." Urban Forest Urban Greening 11: 110.

Butler, C.; Orians, C.M. 2011. "Sedum cools soil and can improve neighboring plant performance during water deficit on a green roof." Ecological Engineering. 37, 1796–1803.

Calkins, M. 2012. The Sustainable Sites Handbook: A Complete Guide to the Principles, Strategies, and Best Practices for Sustainable Landscapes. NY: John Wiley & Sons, Inc.

Cook-Patton, S.C. 2015. "Chapter 8 - Plant biodiversity on green roofs." In Green Roof Ecosystems (Ed. by R. Sutton). London: Springer Science. 193-210.

Cook-Patton, S. C., and T.L. Bauerle. 2012. "Potential Benefits of Plant Diversity on Vegetated Roofs: A Literature Review." Journal of Environmental Management 106 (September): 85–92. https://doi.org/10.1016/j.jenvman.2012.04.003

Dunnett, Nigel, Ayako Nagase, and Adrian Hallam. 2008a. "The Dynamics of Planted and Colonising Species on a Green Roof over Six Growing Seasons 2001–2006: Influence of Substrate Depth." Urban Ecosystems 11 (4): 373–84. https://doi.org/10.1007/s11252-007-0042-7.

Dunnett, N., A. Nagase, R. Booth and P. Grime. 2008b. "Influence of vegetation composition on runoff in two simulated green roof experiments." Urban Ecosystems 11:385-398.

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: 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.

Emilsson, Tobias. 2008. "Vegetation Development on Extensive Vegetated Green Roofs: Influence of Substrate Composition, Establishment Method and Species Mix." Ecological Engineering 33(3–4): 265–77. https://doi.org/10.1016/j.ecoleng.2008.05.005

Gabrych, M., D.J. Kotze, and S. Lehvävirta. 2016. "Substrate depth and roof age strongly affect plant abundances on sedum-moss and meadow green roofs in Helenski, Finland." Ecological Engineering 86: 95-104.

Getter K.L., and D.B. Rowe. 2007. "Effect of substrate depth and planting season on Sedum plug survival on green roofs." Journal of Environmental Horticulture 25:95-99.

Getter, K.L., Rowe, D.B., 2008. "Media depth influences Sedum green roof establishment." Urban Ecosystems. 11: 361–372. https://doi.org/10.1007/s11252-008-0052-0

Graceson, A., J. Monaghan, N. Hall, and M. Hare. 2014. "Plant Growth Responses to Different Growing Media for Green Roofs." Ecological Engineering 69: 196–201. https://doi.org/10.1016/j.ecoleng.2014.03.067

Heim, A., and J.T. Lundholm. 2014. "Species Interactions in Green Roof Vegetation Suggest Complementary Planting Mixtures." Landscape and Urban Planning 130: 125–33. https://doi.org/10.1016/j.landurbplan.2014.07.007.

Hopman, D., 2014. "The University of Texas at Arlington Extensive Green Roof." The University of Texas at Arlington School of Architecture. Http://www.uta.edu/sustainability/_downloads/Green%20Roof%20Report.pdf

Kirkham, M.B. 2014. Principles of Soil and Plant Water Relations. 2nd Edition. San Diego, CA. Elsevier Science.

Klein, P.M., and R. Coffman. 2015. "Establishment and Performance of an Experimental Green Roof under Extreme Climatic Conditions." Science of The Total Environment 512–513 (April): 82–93. https://doi.org/10.1016/j.scitotenv.2015.01.020

Köhler M. 2006. "Long-term vegetation research on two extensive green roofs in Berlin." Urban Habitats. 4: 326.

Kolb, W. and T. Schwarz. 1986. "New habitats on the roof: the possibilities for the provision of extensive verdure." Anthos 1: 410.

Liu, J., P. Shrestha, L.R. Skabelund, T. Todd, A. Decker, M.B. Kirkham. 2019. "Growth of prairie plants and sedums in different substrates on an experimental green roof in Mid-

Continental USA." Science of the Total Environment. 697(134089):1-11. https://doi:10.1016/j.scitotenv.2019.134089

Lundholm, J. T. 2015. "Green Roof Plant Species Diversity Improves Ecosystem Multifunctionality." Journal of Applied Ecology 52 (3): 726–35. https://doi.org/10.1111/1365-2664.12425

Lundholm, J. and P. Richardson. 2010. "Habitat analogues for reconciliation ecology in urban and industrial environments." Journal of Applied Ecology. 47: 966–975.

Lundholm J, J.S. MacIvor, Z. MacDougall, and M. Ranalli. 2010. "Plant species and functional group combinations affect green roof ecosystem functions." PLOS One. 5(3): 1-11.

Lundholm, J.T., and N.S. Williams. 2015. "Chapter 9 - Effects of vegetation on green roof ecosystem services." In Green Roof Ecosystems (Ed. by R. Sutton). London: Springer Science. 211-232.

MacIvor, J. and J. Lundholm. 2011. "Performance evaluation of native plants suited to extensive green roof conditions in a maritime climate." Ecological Engineering. 37(3): 407-417. DOI:10.1016/j.ecoleng.2010.10.004

MacIvor, J. Scott, Liat Margolis, Curtis L. Puncher, and Benjamin J. Carver Matthews. 2013. "Decoupling Factors Affecting Plant Diversity and Cover on Extensive Green Roofs." Journal of Environmental Management 130 (November): 297–305. https://doi.org/10.1016/j.jenvman.2013.09.014

McCoy, E., M. Braco, and L. Mandel. 2018. A landscape performance + metrics primer for landscape architects: Measuring landscape performance on the ground. LATIS, Landscape Architecture Technical Information Series; American Society of Landscape Architects: Washington, DC, USA.

Millennium Ecosystem Assessment (MEA). 2005. Ecosystems and Human Well-Being, Biodiversity Synthesis. World Resources Institute, Washington, D.C.

Missouri Botanical Garden (MBG). "Plant Finder." Accessed March 2020. http://www.missouribotanicalgarden.org/plantfinder/plantfindersearch.aspx

Metselaar, K. 2012. "Water Retention and Evapotranspiration of Green Roofs and Possible Natural Vegetation Types." Resources, Conservation and Recycling 64 (July): 49–55. https://doi.org/10.1016/j.resconrec.2011.12.009

Monterusso M.A., D.B. Rowe, and C.L. Rugh. 2005. "Establishment and persistence of Sedum spp. and native taxa for green roof applications." Hortscience. 40:391-396.

Nagase, A., and N. Dunnett. 2010. "Drought Tolerance in Different Vegetation Types for Extensive Green Roofs: Effects of Watering and Diversity." Landscape and Urban Planning 97 (4): 318–27. https://doi.org/10.1016/j.landurbplan.2010.07.005

Nagase, A. and N. Dunnett. 2010. "Drought tolerance in different vegetation types for extensive green roofs: Effects of watering and diversity." Landscape Urban Planning 97: 318–327.

Nagase, A., and N. Dunnett. 2011 "The Relationship between Percentage of Organic Matter in Substrate and Plant Growth in Extensive Green Roofs." Landscape and Urban Planning 103 (2): 230–36. https://doi.org/10.1016/j.landurbplan.2011.07.012

Nagase, A. and N. Dunnett. 2012. "Amount of Water Runoff from Different Vegetation Types on Extensive Green Roofs: Effects of Plant Species, Diversity and Plant Structure." Landscape and Urban Planning 104 (3–4): 356–64. https://doi.org/10.1016/j.landurbplan.2011.11.001

Nagase, A. and N. Dunnett. 2013. "Establishment of an annual meadow on extensive green roofs in the UK." Landscape Urban Planning 112: 50-62.

Nektarios, P.A., I. Amountzias, I. Kokkinou, and N. Ntoulas. 2011. "Green roof substrate type and depth affect the growth of the native species Dianthus fruticosus under reduced irrigation regimens." HortScience 46: 1208–1216.

Nippert, Jesse B., and Alan K. Knapp. 2007. "Linking Water Uptake with Rooting Patterns in Grassland Species." Oecologia 153 (2): 261–72.

Nippert, J.B., R.A. Wieme, T.W. Ocheltree, and J.M. Craine. 2012. "Root characteristics of C-4 grasses limit reliance on deep soil water in tallgrass prairie." Plant and Soil. 355: 385 - 394. https://doi.org/10.1007/s11104-011-1112-4

Rasband, W.J., 2018. ImageJ, U.S., 1997–2018. National Institutes of Health, Bethesda, Maryland, USA https://imagej.nih.gov/ij

Rowe, DB. 2017. "Green roofs: plant production and installation methods." In Proceedings of the 2017 Annual Meeting of the International Plant Propagators' Society. 97-100.

Schroll E, J. Lambrinos, and D. Sandrock. 2009. "Irrigation requirements and plant survival on northwest green roofs." Atlanta, GA: The Cardinal Group; Seventh Annual Greening Rooftops for Sustainable Communities Conference, Awards and Trade Show. Toronto.

Silvola, J. 1985. "Photosynthesis measurements on a CAM plant, Sedum telephium (Crassulaceae)." Annales Botanici Fennici 22(3): 195-200.

Skabelund, L.R., C. Blocksome, D. Brokesh, J.H. Kim, M. Knapp, and M. Hamehkasi. 2014. "Semi-arid green roof research 2009–2014: resilience of native species." Paper Presented at the 12th Annual Green Roof & Wall Conference, Nashville, TN.

Skabelund, L., A. Decker, T. Moore, P. Shrestha, and J. L. Bruce. 2017. "Monitoring two large-scale prairie-like green roofs in Manhattan, Kansas." Cities Alive 15th Annual Green Roof and Wall Conference Proceedings. 30 pp. Paper presented at Cities Alive 15th Annual Green Roof and Wall Conference.

Snodgrass, E.C., and L.L. Snodgrass. 2006. Green Roof Plants: A Resource and Planting Guide. Timber Press.

Sutton, R.K., J.A. Harrington, L.R. Skabelund, P. MacDonagh, R.R. Coffman, and G. Koch. 2012. “Prairie-Based Green Roofs: Literature, Templates, and Analogs.” Journal of Green Building 7 (1): 143–72. https://doi.org/10.3992/jgb.7.1.143

Sutton, Richard. 2008 “Media Modifications for Native Plant Assemblages on Extensive Green Roofs.” Conference Proceedings, 13.

USDA NRCS National Plant Materials Center, 2020. “Plant guide and fact sheet (Bouteloua curtipendula, Bouteloua dactyloides, Bouteloua gracilis, Schizachyrium scoparium).” Plants Database https://plants.sc.egov.usda.gov/java/ , Accessed date: May 2020

VanWoert, N. D., D. B. Rowe, J. A. Andresen, C. L. Rugh and L. Xiao. 2005. "Watering regime and green roof substrate design affect Sedum plant growth." HortScience 40: 659-664.

Verheyen, K., H. Bulteel, C. Palmborg, B. Olivié, I. Nijs, D. Raes and B. Muys. 2008. “Can Complementarity in Water Use Help to Explain Diversity-Productivity Relationships in Experimental Grassland Plots?” Oecologia 156: 351-361.

Vijayaraghavan, K. 2016. “Green Roofs: A Critical Review on the Role of Components, Benefits, Limitations and Trends.” Renewable and Sustainable Energy Reviews 57: 740–53. https://doi.org/10.1016/j.rser.2015.12.119

Weatherbase. 2021. “Manhattan, Kansas.” https://www.weatherbase.com/weather/weather-summary.php3?s=55427&cityname=Manhattan%2C+Kansas%2C+United+States+of+America&units=

Wolf, D., and J.T. Lundholm. 2008. “Water uptake in green roof microcosms: effects of plant species and water availability.” Ecological Engineering 33:179-186.

Zhang, Zheng, Christopher Szota, Tim D. Fletcher, Nicholas S.G. Williams, Joerg Werdin, and Claire Farrell. 2018. “Influence of Plant Composition and Water Use Strategies on Green Roof Stormwater Retention.” Science of The Total Environment 625 (June): 775–81. https://doi.org/10.1016/j.scitotenv.2017.12.231.

Chapter 5 - Conclusions

Green roofs are increasingly common as cities seek environmentally sustainable approaches to mitigate climate change impacts while providing urban amenities. Previous green roof biodiversity studies have investigated the use of natives for green roof plantings (Bousselot et al. 2010; Butler et al. 2012; Ksiazek et al. 2014; Lundholm et al. 2010; Decker et al. 2015). However, more research is needed on the relationship between diverse green roof plantings and green roof components such as substrate type (Bousselot et al., 2020). To help address this knowledge gap, the primary goal of this dissertation was to understand the relationships between substrate type and depth, and mixed-species performance on our three-bed, 72-plot experimental green roof system on the Kansas State University (KSU) campus. This research provides evidence for suggestions on what might happen on similarly planted green roofs having 4-inch, 6-inch, and/or 8-inch substrates of similar composition in a similar climate regime.

Substrate-plant-water relationships within green roof ecosystems are not deeply understood and continuing to investigate the effect of plant mix and substrate combinations will help bridge this knowledge gap. This research has begun the process of understanding the relationships between green roof substrate type and substrate-water characteristics (roof capacity and matric potential), along with observing how different green roof species mixes perform within the different substrate types.

The plant and substrate materials for this study were carefully selected prior to the framing of the specific questions addressed in this dissertation. The intent of designer and researcher Lee R. Skabelund was to be sure that regional materials were being used to create a green roof ecosystem well suited to the characteristics of the Flint Hills Ecoregion. Two substrates were selected for this study by Skabelund, one being regionally supplied and commercially available (the Rooflite® Extensive MC substrate), and the second a locally blended product (called Kansas BuildEx by the KSU Green Roofs research team and blended at the nearby Blueville Nursery). Plant materials were provided by plant nurseries in the region (Taylor Creek Restoration Nurseries, a part of Applied Ecological Services, Inc. in Baldwin City, Kansas and Blueville Nursery, Inc. in Manhattan, Kansas, USA).

Substrate chemical and physical properties can greatly influence plant health and plant growth, and thus the structural, chemical, and water-related characteristics of each substrate were investigated. Differences between the two substrates used for this study were evaluated. There were significant differences between Kansas BuildEx and Rooflite® Extensive MC substrates for several physical properties (dry density, saturated density, maximum water retention, total pore space and water permeability). There were also significant differences between Kansas BuildEx and Rooflite® Extensive MC substrates for several chemical properties (Total C, Cu, Zn, Mn, and Fe). These results indicate that there are differences in substrate chemical and physical properties between Kansas BuildEx and Rooflite® Extensive MC substrates and have the potential to affect how water is stored and dispensed and the long-term and plant performance.

Assessments on how water is stored and dispensed within Kansas BuildEx and Rooflite® Extensive MC substrate at the three green roof depths of 4, 6, and 8 inches were made. There were significant differences in how the two substrates stored water at the three depth profiles. Kansas BuildEx held a greater amount of water by volume than Rooflite® Extensive MC substrate in all three depths. Increasing substrate profile depth does not necessarily increase roof capacity by the same factor. Green roof designers and researchers will have to make decisions about whether increasing the substrate depth as an attempt to increase water availability to the plants is worth increasing the structural load to a building since this will only provide a small amount of plant available water.

There did not seem to be a meaningful difference in how water was dispensed between Kansas BuildEx and Rooflite® Extensive MC substrates. At the 4-inch depth, the Rooflite® Extensive MC substrate had a greater water recession rate than Kansas BuildEx for the 1-hour period following peak soil moisture levels that were due to precipitation events greater than one inch. When sensor configuration allowed for comparisons between two of the selected mixes and the two substrates, it was found that in the 8-inch bed the all-Sedums mix dried out faster than the all-natives mix for the 1-hour period following peak soil moisture following a precipitation event.

In terms of roof capacity, soil moisture recession, and soil moisture characteristics a locally blended green roof substrate such as Kansas BuildEx is a promising choice for green roof designs. As a regionally mixed commercial substrate, Rooflite® Extensive MC substrate also has promise in support most of the selected native plants and Sedums.

The relationship between substrate type and plant performance (in terms of vegetative cover and above-ground biomass) for the three green roof depths of 4, 6, and 8 inches were assessed. Plant coverage was greater than 65% in the 8-inch bed for the three mixes at end of 2019—Sedums-only (Mix A) averaging 65%, and Sedums and native grasses and all-natives (Mixes B and C) averaging 85%, with greater vegetative cover in the sandy BuildEx when compared to the Rooflite® Extensive MC in the 8-inch cells. By the end of 2019 6-inch bed plant cover ranged from 40% to 85%—with the lowest for the Sedums-only (Mix A), then for the all-natives (Mix C), and then for the *Sedums* and native grasses (Mix B). For the 4-inch depth there were no differences between the substrates by 2019, however, plant cover ranged from

30% to 60%, with *Sedums*-only (Mix A) being the lowest and all-natives (Mix C) and *Sedums* and native grasses (Mix B) having the greatest percent cover. Also, by the end of 2019, there was not much difference in above-ground biomass between the substrate types—only for a few species planted in certain substrate depths (*Bouteloua curtipendula* – Mix B at 6 inches, *Dalea purpurea* – Mix C at 6 inches, *and Schizachyrium scoparium* – Mix B at 4, 6, and 8 inches and Mix C at 4 and 6 inches).

This study shows that native planting palettes can perform exceptionally well in extensive, semi-intensive and intensive green roof systems with supplemental irrigation. Native graminoids and forbs are great contenders for green roof plantings in the Flint Hills Ecoregion and areas with similar climates. Also, study findings show that locally blended substrates can yield high cover and above-ground biomass for native and *Sedum* green roof species at and 8 inch depth. Additionally, the lack of a significant difference in above-ground biomass between Kansas BuildEx and Rooflite® Extensive MC substrate shows that locally blended substrates can perform as well as a commercially provided substrate in terms of producing above-ground biomass on green roofs for the following native grasses and forb species at certain substrate depths (*Bouteloua curtipendula* – 4 and 8 inches, *Bouteloua gracilis* – 4, 6, and 8 inches, *Carex brevoir* – 4, 6, and 8 inches, *Dalea purpurea* – 4 and 8 inches, *Koeleria pyramidata* – 4, 6, and 8 inches, *Schizachyrium scoparium* – Mix C only at 8 inches, and *Sporobolus heterolepis* – 4, 6, and 8 inches). These findings show that selected native species are great candidates for extensive green roof plantings in full-sun settings with early evening shade in the summer months. Furthermore, green roofs having these two substrate types seem to be an excellent habitat for buffalograss. This drought-tolerant grass thrives in rocky soils and on the green roof there may be minimal competition with taller grasses for sunlight. On the other hand, given how poorly many *Packera obavata* plants fared in 2018 and 2019, this species is risky and perhaps unwise on full-sun green roofs in the Flint Hills Ecoregion and other locations with similar climates.

It is important to note that the plant-spacing used on the APD-EGR was meant to allow researchers to easily track each species type over time and was not necessarily the optimum spacing for rapid coverage of the two substrates. Also, to assist in tracking plant cover changes of the six planted species in each mix (18 live plants within each cell), extensive weeding of the APD-EGR was done. The weeding protocol employed for this study was very time consuming and not ideal in terms of supporting vegetative surface coverage by non-invasive pioneering plants.

Some of the species weeded and removed from the cells during the study period exhibit beneficial traits of green roof species. For example, prostrate spurge (*Euphorbia maculata*) is a common species weeded from the APD-EGR. Prostrate spurge is a rapid and low-growing plant that can be found in dry, sandy and/or nutrient-poor soils. Prostrate spurge forms a dense mat and provides shade to the soil surface (Patton and Beck, 2021). Because of these growing characteristics prostrate spurge can be used as a pioneer species for green roof ecosystems. Although *Euphorbia maculata* may be viewed by some as “unsightly” this species can help provide valuable cover and nutrients. Future studies could compare plots or cells where prostrate spurge is allowed to grow to those where this plant is removed.

The results of this dissertation show there are important relationships occurring between substrate type and depth, and mixed-species performance on green roof systems. Substrate composition (Chapter 2), and substrate water characteristics (Chapter 3), provide insight on how the selected species mixes vary in terms of cover and above-ground biomass when planted in a locally blended substrate versus a commercially provided and regionally mixed substrate (as noted in Chapter 4), and these findings can be used to aid future green roof design, implementation, and management practices.

The design intent of the APD-EGR was to use regional substrates and test 8-10 native plants to help limit the carbon footprint of this green roof study, and this purpose was largely met during APD-EGR construction. From this two-year (2018-2019) study, it is shown that well-designed and irrigated green roofs can produce lush and thriving green roof ecosystems during their establishment period. What happens when minimal or no water is provided is yet to be determined, but 2021 observations by the research team indicate that severe stress can occur when insufficient water is available to the species growing on the APD-EGR (Lee Skabelund, KSU-LARCP, pers. comm., Aug 2021).

This research investigated how water is stored and dispensed in two different regionally available substrates and how these two substrates support plant growth. I conclude that a locally blended substrate can support the selected species mixes as well as (and sometimes better) than a commercially supplied and regionally available substrate. The results of this study show that by carefully selecting native species a green roof can yield higher cover than *Sedum*-only species when planted in a natives-only mix or when the native grasses and forbs are planted in combination with hardy, competitive *Sedum* species. Nevertheless, because of the short duration of this study and the need to assess different levels of supplemental irrigation the findings do not provide a long-term picture about the future of these plant mixes in relation to the two substrate types and three substrate depths.

APD-EGR Research Limitations

Two main limitations of this study are the time frame (the research team had hoped to begin the study during the summer of 2017) and irrigation protocol (ample supplemental water and/or precipitation in 2018 and 2109 did not provide a stress-test for the plants used on the APD-EGR). Due to the delay in construction and planting errors this was a two-season study instead of a three-season study and there is a need for longer-term green roof research in North America (Sutton and Lambrinos, 2015; Bousselot et al., 2020). As such, this research can only provide a foundation for longer-term investigations regarding substrate-plant-water relations of green roofs in the Flint Hills Ecoregion.

Importantly, the APD-EGR was irrigated on an as-need basis throughout this study. Not all green roof managers will want to irrigate. Limiting the irrigation regime in the future will allow APD-EGR researchers to better understand the relationships between substrate type and species mix under conditions that may be more practical in terms of operations and management. It is important to note that limits on providing supplemental irrigation at the APD-EGR are already underway, revealing that many of the species experience great stress and even dieback with much more limited supplies of water during extended hot, dry periods (Lee Skabelund, KSU-LARCP, pers. comm., Aug 2021).

In terms of data collection and analysis methods, there were limitations associated with sensors used and vegetative cover measurements. Deriving substrate specific calibration curves was very difficult, resulting in the use of the METER factory setting for soil moisture recordings. Plant cover was recorded on the mix level and the individual species in each mix may have cover that changes substantially over time. Using methods for measuring cover outlined in Shrestha (2019) and Liu et al. (2019) may be a good approach for understanding how total cover and individual species cover change throughout time for each mix. Use of imagery taken from a sUAS is another possibility for measuring total vegetative cover. Additionally, studying how cover changes throughout the year and over much longer periods of time for specific species should help guide species selection for future green roof designs in the Flint Hills Ecoregion or in regions with a similar climate.

APD-EGR Planting Challenges

There were several challenges using live plant plugs versus seeding the green roof. Not having to wait for seeds to germinate is a benefit of using live plant plugs, and plugs can provide larger plants at the outset, with more extensive root systems providing the green roof with better wind and sun protection (Sutton, 2012). However, the use of plugs is much more costly. Sutton (2012) found that planting native grasses by plug cost $4.28/ft^2$ more than seeding native grasses. Also, plant plugs can become root bound and it can be very troublesome if the plugs are not installed correctly. For example, when the APD-EGR was initially planted, many of the live plants were not installed properly, which may have been the cause of plant death or decline resulting in many plants needing to be replaced. The plugs need to have their roots loosened after being removed from nursery trays or pots, and it is critical to ensure that the root ball is completely below the soil surface to avoid drying out of the roots. In very shallow substrates (less than about 3 inches or 7.5 cm deep) the roots of larger plugs may be pushed against the underlying filter fabric or other layers (as was the case for some of the plants on the APD-EGR). In addition, when planting from plugs, individual plants need to be immediately watered when they are planted on warm days, and soon after on cooler days. Supplemental irrigation will likewise be needed during establishment for a longer period due to plugs typically being more temperamental than the plants grown from seed or cuttings (Lee Skabelund, KSU-LARCP, pers. comm., Aug 2021).

Future APD-EGR Research

As a two-year study, this research was conducted on a relatively short-term time scale. It is important to continue to monitor and evaluate the relationship between the substrate type and plant mixes and how these relationships change over 5-10 years. The soil moisture sensors can continue to be used to continue to monitor the soil moisture dynamics of the APD-EGR and how the green roof changes in its ability to store water as long as the sensors and associated data-loggers function properly.

Since the results of this study show that a number of native species and *Sedums* (within mixes) can do well on green roofs in the Flint Hills Ecoregion during establishment, it is important to continue to evaluate the ecosystem services that this experimental green roof can provide even as irrigation, weeding, and other green roof management changes are made. Some of the potential areas of investigation for the APD-EGR include investigating the capacity of species mixes and substrate combinations to provide evapotranspiration cooling, assessing how a particular species mix and substrate combinations affect stormwater retention, and evaluating the affect that species mixes and substrate combinations have on carbon sequestration. Close, systematic observations of the adjacent, unirrigated green roofs on the APDesign building would also be instructive.

These kinds of investigations (along with many others) are outlined as research needs by an extensive review of green roof research in North America by Bousselot et al. (2020). The authors contributing to chapters published in *Green Roof Ecosystems* (Sutton, 2015), *Ecoregional Green Roofs* (Dvorak, 2021), and many journal articles likewise share insights on important green roof research needs.

References

Bousselot, J., J. Klett and R. Koski. 2010. Extensive green roof species evaluations using digital image analysis. HortScience, 45(8): 1288-1292. DOI:10.21273/HORTSCI.45.8.1288.

Butler, C., E. Butler and C. Orians. 2012. Native plant enthusiasm reaches new heights: Perceptions, evidence, and the future of green roofs. Urban Forestry and Urban Greening, 11(1): 1-10. DOI:10.1016/j.ufug.2011.11.002.

Decker, A., G. Koehler, S. Morgan, K. Luckett and W. Retzlaff. 2015. "Native plant survival on a Mid-western green roof." Cities Alive 13th Annual Green Roof and Wall Conference Proceedings.

Ksiazek, K., J. Fant and K. Skogen. 2014. Native forbs produce high quality seeds on Chicago green roofs. Journal of Living Architecture, 1(2): 21-33. https://doi.org/10.46534/jliv.2014.01.02.021

Liu, J., P. Shrestha, L.R. Skabelund, T. Todd, A. Decker, M.B. Kirkham. 2019." Growth of prairie plants and sedums in different substrates on an experimental green roof in Mid-Continental USA." Science of the Total Environment 697(134089):1-11. doi: 10.1016/j.scitotenv.2019.134089.

Lundholm, J., J. MacIvor, Z. MacDougall and M. Ranalli. 2010. Plant species and functional group combinations affect green roof ecosystem functions. PloS one, 5(3), p.e9677. https://doi.org/10.1371/journal.pone.0009677

Patton, A., and L. Beck. 2021. "Prostrate Spurge." Accessed May 2021 https://turf.purdue.edu/prostrate-spurge/

Shrestha, P. 2019. "Assessment of first-year survival, growth, and physiological performance of seven species of graminoids within two substrate types on a green roof in the Flint Hills Ecoregion." Master of Landscape Architecture Thesis. Kansas State University, Manhattan, KS. KREX thesis publishing.

Sutton, R.K. 2012. "Seeding Green Roofs with Native Grasses." Landscape Architecture Program: Faculty Scholarly and Creative Activity. http://digitalcommons.unl.edu/arch_land_facultyschol/21

Sutton, R.K., and J. Lambrinos. 2015. "Chapter 17 - Green Roof Ecosystems: Summary and Synthesis." In Green Roof Ecosystems (Ed. by R. Sutton). London: Springer Science. 423-340.

Appendix A - Appendix for Chapter 3

Figure A.1. Sensor Characterization Setup.

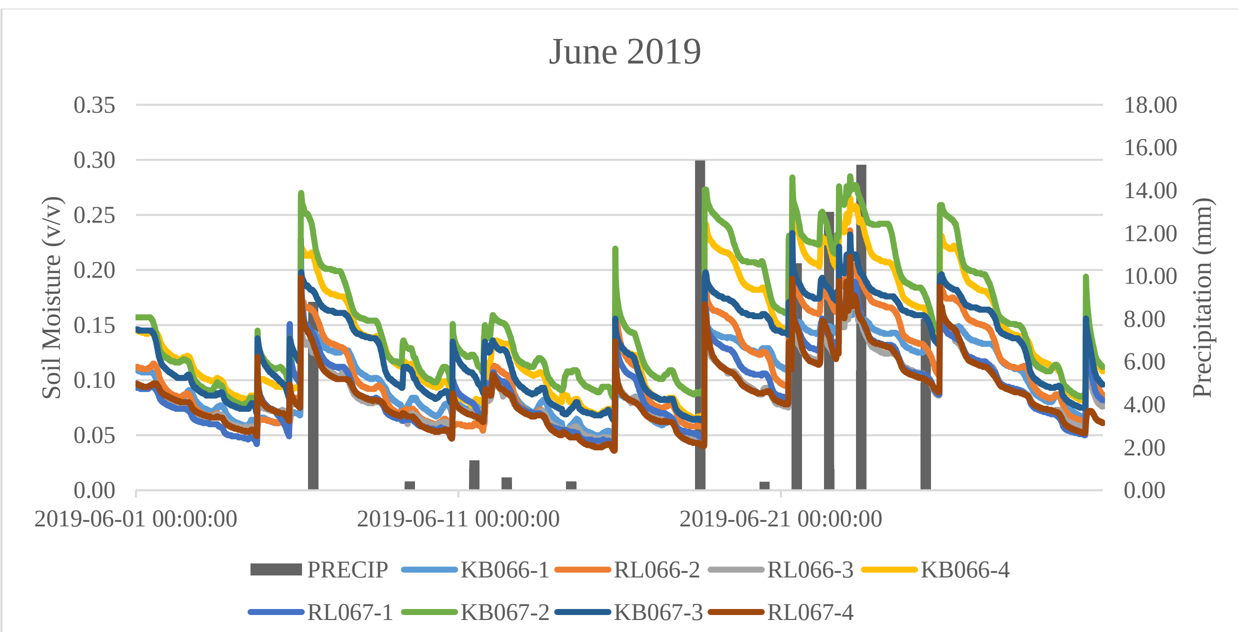


Figure A.2. Example of Configuration 1 4-inch Soil Moisture Data for June 2019.

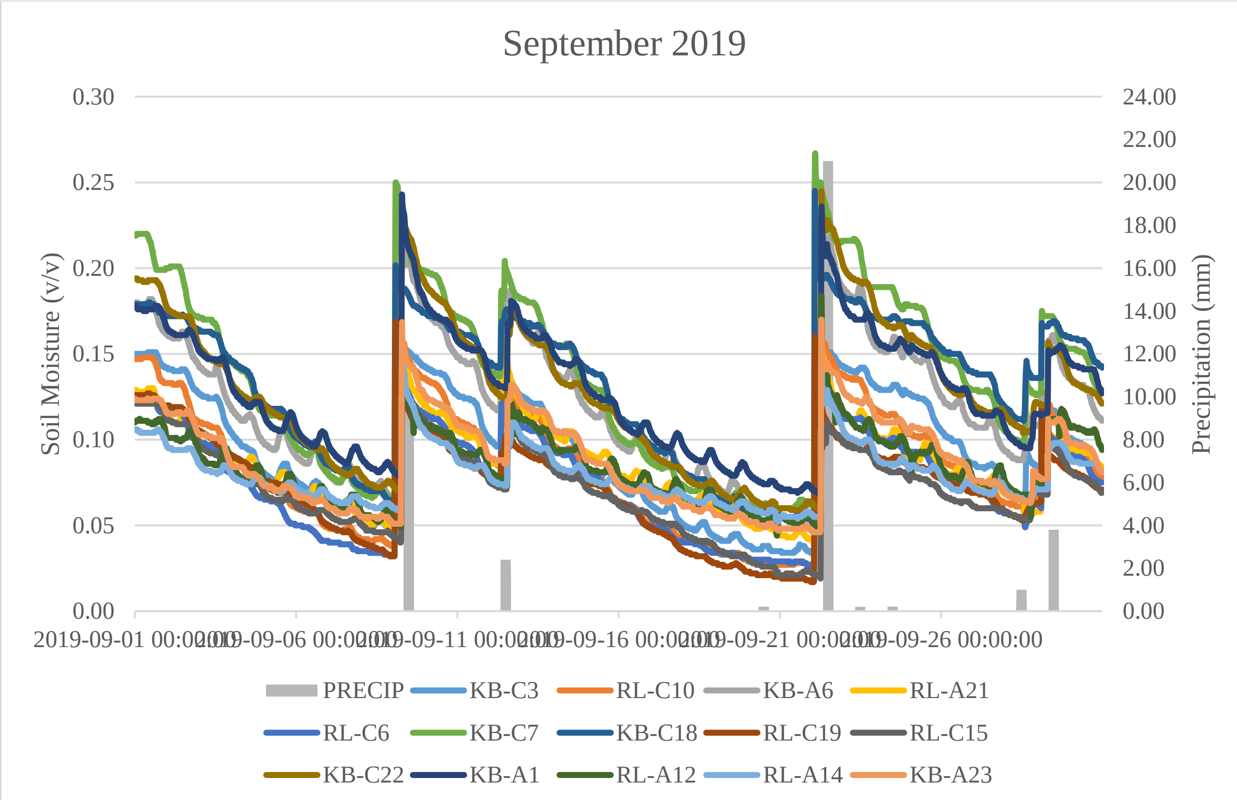


Figure A.3. Example of Configuration 2 4-Inch Soil Moisture Data for September 2019.

Table A.1. Roof Capacity Tukey Grouping for DEPTH*TYPE Least Squares Means (α=0.05). LS-means with the same letter are not significantly different.

DEPTH	SUBSTRATE	ESTIMATE	TUKEY GROUPING	
4	BX	0.4053		A
8	BX	0.3396	B	A
6	BX	0.3015	B	C
4	RL	0.2609	D	C
8	RL	0.2137	D	
6	RL	0.1950	D	

Soil Moisture Data Links:

5G066m4E-28Apr2019-1915.xls-part2

5G066m4E-28Apr2019-1915.xls-part1

5G067m4W-24Mar2019-1122

5G063m6E-24Mar2019-1141

5G063m6E-24Mar2019-1141

5G063m6E-28Apr2019-1912

5G063m6E-20Jul2019-1122

5G060m6W-24Mar2019-1145

5G060m6W-28Apr2019-1909

5G071m8E-24Mar2019-1148

5G073m8W-24Mar2019-1154

5G073m8W-24Mar2019-1152

5G066m4E 20May20-1553

5G067m4W 20May20-1550

5G063m6E 20May20-1538

5G060m6W 20May20-1534

5G071m8E 20May20-1548

5G073m8W 20May20-1545

Appendix B - Appendix for Chapter 4

Table B.1. APD-EGR Plant Information.

Species	Common Name	Mix	Description
Sedum album murale	White stonecrop	A	Easily grown in average, dry to medium, well-drained soils in full sun. Tolerates very light shade. Prefers well-drained sandy soils of moderate to low fertility. Drought and heat tolerant, particularly once established.
Sedum ellacombianum or Phedimus ellacombianus	Stonecrop	A	Similar to *Sedum kamtschaticum*. Vigorous grower that creates mounds of shiny, bright green leaves. Bright yellow flowers bloom in summer. Most of the foliage disappears in winter, but small green rosettes remain and begin to grow with warmer weather. Tolerates some shade.
Sedum hybridum	Little evergreen	A	Adaptable plant. Quickly spreads to create a mat. Slower growing than the similar *Sedum kamtschaticum*. Tolerates some shade
Sedum kamtschaticum var. *floriferum*	'Weihenstephaner Gold' or Orange stonecrop	A	Easily grown in average, dry to medium moisture, well-drained soils in full sun. Grows well in sandy or gravelly soils. Tolerant of hot dry sites and some poor soils but must have good soil drainage to perform well.

Sedum sexangulare	Tasteless stonecrop	A	Easily grown in average, dry to medium, well-drained soils in full sun. Good tolerance for light shade. Also tolerates moist (not wet) soils with good drainage. Thrives in sandy to gravelly soils of moderate to low fertility. Plants will naturalize to form an excellent ground cover. Propagate by division or seed.
Sedum spurium	Crimson stonecrop	A	Easily grown in acidic, average, dry to medium moisture, well-drained soils in full sun. Tolerates some light shade. Likes sandy or gravelly soils. Tolerates poor soils. Needs good soil drainage to perform well. Drought tolerant. Avoid overwatering. Plants may be sited 12" apart when grown as a ground cover. Plants spread easily (root where nodes touch the ground). Plants are evergreen in warm winter climates.
Bouteloua curtipendula	Sideoats grama	B	C_4 grass, found on rocky open slopes, woodlands, and forest openings up to an elevation of about 7,000 feet. Thrives in dry mid-grass prairie section of the Great Plains. Occurs naturally with *Bouleloua gracilis*
Bouteloua dactyloides	Buffalograss	B	C_4 grass, prefers clay-loam soil, thrives in dry prairies, can tolerate moderate to low precipitation (15 to 30 inches annually)

Bouteloua gracilis	Blue grama	B	C4 grass that grows best in the dryer areas of the Great Plains. Has drought tolerance and grows in mixed sandy-clayey soils.
Schizachyrium scoparium	Little bluestem	B, C	C4 grass that grows easily in well-drained soils with dry to medium moisture in full sun. Tolerates clay soils and achieves good drought resistance once established. Tolerates both high humidity and high heat. Naturally found in prairies, fields, clearings, hills, limestone glades, roadsides"
Sedum reflexum	Blue spruce stonecrop	B	Low growing, mat forming *Sedum* with blue-green needle-like leaves. Quickly spreads. Drought tolerant once established. Grows best in partial shade to full sun. Thrives in well drained soils with dry to medium moisture.
Sedum ruprestre	Reflexed stonecrop or blue stonecrop	B	Low growing and thrives in well drained soils with dry to medium moisture. Has best success in sandy to gravelly soils
Carex brevoir	Shortbeak sedge	C	Cool season perennial sedge, found in sandy prairies, meadows, ditches, and woodland. Mostly found in dry, disturbed habitats.

Dalea purpurea	Purple prairie clover	C	Native warm season legume. Grows in rocky open glades and sand, hill, and gravel-hill prairies. Most plentiful in upland prairie.
Koeleria pyramidat a	Prairie junegrass	C	C_3 bunchgrass that is adapted to many habitat types. Mostly observed in rocky to sandy loam soils. Dominates the northern plains mixed prairie. Cold, heat, and drought tolerant. Thrives in rangelands, plains, mountain foothills, and open forestlands. Often is a primary component in open rocky areas.
Packera obovata	Spooned leaf ragwort	C	Thrives in well drained soils that are moist. Tolerates full to partial sun. Native to rocky wooded hillsides, rocky glades, limestone ledges, stream banks, and wet meadows.
Sporobolus heterolepis	Prairie dropseed	C	C4 grass mostly observed in prairies, roadsides, woodlands edges. Thrives in sandy to clay loam soils.

Table B.2. Differences of Least Square Means for 6inch End of Season Cover 2019.

Differences of Least Square Means									
Effect	**mix**	**Subs**	**_mix**	**_subs**	**Estimate**	**stderr**	**df**	**t Value**	**Pr > |t|**
Mix	A		B		-33.6016	4.4021	6	-7.63	**0.0003***
Mix	A		C		-19.1715	4.4021	6	-4.36	**0.0048***
Mix	B		C		14.4301	4.4021	6	3.28	**0.0169***
Subs		BX		RL	-4.6139	2.9310	3	-1.57	0.2135
Mix*Subs	A	BX	A	RL	-17.9335	5.0767	6	-3.53	**0.0123***
Mix*Subs	A	BX	B	BX	-40.4015	5.6802	6	-7.11	**0.0004***
Mix*Subs	A	BX	C	BX	-32.3510	5.6802	6	-5.70	**0.0013***
Mix*Subs	A	RL	B	RL	-26.8018	5.6802	6	-4.72	**0.0033***
Mix*Subs	A	RL	C	RL	-5.9920	5.6802	6	-1.05	0.3321
Mix*Subs	B	BX	B	RL	-4.3338	5.0767	6	-0.85	0.4261
Mix*Subs	B	BX	C	BX	8.0505	5.6802	6	1.42	0.2062
Mix*Subs	B	RL	C	RL	20.8098	5.6802	6	3.66	**0.0105***
Mix*Subs	C	BX	C	RL	8.4255	5.0767	6	1.66	0.1481

Note: An asterisk (*) shows a significant effect on plant cover (α=0.05).

Table B.3. 2018 Sedums and Natives Mix Biomass Summary Table for Kansas BuildEx (BX) and Rooflite® Extensive MC (RL).

Depth	Species	BX biomass (g)	RL biomass (g)
4	BC	20.525	24.15
4	BG	11.9	10.825
4	SC	33	20.175
6	BC	36.05	73.375
6	BG	28.125	14.125
6	SC	57.675	67
8	BC	44.45	34.075
8	BG	24.125	16.925
8	SC	151.53	133.83

Table B.4. 2018 All-Natives Mix Biomass Summary Table for Kansas BuildEx (BX) and Rooflite® Extensive MC (RL).

Depth	Species	BX biomass (g)	RL biomass (g)
4	CB	28.45	25.8
4	DP	21.275	33.6
4	KP	26.425	22.35
4	SC	38.175	33.65
4	SH	15.35	15.875
6	CB	50.6	60.675
6	DP	31.325	53
6	KP	34.425	30.9
6	SC	47.375	114.25
6	SH	16.65	31.4
8	CB	68.475	45.675
8	DP	40.75	56.6
8	KP	34.85	31.825
8	SC	103.55	50.575
8	SH	23.775	19.6

Table B.5. 2019 Sedums and Natives Mix Biomass Summary Table.

Depth	Species	BX biomass (g)	RL biomass (g)
4	BC	28.6	39.925
4	BG	18.125	14.95
4	SC	39.15	91.6
6	BC	38.975	93.65
6	BG	13.575	9.475
6	SC	70.6	179.87
8	BC	60.45	75.85
8	BG	7.05	6.05
8	SC	141.37	252.85

Table B.6. 2019 All-Natives Mix Biomass Summary Table for Kansas BuildEx (BX) and Rooflite® Extensive MC (RL).

Depth	Species	BX biomass (g)	RL biomass (g)
4	CB	127.13	73.75
4	DP	312.3	284.83
4	KP	31.575	31.275
4	SC	164.75	192.4
4	SH	16.25	15.15
6	CB	106.9	130.15
6	DP	310.63	259.25
6	KP	34.2	44.925
6	SC	97.325	260.83
6	SH	13.5	38.425
8	CB	51.85	64.125
8	DP	182.63	203.9
8	KP	31.1	40.875
8	SC	96.95	165
8	SH	22.75	29.05