# Soil, Water, and Plant Relations in Green Roof Management

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# ABSTRACT

Green roofs are forms of green infrastructure that are a growing solution to stormwater runoff and other problems caused by urbanization. The design and performance of green roofs depends largely on geographic location, but research on green roofs in the U.S. Great Plains is sparse. This study investigates how irrigation frequency, substrate depth, substrate types and vegetation cover affect the performance of an extensive green roof in the Great Plains region of Kansas. The goal of this research is to find the best design parameters and management techniques for a thriving green roof in the Great Plains. This was done by examining soil moisture and temperature, soil organic matter, bulk density, and vegetative cover across one growing season. Soil moisture and temperature were measured using sensors embedded in the plots. Soil organic matter and bulk density data were collected by soil sampling, with loss on ignition for organic matter analysis. Vegetation cover was determined using the Normalized Difference Vegetation Index (NDVI) from drone imagery. Results were consistent in showing that substrate depth had a strong influence on both soil moisture and soil temperature. Although the 8-inch plots had slightly lower average soil moisture content than the 4-inch plots, they had greater total water storage and lower moisture variability. The 8-inch plots also had slightly lower average soil temperature and more stable temperature conditions over time. These favorable conditions led to a higher NDVI index, indicating a better vegetation uniformity and density. Irrigation improved soil moisture stability, but its effects were less consistent for organic matter and bulk density. Substrate type also influenced performance, with Kansas Buildex® generally showing more stable moisture conditions and stronger vegetative performance than rooflite®. Overall, results showed that the 8-inch substrate depth and Kansas Buildex® substrate were the strongest design choices for favoring green roof performance. These findings can act as a guide for future green roof design and management strategies aimed at improving water retention, thermal stability, and vegetation health.

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# 1. INTRODUCTION

As urban sprawl increases across the world, it brings with it a critical challenge: increased stormwater runoff. Green infrastructure has become a growing solution to this and other problems that urbanization brings. The United States Environmental Protection Agency (USEPA) defines green infrastructure as infrastructure that uses "filtration, infiltration, and evapotranspiration to treat and soak up rainwater where it falls" (USEPA, 2015). Its value extends well beyond managing runoff; research over the past couple decades has shown a broad range of benefits, including carbon sequestration, habitat creation, and social gains (Alam, 2022; Lundholm 2015; USEPA, 2015).

One type of green infrastructure is green roofs. A green roof is a green space on the roof of a man-made structure, repurposing a roof's impermeable surface with the intent of lowering impacts of urban-centric environmental drawbacks (Longobardi et al., 2019). Green roof construction normally consists of a vegetative layer above layers of composite soil substrate(s), geotextile filters, a root barrier, a storage or pathway for water runoff, and a waterproofing membrane (Berretta et al., 2014; Elliott et al., 2016; Skala et al., 2019; Wang et al., 2021; Cuadrado-Alarcon et al., 2024; Ji et al., 2024). Green roofs can be divided into two main types: intensive and extensive. They can also be categorized into managed and unmanaged.

Extensive green roofs typically have thinner (less than 150 mm) substrate, lower maintenance requirements, and less need for irrigation, while intensive green roofs have thicker substrate and high maintenance and irrigation requirements (Berretta et al., 2014; Nagase & Dunnett, 2011). Extensive green roofs are more popular since there is less structural loading due to the thinner construction practices, but this thinner substrate layer presents more limitations to overall green roof performance (Berretta et al., 2014; Ji et al., 2024). Extensive green roofs, due to their relatively thin substrate construction profiles, have a smaller stormwater retention capacity (Berretta et al., 2014). This has led to many studies to better understand the hydrological properties and performance of multiple green roof construction schemes and growing media (Longobardi et al., 2019; Wang et al., 2021; Ji et al., 2024).

Substrate depth influences other soil parameters, which is why choosing between an intensive or extensive green roof is an important consideration. Deeper substrates tend to retain more moisture, which increases thermal mass and improves insulation. Studies by Reyes et al. (2016) and Pianella et al. (2017) show that deeper soil layers lead to more stable temperature profiles and reduced heat flow through the roof. Cooling in green roofs is largely driven by evapotranspiration, which occurs when water evaporates from the soil and is transpired from plant leaves. This process removes heat from the system and helps lower surface temperatures. Intensive roofs tend to have higher rates of evapotranspiration because they maintain more consistent moisture levels, allowing cooling to occur over longer periods, especially during warm conditions (Shetty et al., 2022). Overall, these relationships show that management, soil moisture, and soil temperature are closely connected. Together, they play a major role in determining how effectively a green roof can regulate temperature and manage water.

Another distinction in green roof type is managed and unmanaged green roofs. Managed green roofs typically include irrigation, plant selection, and ongoing maintenance, while unmanaged systems rely mostly on natural rainfall and minimal human intervention (Reyes et al.,2016; Schrieke et at., 2021). This difference in management ends up influencing almost every part of how the system functions. The type of green roof selected typically depends on the intended purpose of the green roof and the ecoregion of the roof (Jim & Peng, 2012; Elliott et al., 2014).

Green roofs can be built to accomplish different environmental, social, and economic goals. A common purpose for green roofs is filtering and storing stormwater runoff. The USEPA describes stormwater as one of the biggest threats to water quality in the US, as runoff can transport pollutants into local waterways (USEPA, 2015). One of the main functions of a green roof is to reduce the peak water flow of city stormwater systems. Green roofs do this by increasing the delay in water runoff through infiltration and storage both during and after rainfall events (Skala et al., 2019; Wang et al., 2021). Green roofs can also help filter out potentially harmful pollutants and improve air quality, as well as adding thermal and acoustic insulation for buildings (Jim & Peng, 2012; Berretta et al., 2014; Chenot et al., 2017; Longobardi et al., 2019; Skala et al., 2019; Cuadrado-Alarcon et al., 2024). With further research, green roofs could even provide a net carbon benefit over their lifespan, sequestering more carbon than what is emitted during their installation and material production (Alam et al., 2025). The intended purpose of the green roof, as well as what ecoregion the roof is located in, can influence the impacts of different green roof parameters, like substrate, vegetation, organic matter, and additional factors.

## 1.1 Soil Moisture

Across many studies, one idea shows up consistently: soil moisture plays a central role in determining green roof performance. Soil moisture directly affects soil temperature, and soil temperature controls how heat moves through the roof system and into the building below (Jim &Peng, 2012; Arkar et al., 2019). When moisture is maintained, soil temperatures tend to be more stable, which helps reduce heat transfer and improve overall performance. In contrast, when moisture is lost, temperature fluctuations increase and the system becomes less effective. Because of this relationship, understanding how management affects soil moisture helps explain why some green roofs perform better than others. Managed systems tend to maintain higher moisture levels because they include irrigation and plant selection strategies that prevent the soil from drying out (Charalambous et al., 2019). These systems receive water from both rainfall and irrigation, the latter contributing to more stable conditions over time. This is especially important in climates where rainfall is uneven. As a result, managed roofs are often able to retain a larger percentage of rainfall, reducing runoff and improving water storage (Shetty et al., 2022). In comparison, unmanaged roofs often experience rapid drying after rainfall events. Without irrigation or water storage systems, the soil loses moisture quickly, particularly during warm or dry conditions. Cirkel et al. (2018) found that this rapid drying reduces the roof's ability to retain water and limits its cooling potential. Because moisture is so closely tied to both hydrological and thermal performance, it becomes a key factor in determining how effective a green roof will be.

The role of initial soil moisture content prior to rainfall events and the construction and thickness of the green roof installations have been identified as the primary considerations for green roof performance. Several studies found that water retention ability and runoff generation rates were highly influenced by the initial soil moisture content of the substrate (Longobardi et al., 2019; Skala et al., 2019; Mobilia et al., 2021). While a specific substrate may have a desirable permeability or rainwater retention capability, the frequency of rainfall events has a strong influence on the overall performance of the substrate. These studies found that high initial soil moisture concentrations negatively impacted the storage capabilities and correlated to higher runoff generation. For instance, Mobilia et al. (2021) found that soil moisture concentrations lower than 35% prior to all 56 rainfall events resulted in no generation of runoff regardless of the event duration. This potentially represents a non-linear relationship between initial soil moisture concentrations and rainwater runoff generation.

Researchers also found that thicker substrate layers had less variability in soil moisture over time (Elliott et al., 2016; Chenot et al., 2017; Wang et al., 2021). In the study by Chenot et al. (2017), multiple green roof plots of 5 cm and 15 cm were analyzed. They found that the thinner 5 cm plots had a higher soil moisture concentration one day after a rainfall event, however, after three days, the 15 cm plots had higher concentrations. Interestingly, they found that regardless of substrate composition, the 15 cm plots had consistently higher soil moisture concentrations than the 5 cm plots. It was also observed that while the 5 cm plots had higher initial post-rainfall-event soil moisture, they had lower soil moisture during the dry periods.

The influence of substrate composition on soil moisture was also studied extensively. In the study by Chenot et al. (2017), they found that finer particle sizes associated with silts and clays were associated with higher soil moisture. Jim & Peng (2012) noted that the pore size of the substrate was negatively proportional to the ability of the substrate to retain water. This represents the capillary action of smaller pore media to hold moisture, however, Chenot et al. (2017) states that when pore spaces are too small, the water that is retained would not be usable by vegetation used in green roof construction. Cuadrado-Alarcon et al. (2024) experimented with substrate compositions that included construction-recycled aggregates to tailor the pore size within the substrate layer to better control the hydraulic conductivity of the green roof system. They found that higher proportions of recycled aggregates showed higher diffusivity and decreased the hydraulic conductivity of the substrate. Through various means of substrate composition and construction, a green roof can be constructed in a way that optimizes soil hydrological properties for different climate conditions. For our research, we investigated how more irrigation compared to less irrigation impacted soil moisture in our green roof of interest.

We hypothesized that the more irrigated plots of the green roof would have higher and more consistent levels of soil moisture.

## 1.2 Soil Temperature

Soil temperature is a key factor in determining green roof performance, particularly in relation to heat transfer and overall thermal regulation. Across the literature, soil temperature is closely connected to moisture conditions within the substrate, which influence how heat is absorbed, stored, and released. Studies consistently show that when soil moisture is adequate, temperature fluctuations are reduced because water increases the heat capacity of the substrate (Jim & Peng, 2012). This allows the soil to absorb heat during the day and release it more gradually at night, resulting in more stable temperature conditions within the green roof systems. In comparison, dry substrates experience much greater variability in temperature (Jim & Peng, 2012). Without sufficient moisture, soil heats up quickly when exposed to solar radiation and cools down just as rapidly once temperatures drop. This leads to larger temperature swings, which can increase stress on vegetation and allow more heat to transfer into the building below (Arkar et al., 2019). Because of this, soil temperature is not only controlled by external environmental conditions, but also by how well moisture is retained within the entire system.

Substrate characteristics also play an important role in soil temperature behavior. Depth, in particular, has been shown to influence thermal performance. Deeper substrates are able to retain more moisture and provide greater thermal mass, i.e., they have a superior ability to absorb, store, and release heat, which helps stabilize temperatures and reduce heat flow through the roof (Reyes et al., 2016; Pianella et al., 2017). In contrast, shallow substrates tend to dry out more quickly and allow heat to move more rapidly, increasing temperature variability and reducing insulation effectiveness. In addition to substrate depth, evapotranspiration contributes to temperature regulation by removing heat from the system. This process depends heavily on the availability of moisture, as water must be present in the soil and vegetation for evaporation to occur. Systems that maintain adequate moisture levels are able to support ongoing evapotranspiration, which enhances cooling and improves overall thermal performance (Shetty et al., 2022). Overall, the literature shows that soil temperature is strongly influenced by a combination of moisture conditions, substrate properties, and energy exchange processes. Systems that maintain consistent moisture levels and appropriate substrate depth tend to exhibit more stable temperature profiles and improved performance, while dry shallow systems experience greater variability and reduced effectiveness. Our research questioned how the different irrigation levels in our green roof of interest (more irrigated or less irrigated) would impact soil temperature, and we hypothesized that plots receiving more irrigation would maintain lower soil temperatures.

## 1.3 Soil Properties

The soil properties included in this study are organic matter and bulk density. Because there are no consistent measurements of these soil properties throughout the green roof lifetime, this analysis served as a snapshot to understand possible shifts on soil properties, e.g., accumulation of organic matter, compared to the substrate initial conditions.

### 1.3.1 Soil Organic Matter

Soil organic matter (OM) is a substrate component composed of organic material, which includes soil microbes, decaying material from dead organisms, fecal material, and products formed from decomposition (Alam, 2022). Organic matter is a beneficial component of soil, known to maintain good soil structure, increase cation exchange capacity, improve soil water retention, reduce soil bulk density, increase water infiltration, and increase available nutrients in the soil (Nagase & Dunnett, 2011; Frene, Pandey, & Castrillo, 2024). It also influences the soil's thermal storage capacity (Alam, 2022). Organic matter is regulated by net primary production, photosynthate (products of photosynthesis) distribution in roots and shoots, and rate of decomposition (Alam, 2022). Part of OM is soil organic carbon, which, combined with inorganic carbon, makes up the total carbon in the soil.

The benefits of organic matter as a soil component make OM vital to the function and longevity of green roofs. The amount of organic matter that should be present in a green roof varies based on factors like substrate, climate, and vegetation. One important consideration for green roof OM is how the OM content changes over time. Assuming the same plant richness and decomposition rates from green roof construction to a future time of sampling, organic matter is likely to accumulate and therefore increase with time. However, based on a study on green roofs with an average lifespan of 11 years, age does not have a consistent effect on organic matter content (Swanson & McKinney, 2025). Organic matter content depends on many factors, such as decomposition rates, turnover rates, and plant growth, so the trend over time appears to vary.

The change in OM content over time depends largely on the rate of OM decomposition compared to how fast the OM is being replenished. High short-term respiration rates can indicate OM loss, as soil respiration is influenced by organic matter decomposition (Alam, 2022). This loss can have negative effects on the long-term function of green roofs. Organic matter decomposition is impacted by a few different factors, including irrigation and management. One study determined through the tea bag index that increasing irrigation increased decomposition (Swanson & McKinney, 2025). However, increasing management intensity in ways other than irrigation, such as chemical treatments, weeding, and replanting, decreased decomposition rates (Swanson & McKinney, 2025). Roof size, substrate additions, and substrate depth showed no impacts on decomposition in the study (Swanson & McKinney, 2025). One of our questions for this research was what the OM content would be in the less irrigated plots of the green roof compared to the more irrigated plots. We hypothesized that there would be more organic matter in the more irrigated plots of the roof. While irrigation has shown to increase decomposition, we also expect more vegetation growth in the more irrigated plots, and therefore greater turnover of organic matter.

### 1.3.2 Bulk Density

Bulk density is the mass of dry soil per unit volume, which functions as an important indicator of soil compaction. Soil bulk density depends largely on soil texture, but a high bulk density may be indicative of compaction, which translates to decreased plant growth and infiltration. According to the USDA Natural Resource Conservation Service (NRCS), bulk densities that restrict root growth for sandy, silty, and clayey soils respectively are bulk densities greater than 1.80, 1.65, and 1.47 g/cm$^3$ (2008). Soil compaction is largely affected by management practices. In modern agriculture, the use of heavy machinery in crop fields is a major source of compaction. Irrigation practices also play a significant role, as wetter soils are less resistant to compaction than dry soils. Higher water content decreases macropore space, which lowers the ability of soil to withstand pressure without changing density (Frene, Pandey, & Castrillo, 2024). Minimizing compaction, or controlling the areas being compacted, is necessary to maintain healthy soil bulk densities in the long term.

While there is a lack of literature explicitly describing bulk density in green roof substrate, there are assumptions that can be drawn from bulk density research in agriculture. First, organic matter decreases bulk density. However, the long term effects of organic matter in green roof substrates are uncertain. Organic matter decomposing faster than the turnover rate can cause the soil media to shrink, which increases the bulk density (Nagase & Dunnett, 2011). Additionally, the increase of bulk density with irrigation in agriculture could potentially translate to green roofs as well. Further research on changes in green roof bulk density over time is necessary to confirm this. Finally, increasing other types of management (treatments, weeding, etc) would likely also increase bulk density of green roofs from increased foot traffic on the substrate. One question in our research was how irrigation impacts soil bulk density in a green roof. As mentioned in the soil organic matter section, we hypothesised that there would be more organic matter in the more irrigated plots. Therefore, we also expected the bulk density to be lower in the more irrigated plots. Previous research suggests the more irrigated plots are more prone to compaction; however, since the green roof does not experience much compaction, we still predicted lower bulk densities in the more irrigated plots.

## 1.4 Vegetation

Choosing the correct vegetation to establish on a specific green roof is crucial to the success of the green roof. The vegetation type of green roofs have been studied in order to find the best mix of plants to establish. Historically, a sedum mix is the most common and easiest plant mix implemented into green roofs. But, in recent research, monocultures on green roofs have been found to lead to lower ecosystem services, while plant biodiversity can lead to better performance and outcomes (Lundholm 2015). This has led to many people turning towards native mixes when looking into green roof vegetation. Without vegetative cover, a green roof would not be a green roof.

With this in mind, an overarching consideration for this research was how each of the investigated parameters (soil moisture, soil temperature, and soil properties) impacted the ability of plants to grow and thrive on the green roof of interest. The main goal of the study was to determine how the parameters of more irrigated plots compared to the parameters of less irrigated plots. Our hypothesis over the course of this experiment is that vegetation cover will be more uniform and widespread with increased irrigation.

As climate change worsens, mapping and remote sensing of green roofs are becoming increasingly important for understanding how green roofs can help mitigate its perverse effects. Accurate estimation of aboveground biomass (AGB) is critical for assessing ecosystem productivity, carbon sequestration, and vegetation health (Poley & McDermid 2020). Many different researchers have spent time trying to find the best methodology and practices in order to estimate AGB without being destructive. Historically, the most accurate way to quantify AGB is by removing plants from the ground to weigh the total vegetation. This method is destructive to vegetation and extremely time-consuming. So, better indices of measurement have been developed. The Normalized Difference Vegetation Index (NDVI) can be used to assess AGB, and is found to be very accurate (Poley & McDermid 2020). NDVI contrasts red and near infrared wavelengths to predict volume of chlorophyll pigments in a photo, which in turn can accurately describe the 'greenness factor' or vegetation cover of a plot. Ni et al. estimated the AGB in a tallgrass prairie using unmanned aerial vehicles (UAVs) and found that the NDVI and actual biomass were positively related; accuracy was improved the closer to the ground the UAV got. In addition, Maimaitijiang et al. reported that the target time to predict AGB by canopy height is during the mid-season before the reproductive stage appears (Poley and McDermid 2020). Visible light (RGB) imaging was found to be the most accurate and accessible type of remote sensing method to use in grasslands. The benefits of RGB imaging is the ease of data processing and cost effectiveness. Still, NDVI is the most common vegetation index used to analyze AGB and it is prevalent in agricultural settings (Bazzo et al., 2023).

# 2. MATERIALS AND METHODS

Because this project focused on how different green roof design factors affect performance, the methods included measurements of soil moisture, soil temperature, soil properties, and vegetative cover. The measurements were used to compare substrate depth, substrate type, irrigation treatment, and plant response across this experimental green roof. These sections explain the green roof setup, sensor data collection, soil sampling procedures, drone imagery, and statistical analyses used for this project.

## 2.1 Green Roof Description

This study was conducted on the Kansas State University College of Architecture, Planning and Design Experimental Green Roof (APDesign Experimental Green Roof) located on Regnier Hall in Manhattan, Kansas (**Figure 1**). The APDesign Experimental Green Roof was constructed during summer and early fall of 2017 (Decker, 2021). This site was established as a long-term research roof for evaluating green roof performance under Great Plains climate conditions (Kansas State University, 2025). The roof is organized into experimental beds that allow different construction and management factors to be compared under the same conditions. The installation includes three substrate depths: 4 inches, 6 inches, and 8 inches (Decker, 2021). This project focused on the 4-inch and 8-inch plots.

Each bed contains one of two substrates: Kansas Buildex®, a locally sourced expanded shale-based substrate, and rooflite®, a commercial green roof substrate (Kansas State University, 2025). rooflite® substrate is characterized by low bulk density, high pore space, and low water-holding capacity, while the Kansas Buildex® (K) is dense and sandy (Alam et al., 2025). These materials were included to compare how local and commercial substrates perform in the same roof environment.

The plots also include three vegetation mixes: an all-sedum mix, a sedum and native grass mix, and a native grass and forb mix (Kansas State University, 2025). This design allows vegetation response to be evaluated across different combinations of depth, substrate, and irrigation treatment. Some plots received additional irrigation based on plant conditions and drought stress (more irrigated), while less irrigated plots relied more heavily on natural rainfall. The green roof is equipped with buried soil moisture and soil temperature sensors and weather monitoring equipment, shown in **Figure 1**. These instruments recorded environmental and soil conditions over time and allowed us to compare how different plot designs performed throughout the study period. Overall, the site provides a realistic experimental setting for evaluating green roof design choices in the Great Plains region.

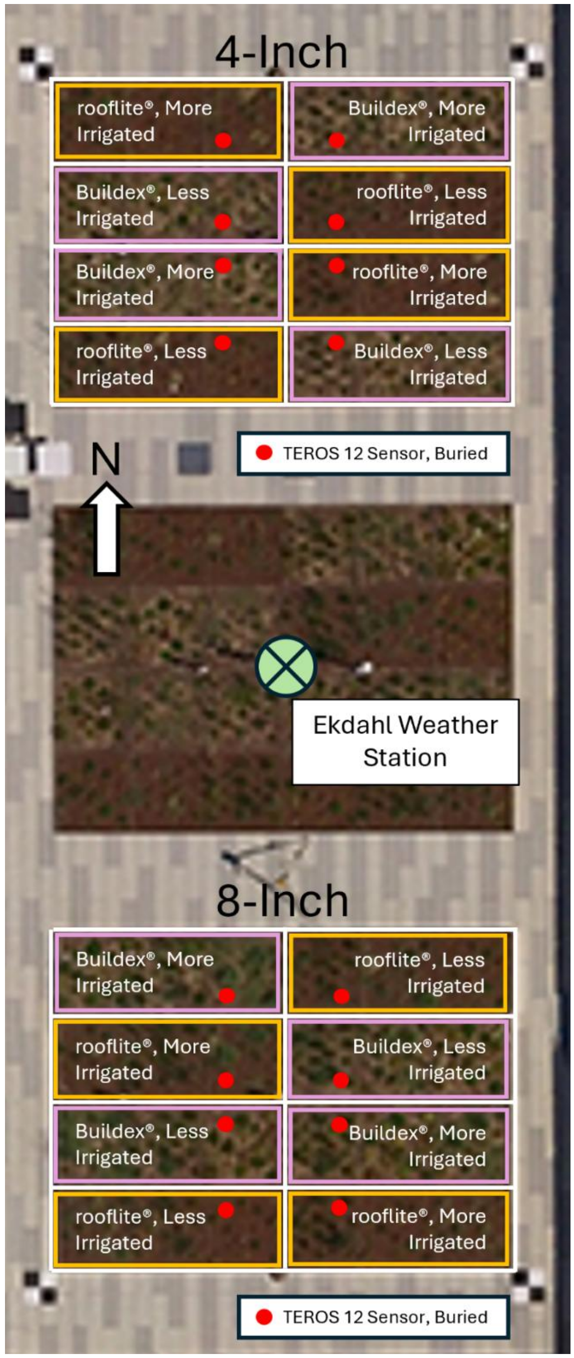



**Figure 2:** Drone picture of APDesign Experimental Green Roof with annotations for sensor locations, substrate type, depth, and irrigation methods used.

## 2.2 Soil Moisture and Temperature

Soil moisture ($m^3/m^3$) and temperature (°C) were recorded using buried TEROS 12 (METER Group) sensors throughout the green roof installation. Data was collected and stored using dataloggers in sub-hourly increments in conjunction with a weather station named Ekdahl, maintained by Kansas Mesonet and installed at the time of construction. The weather station provides sub-hourly air temperature (°C), wind speed (mph), and precipitation (inch/day) measurements along with several other variables that were not used for this study. The hourly values for soil moisture, soil temperature, and air temperature were used to calculate a daily average value for each parameter. The period ranging from July 1st to November 5th, 2025, was used for statistical and analytical comparisons of key design and construction factors of this green roof (i.e.: depth, substrate, irrigation method, location within the installation). Each parameter comparison was conducted by using paired t-tests with 128 paired variables. When necessary, data from June 30th, 2025, was used to calculate antecedent conditions. The software Statistical Analysis System (SAS) was used for regression models and paired t-tests. Due to the high autocorrelation of the time-series data involved in this study, the Autoregression (AUTOREG) function was used for its ability to correct for autocorrelation by fitting autoregressive error models.

## 2.3 Organic Matter

The samples for organic matter analysis were collected through random sampling and placed into plastic bags, as per Appendix A. The most commonly used testing methods for soil organic matter are loss on ignition (LOI) and wet oxidation. Both methods have benefits and drawbacks, but LOI has become the more commonly recommended method in the past couple decades. This is largely due to the ease of analysis and lack of hazardous waste creation compared to wet oxidation. Organic matter analysis for our soil samples was conducted by the Kansas State University Soil Testing Laboratory using standard LOI procedures. After drying 1 gram of ground soil at 150°C for 2 hours, the dry weight is recorded. Samples are then heated to 400°C for three hours, allowed to cool back down to 150°C, and weighted again. The percentage organic matter in the soil (%LOI) is calculated using **equation 1**.

$$\%LOI = \frac{(\text{wt.at } 105°\text{C}) - (\text{wt. at } 360°\text{C}) \text{ x } 100}{(\text{wt.at } 105°\text{C})} \quad \textbf{(Equation 1)}$$

## 2.4 Bulk Density

The samples for bulk density analysis were collected at the same time using the same methodology as the soil organic matter samples, as per Appendix A. The samples were placed into tins and analyzed using methodology adapted from procedures by the Kellogg Biological Station (2024) and Soil Health Institute (2023). We collected a known volume of soil (128 cubic centimeters) and dried the samples in an oven at 105 °C for approximately 24 hours. After drying, we weighed the samples and calculated the bulk density using **Equation 2.**

$$\text{Bulk Density}\left(\frac{g}{cm3}\right) = \frac{\text{Dry Soil Weight (g)}}{\text{Soil Volume (cm3)}}$$ **(Equation 2)**

## 2.5 Vegetative Cover

The established green roof that we studied had 3 different plant mixes. Mix A is an all sedum mix, mix B is a mix of sedum and native grass, and mix C is a native grass and forbs mix. They were laid out in different sectors in the plots, and the species used are detailed in **Table 1**. The 4 inch and 8 inch varied by substrate and plant mix locations (**Table 2)**.

**Table 2**: Table showing the different plant mixes established in the experimental green roof.

| **Mix A: Sedums** | **Mix B: Sedums + Natives** | **Mix C: Native grass/forbs** |
|---|---|---|
| Sedum album var. murale | Bouteloua curtipendula | Carex brevoir |
| Sedum ellacombeanum | Bouteloua dactyloides | Dalea purpurea |
| Sedum hybridum | Boutelous gracilis | Koeleria pyramidata |
| Sedum kamtschaticum var. floriferum | Schizachryrium scoparium | Packera obovata |
| Sedum sexangulare | Sedum reflexum | Schizachryrium scoparium |
| Sedum spurium | Sedum ruprestre | Sporobolus heterolepis |

**Table 2:** 4 and 8 inch depth plots, respectively, showing the locations of the different plant mixes, listed in Table 1 (mixes A, B and C). The shaded regions are filled with Kansas Buildex substrate and the unshaded regions are filled with rooflite® substrate.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| A | A | B | B | | A | A | B | B |
| B | B | A | A | | B | B | A | A |
| C | C | C | C | | C | C | C | C |
| B | B | A | A | | B | B | A | A |
| A | A | B | B | | C | C | C | C |
| C | C | C | C | | A | A | B | B |

Aerial drone imagery of the Kansas State University Experimental Green Roof on Regnier Hall was collected on July 9th, August 9th, September 19th, and November 1st. From these images, mean green, mean red, red edge, and near-infrared band values were extracted to generate the plot NDVI. **Figure 2** contains the four images generated from the drone pictures, from July to November.

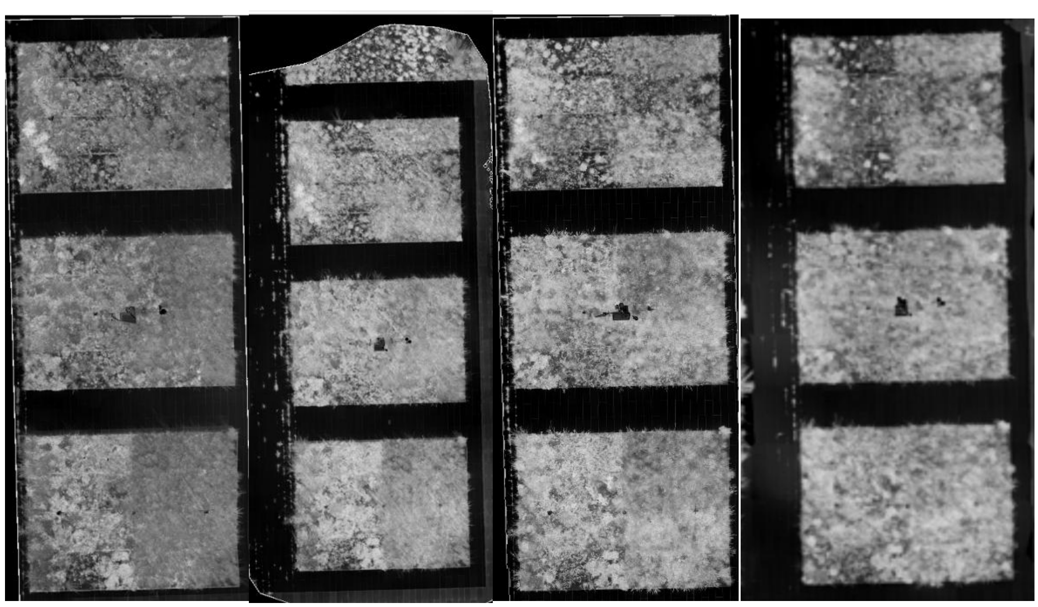


**Figure 3:** July 9th, August 9th, September 19th, and November 1st (left to right) drone images taken 20 feet above roof in order to calculate NDVI for each plot.

# 3. DISCUSSION

The results of this study show that green roof performance is influenced by several interacting factors rather than a single feature alone. While substrate depth, irrigation, substrate type, and vegetation cover were all analyzed separately throughout the results section, many of these variables are closely connected and influence each other. For example, soil moisture appears to play a central role in regulating soil temperature, vegetative performance, and overall system stability. By examining how these parameters interact, a clearer understanding of long-term green roof function and performance can be developed. The following sections discuss several of the most important relationships observed throughout this study and explain how these interactions contribute to effective green roof design and management.

## 3.1 Soil moisture

The effects of multiple green roof parameters were analyzed with respect to soil moisture content. Soil thickness, irrigation frequency, and substrate properties all have complex interactions that have varying effects on soil moisture response and retention. A high soil moisture content with a low variability over time are preferred characteristics of a green roof system for limited maintenance applications

### 3.1.1 Substrate Thickness

When comparing the difference in performance of depth (4-inch vs 8-inch), the thicker 8-inch plots showed a lower average soil moisture content of 0.119 $m^3/m^3$ when compared to the 4-inch plots averaging a higher content of 0.130 $m^3/m^3$. However, the 8-inch plots achieved a lower variability in soil moisture content compared to the thinner 4-inch plots with standard deviation (SD) values of 0.041 and 0.058 as well as interquartile ranges (IQR) of 0.0661 and 0.0691 respectively. The lower SD and IQR values for the 8-inch plots demonstrate a tighter dispersion in the soil moisture readings which equates to less variability and a more stable water content (**Figure 3**). Although the thicker substrate plots had lower average daily soil moisture content, the greater substrate volume of the 8-inch plots resulted in a nearly 83% increase in total water storage compared to the 4-inch plots, based on the daily average soil moisture content. When factoring in the lower variability of the soil moisture content of the 8-inch plots with the higher total water storage, the thicker substrate sections demonstrated a larger, more stable total water capacity when compared to the 4-inch plots. These observations are consistent with previous studies that showed the soil moisture in thicker substrate constructions are less variable (Eliott et al., 2016; Chenot et al., 2017; and Wang et al., 2021).

### 3.1.2 Irrigation Method

When comparing irrigation methods across combined substrate types, substrate thicknesses, and locations, the more irrigated plots attained a higher daily average soil moisture content of 0.135 $m^3/m^3$ than the less irrigated sections (0.114 $m^3/m^3$). The variability of the more irrigated plots was slightly lower with a SD of 0.049 and an IQR of 0.0648 compared to the less irrigated plots SD of 0.050 and an IQR of 0.0741 (**Figure 3**). The reduced variability in the more irrigated plots reflects the supplemental watering applied by the custodians as needed.

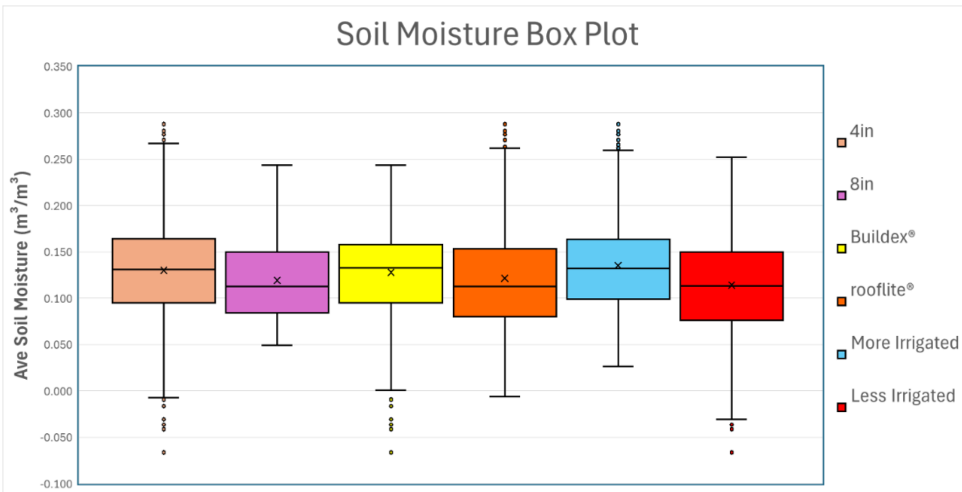



**Figure 3:** Statistical box plot for Average Soil Moisture content ($m^3/m^3$) by substrate depth, type, and irrigation method. Narrower boxes and whiskers represent less variability in soil moisture content. The substrate thickness comparison showed the least variability in the 8-inch plots. Buildex® had slightly higher average daily soil moisture with less variability than rooflite®. The more irrigated sections had an understandably higher average daily soil moisture content than the less irrigated.

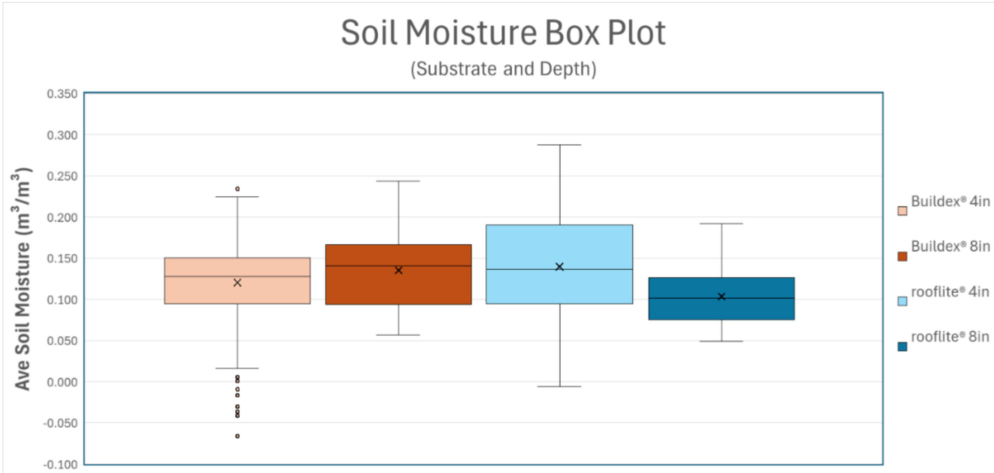



**Figure 4:** Soil Moisture Box Plot comparing substrate type and depth. Narrower boxes and whiskers represent less variability in soil moisture content. The 4-inch rooflite® had the largest variability with the 8-inch rooflite® maintaining the lowest variability and the lowest average moisture. The 8-inch Buildex® had the best combination of mean soil moisture and low variability.

### 3.1.3 Substrate Properties

When comparing soil moisture levels in the two substrate types, the Buildex® substrate had a mean daily soil moisture content of 0.128 $m^3/m^3$, similar to the rooflite® substrate at 0.122 $m^3/m^3$. Buildex® had a higher median content of 0.133 $m^3/m^3$ compared to the rooflite® median content of 0.112 $m^3/m^3$, and maintained a more consistent soil moisture content with a SD of 0.045 and IQR of 0.0630 while rooflite® achieved a SD of 0.055 and an IQR of 0.0730. With lower SD/IQR values, Buildex® showed more stable soil moisture throughout the study period with a slightly lower average moisture content.

When comparing substrate types by thickness, the rooflite® 8-inch plots showed the least variability, with SD of 0.032 and IQR of 0.051. The rooflite® 4-inch plots exhibited the largest variability with a SD of 0.067 and an IQR of 0.957 (**Figure 5**). The Buildex® 8-inch plots were less variable than its 4-inch counterpart, with SD and IQR values falling between those of the two rooflite® depths. When irrigation frequency was considered alongside substrate types, both substrates showed lower variability and higher soil moisture content in the more frequently irrigated plots compared to the less frequently irrigated plots. The more irrigated Buildex® had the highest daily average soil moisture content of 0.139 $m^3/m^3$ with the lowest SD value of 0.039 and IQR of 0.0538. Additionally, the less irrigated Buildex® had a similar distribution pattern compared to the slightly skewed more irrigated rooflite® (**Figure 5**). Although the more irrigated rooflite® showed a higher daily average soil moisture content of 0.132 $m^3/m^3$ compared to the less irrigated Buildex® average of 0.117 $m^3/m^3$, the median values of both are similar at 0.118 $m^3/m^3$ and 0.120 $m^3/m^3$ respectively. The skewness of the more irrigated rooflite® produces similar first and third quartile values and IQR values to the less irrigated Buildex®. The comparable performance between the less irrigated Buildex® plots and the more irrigated rooflite® plots suggests that Buildex® may be a more desirable substrate choice  for green roof installations, as it can achieve similar moisture levels with less frequent irrigation and therefore, lower overall maintenance requirements.

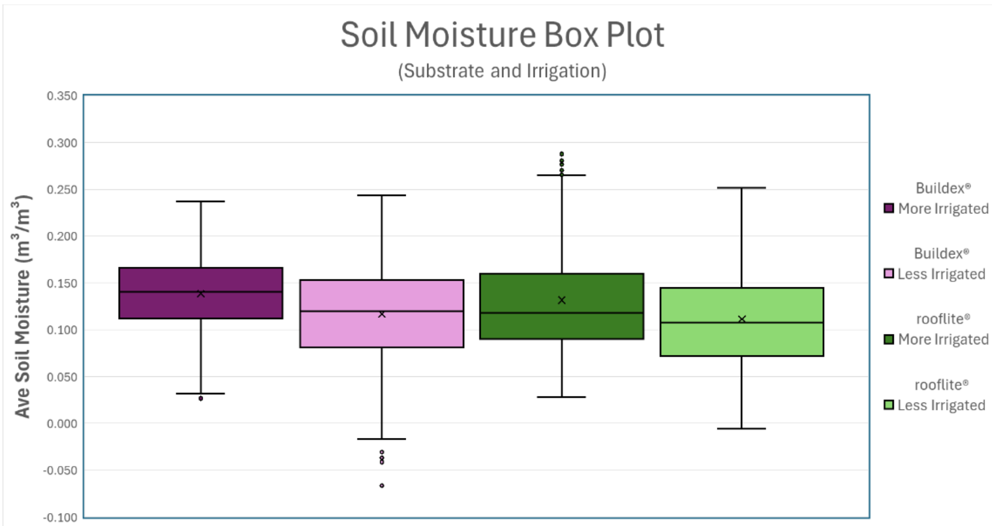



**Figure 5:** Soil Moisture Box Plot comparing substrate type and irrigation method. Narrower boxes and whiskers represent less variability in soil moisture content. The more irrigated Buildex® had the highest average daily soil moisture content with the least variability. The less irrigated Buildex® performed similarly to the more irrigated rooflite®.

### 3.1.4 Soil Moisture Regression Model

Two regression models were developed to better understand the effects of key environmental factors on soil moisture under the two tested irrigation frequencies. For the less irrigated model, daily average soil moisture content (LI) was estimated using three predictor variables: daily recorded precipitation (Precip) in inches, d daily average soil temperature in the less irrigated plots (LIAT) in degrees Celsius, and the antecedent daily average soil moisture content in the less irrigated plots (PDSMS). The model (**equation 3**) generated a favorable Total R-Square value of 0.8850.

$$LI = 0.0344 + 0.0698(Precipitation) - 0.000913(LIAT) + 0.8509(PDSMS) \qquad \textbf{(Equation 3)}$$

The more irrigated model predicted daily average soil moisture content (MI) by using the same daily precipitation values, the more irrigated daily average soil temperature (MIAT) in degrees Celsius, and the more irrigated antecedent daily average soil moisture content (PDSMI). The Total R-Square value was lower at 0.7526 which most likely reflects the model's inability to capture the added variability due to  the human input of supplemental watering . The regression equation generated by this model is shown below in **Equation 4**:

MI = 0.0625 + 0.0535(Precipitation) - 0.001136(MIAT) + 0.7097(PDSMI) **(Equation 4)**

Both models show a high degree of influence of the previous day's soil moisture contents and atmospheric conditions of the current day's soil moisture content which is consistent with several previous studies (Longobardi et al., 2019; Skala et al., 2019; Mobilia et al., 2021).  These models can be used to predict the performance of the green roof with varying conditions to help mitigate the effects of drought conditions or to help tailor future infrastructure modifications.

## 3.2 Soil Temperature

One of the most consistent trends observed in the temperature data was the influence of substrate depth on thermal behavior. When comparing soil temperature between the 4-inch and 8-inch plots, the 4-inch plots had a slightly higher average soil temperature (24.33 °C) than the 8-inch plots  (23.66 °C). Although the difference in average temperature between the two depths was relatively small, the difference in variability between them was more pronounced. The 8-inch plots exhibited lower variability, with a standard deviation (SD) of 6.80 compared to 7.46 for the 4-inch plots. This indicates that the thicker substrate maintained more stable temperature conditions over time, while the thinner sections were more responsive to short-term environmental changes. The paired t-test results indicated that the difference in temperature between the two depths was statistically significant ($p < 0.05$), suggesting that substrate depth has a measurable effect on soil temperature behavior within the system. While the magnitude of the temperature difference was relatively small, the consistency of this difference across the study period supports the reliability of this result.

**Figure 6** shows the variation in soil temperature between the 4-inch and 8-inch plots over the study period. The 8-inch plots display a more stable temperature profile, with fewer extreme fluctuations, while the 4-inch sections exhibit greater variability. This pattern is consistent with the statistical results and supports the interpretation that increased substrate depth contributes to thermal stability.

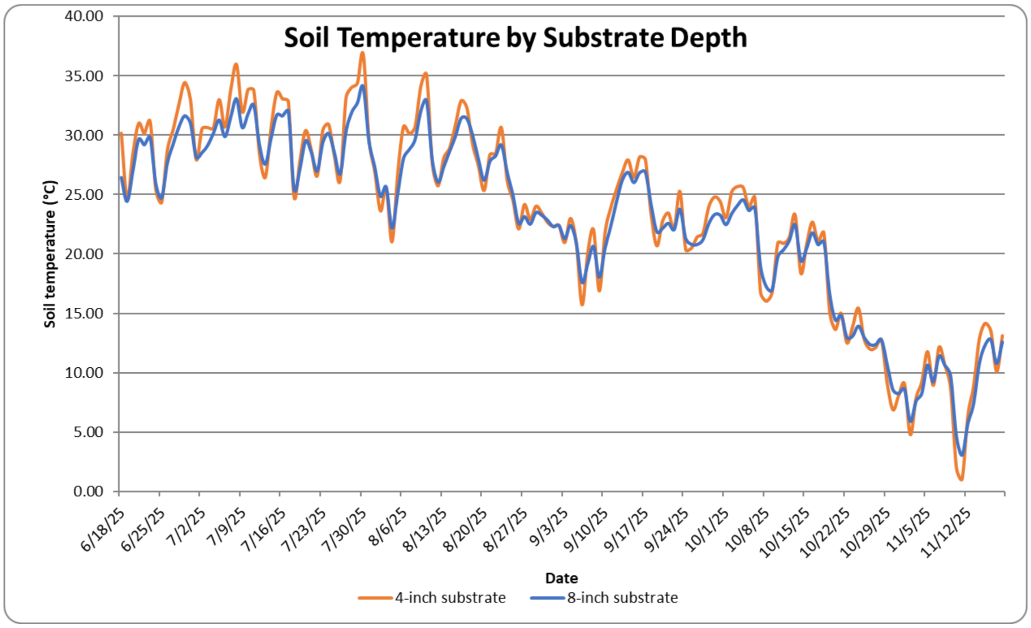



**Figure 6:** Soil temperature across the for the two tested substrate depths (4 inch vs 8 inch). The 8-in plots (in blue) showed a more stable temperature profile.

In addition to depth, differences in soil temperature were also observed when analyzing irrigation frequencies and substrate types. **Figure 7** shows that less irrigated plots generally exhibited slightly higher temperature variability compared to more irrigated plots, although the overall fluctuation patterns remained similar. This indicates that irrigation contributes to more stable temperature conditions by maintaining higher soil moisture levels, which enhance evapotranspiration and help buffer temperature fluctuations.

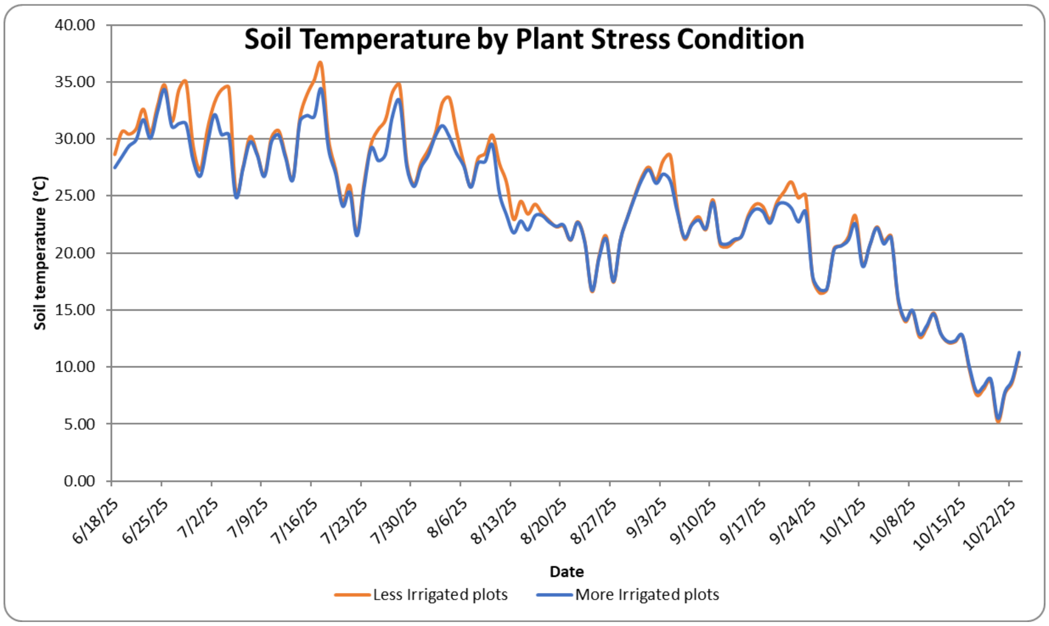



**Figure 7:** Soil Temperature for less irrigated versus more irrigated green roof plots

**Figure 8** shows the mean daily soil temperature for the two different substrates tested, Buildex® and rooflite®. While both substrates followed similar temperature trends, minor differences were observed, indicating that substrate composition may also play a role in thermal behavior. However, these differences were less pronounced than those associated with substrate depth.

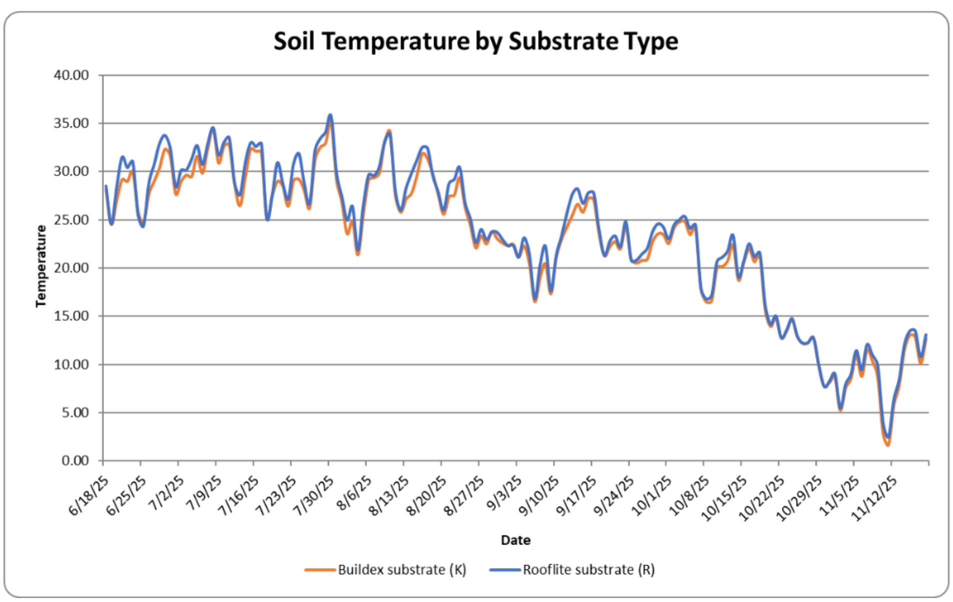



**Figure 8:** Soil Temperature comparing the two substrate types (Buildex® (K) and rooflite® (R))

Overall, the results show that substrate depth has the strongest and most consistent influence on soil temperature, particularly in terms of reducing variability. This matches the general pattern found in previous green roof studies, where deeper substrates usually show smaller temperature fluctuations because they can hold more moisture and provide more thermal mass (Reyes et al., 2016; Pianella et al., 2017). Jim and Peng (2012) also found that moisture in the substrate helps buffer temperature changes by slowing how quickly heat is absorbed and released. While irrigation frequency, plant condition, and substrate type still contributed to temperature patterns, their effects appeared secondary compared to the influence of depth and related moisture conditions. Overall, these results support the existing literature by showing that deeper, more moisture-stable substrates are better at moderating soil temperature changes.

## 2.3 Soil Properties

The soil properties included in this study are organic matter and bulk density. Because there are no consistent measurements of these soil properties throughout the green roof lifetime, this analysis served as a snapshot to understand possible shifts on soil properties, e.g., accumulation of organic matter, compared to the substrate initial conditions.

### 2.3.1 Organic Matter

**Table 3** shows the results of the organic matter analysis. The average percent organic matter for rooflite® ranged from 3.15 to 4.2. The average percent organic matter for the Kansas Buildex® substrate was lower for both substrate depths and irrigation frequencies, ranging from 1.9 to 2.55.

**Table 3**: Results of LOI OM analysis, showing average percent OM of primary and duplicate samples.

| **Sample** | **Average OM LOI (%)** |
|---|---|
| 4-Inch rooflite®, More Irrigated | 4.2 |
| 4-Inch Kansas Buildex®, More Irrigated | 2.2 |
| 4-Inch rooflite®, Less Irrigated | 3.6 |
| 4-Inch Kansas Buildex®, Less Irrigated | 1.9 |
| 8-Inch rooflite®, More Irrigated | 4.2 |
| 8-Inch Kansas Buildex®, More Irrigated | 2.3 |
| 8-Inch rooflite®, Less Irrigated | 3.15 |
| 8-Inch Kansas Buildex®, Less Irrigated | 2.55 |

The substrate depth did not show a significant impact on the organic matter content. **Figure 9** compares the 4-inch and 8-inch organic matter values for like plots.

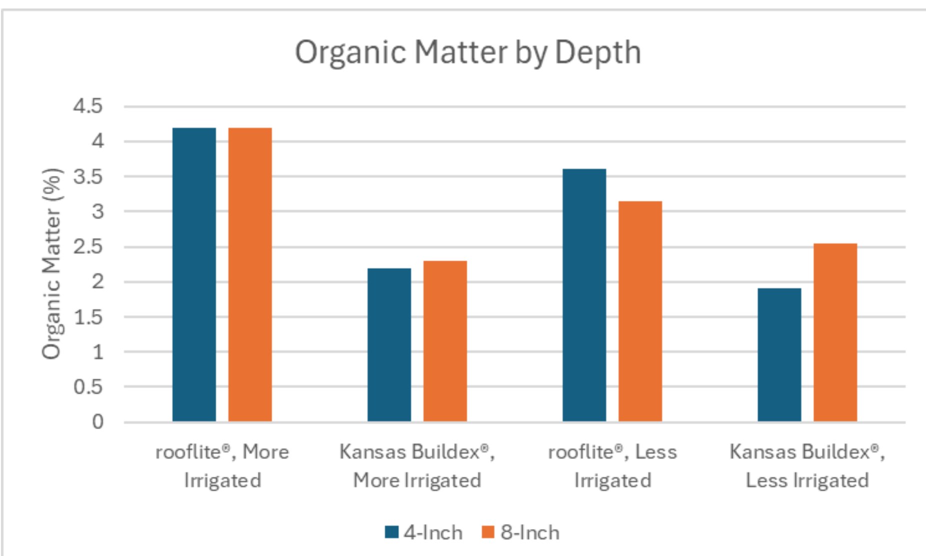



**Figure 9:** Bar Graph Comparison of Organic Matter for 4- and 8-Inch Substrates, Showing Similar Levels of OM for Both Substrate Depths

On the other hand, substrate did have a significant impact on soil organic matter content. The rooflite® had less organic matter than the Kansas Buildex® when the green roof was implemented but accumulated more organic matter over the green roof lifetime, and it now has a higher organic matter content (**Figures 10 and 11**).

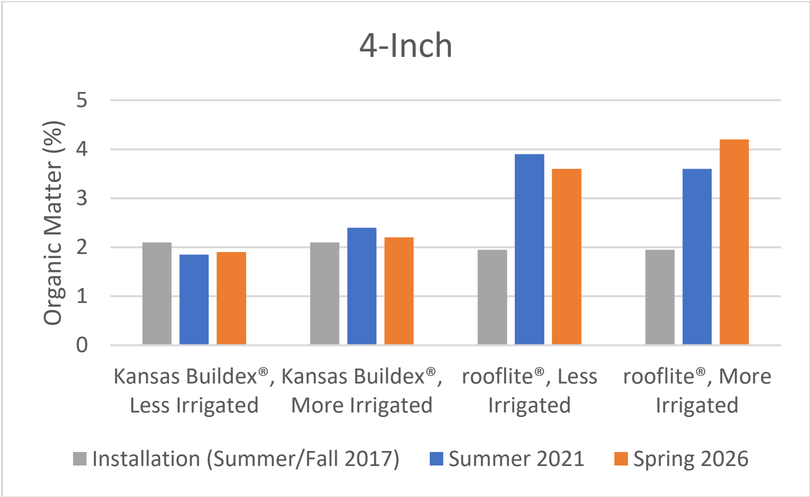



**Figure 10:** Bar Graph of 4-Inch bed percent organic matter by substrate and irrigation, showing Summer 2021 and Spring 2026 content compared to original substrate content. Despite lower starting OM content, rooflite® substrate in the 4-inch bed now has significantly higher levels. Irrigation has not shown a significant effect.

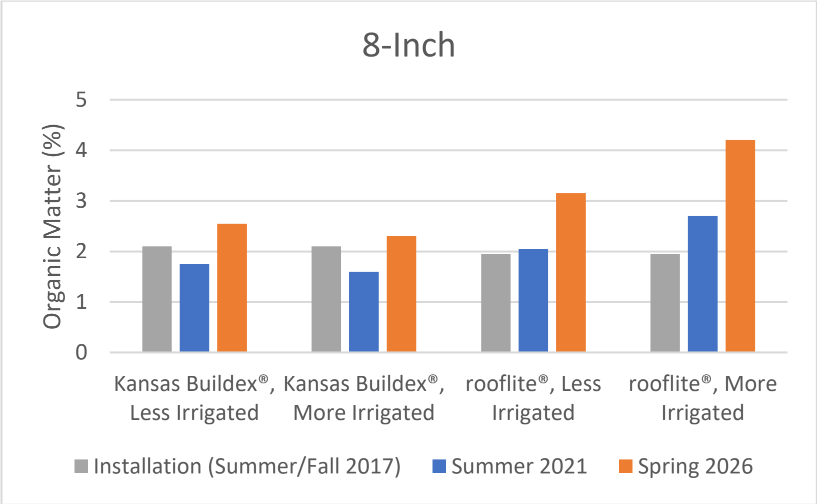



**Figure 11:** Bar Graph 8-Inch bed percent organic matter by substrate and irrigation, showing Summer 2021 and Spring 2026 content compared to original substrate content. Similar to the 4-inch beds, the rooflite® substrate now has more organic matter than the Kansas Buildex®.

Despite our hypothesis that the percentage of organic matter would be higher in the more irrigated plots, irrigation did not appear to have much of an impact. The more irrigated rooflite® plots in the 8-inch bed had higher organic matter levels in both 2021 and 2026, but the same is not true in the 4-inch bed. In the 8-inch Kansas Buildex® plots, the organic matter was actually higher in the less irrigated plots for both 2021 and 2026, though the levels were slightly higher for the same plots in the 4-inch bed. However, given the lack of consistent organic matter data since the green roof installation, we can neither prove nor disprove the hypothesis. With data points from only 2018 (installation), 2021, and 2026, we cannot comprehensively analyze the changes in organic matter content over the course of the green roof's lifespan.

### 3.3.2 Bulk Density

The **table 4** below summarizes the results of bulk density analysis results across all treatment factors, including irrigation frequency, substrate depth, substrate type, and the combined effects of substrate type with irrigation frequency and substrate depth with irrigation frequency.

**Table 4:** Average bulk density results comparing irrigation frequency, substrate depth, substrate type, and sample sets (primary and duplicate). The Kansas Buildex® substrate has a higher average bulk density, and the duplicate (2) sample set has a lower bulk density. Irrigation frequency and substrate depth showed little impact on the bulk density.

| | **Average Bulk Density (g/cm3)** |
|---|---|
| **Irrigation Frequency** | |
| More Irrigated | 0.94 |
| Less Irrigated | 0.96 |
| **Substrate Depth** | |
| 4-inch | 0.97 |
| 8-inch | 0.93 |
| **Substrate Type** | |
| rooflite® | 0.89 |
| Kansas Buildex® | 1.01 |
| **Sample Set** | |
| Primary (1) | 1.02 |
| Duplicate (2) | 0.88 |

One note on these results is the considerable difference between the primary and duplicate sample bulk densities. The duplicates were intended to be taken the same day as the primary samples, but due to logistical constraints, the duplicates were taken a week after the first samples, a delay that may have introduced systematic differences, as every duplicate yielded a lower bulk density value than its primary counterpart. For future research, bulk density samples should all be taken on the same day, or a combination of primary and duplicate samples on each day instead of one day being all duplicates.

Despite our hypothesis that bulk density would be lower in the more irrigated plots, irrigation did not appear to have a significant impact on bulk density. However, similar to organic matter, we do not have enough historical data to gather a comprehensive trend of bulk density in different irrigation schemes.

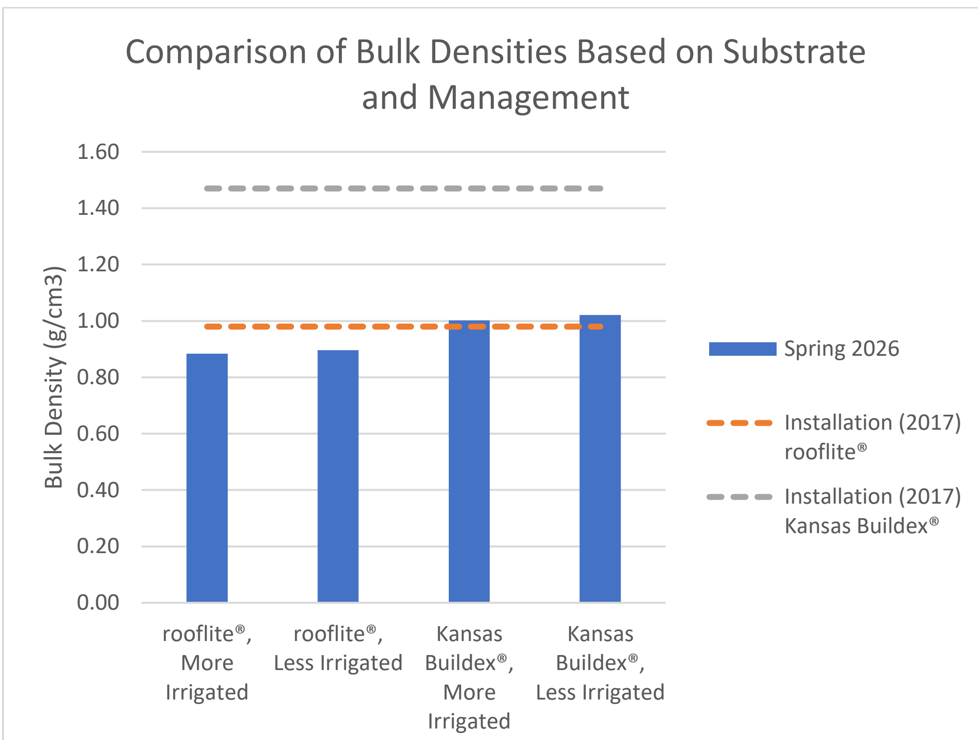



**Figure 12:** Comparison of bulk densities based on substrate and management, with installation substrate bulk densities for reference.

The main factor in determining bulk density was substrate. Kansas Buildex® had the higher bulk densities for both more and less irrigated, but the bulk density was still in a reasonable range that will not result in plant growth impediment (plant growth impediment occurs at bulk densities >1.8 g/cm$^3$ for sandy soils). This explains why Kansas Buildex®, despite having the higher bulk density, was still able to perform better in vegetative cover. **Figure 12** includes reference lines for the installation bulk densities of both substrates, which shows that the bulk densities of both substrates decreased from the time the green roof was installed. This is likely due to the establishment of vegetative cover. The Kansas Buildex® bulk density decreased more than the rooflite® from the original bulk densities, which could be indicative of greater vegetative cover in the Kansas Buildex®.

## 3.4 Vegetation Cover

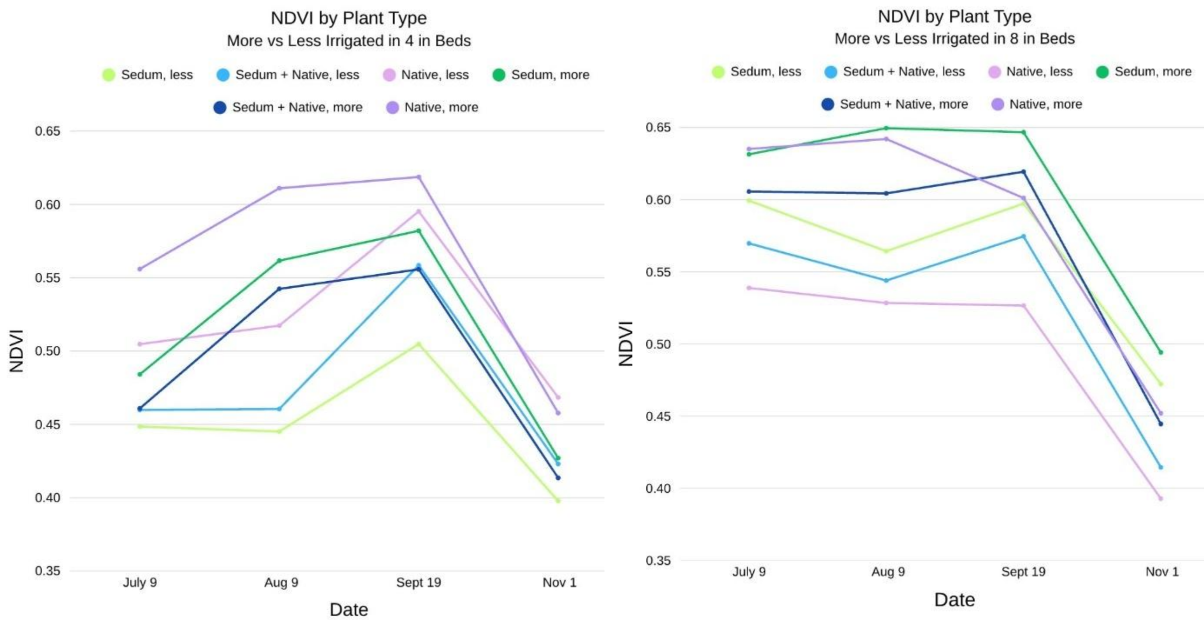
**Figure 2** displays how different plant mixes perform under different irrigation frequency and substrate depths. The NDVI values differed substantially between the 4-inch and 8-inch plots, with each plant mix varying differently across the 2 depths. In the 4-in plots, the more irrigated native mix had the highest NDVI, but in the 8-in plots, the more irrigated sedum mix had the highest NDVI.

The more irrigated plant mixes recorded higher NDVI values in the 8-inch plots. In the 4-in sections, performance was mixed, with both more and less irrigated plant mixes recording comparably high NDVI values. Notably, the less irrigated native mix did not have a high NDVI in the hotter summer months, but then the NDVI shot up to second in September, and had the highest NDVI in November, suggesting that the native mix maintains its greenness and canopy for longer compared to the other plant mixes.

Overall, the 8-inch substrate depths recorded a higher NDVI value compared to the 4-inch depth, and also maintained more steady NDVI levels across the study period, whereas the 4 inch depth is more variable. Higher and more steady NDVIs are generally indicative of better vegetation health and cover (Falcão et al. 2025), suggesting that the 8-inch depth is a more favorable option for green roof installations. In terms of types of vegetation cover, the native mix performed well in both depths, making it arguably the better choice. As discussed in the literature, more biodiversity in vegetation choices leads to better ecosystem services (Lundholm, 2015). This result suggests that turning away from all Sedum roofs can be a beneficial choice, not only for the health of the green roof, but for the health of the environment as well.

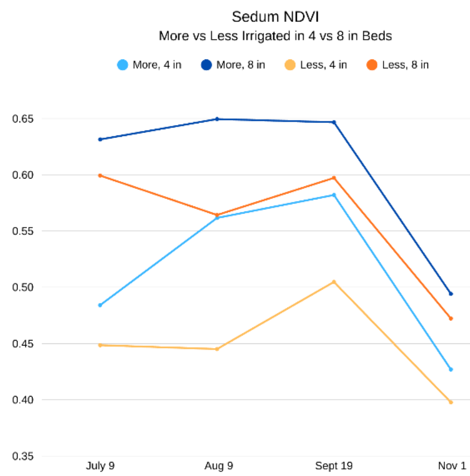
In a previous study, Shetty et al. 2017 proved our findings further by displaying that an irrigated, native green roof retained more stormwater when compared to a non-irrigated Sedum green roof. Retaining stormwater is one of the most favorable ecosystem services a green roof can do for the surrounding buildings and ecosystems.

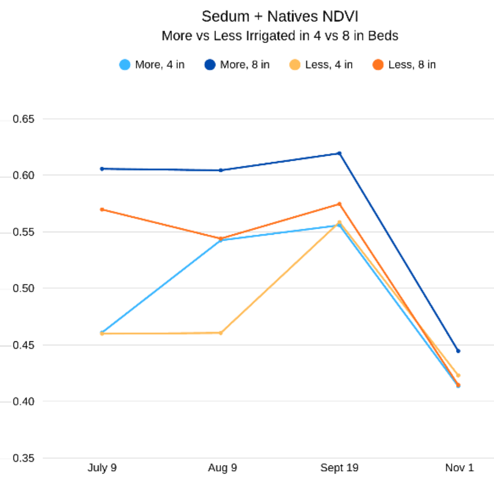
**Figures 13 and 14** compare each individual plant mix's NDVIs by their depth and irrigation level. As mentioned previously, the more irrigated plots in the 8-inch depth had the highest NDVI. The only case where this is not true is the native grass mix (Mix C), where the more and less irrigated plots in the 4-inch beds are either slightly above or tied with the more irrigated 8-inch plot for NDVI in September and November.

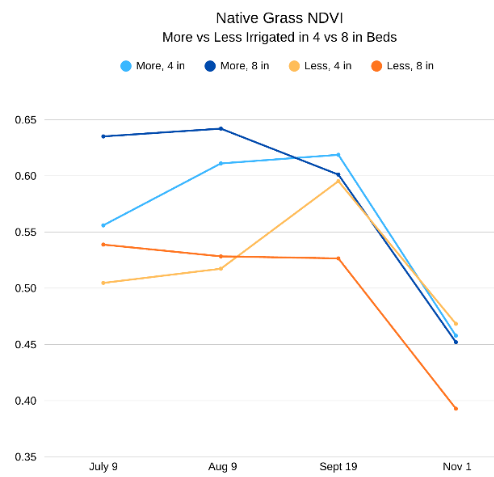



**Figures 13 and 14:** The NDVIs for 4 in and 8 in plots by plant type and irrigation levels, respectively.

When considering substrate depth separately, the more irrigated plots typically have greater NDVI values **(Figures 15, 16, and 17)**. The 8-inch depth consistently recorded a higher NDVI over the course of the season when compared to the 4 inch. This is consistent with what was found comparing plant types in two different depths. There are also less swings in greenness levels across the 8-inch plots, compared to the 4-inch plots. This arguably makes the 8 inch plot the more desired depth again. **Figures 15, 16, and 17** demonstrate that depth and irrigation levels are key factors to consider when thinking about how to design and manage a green roof.

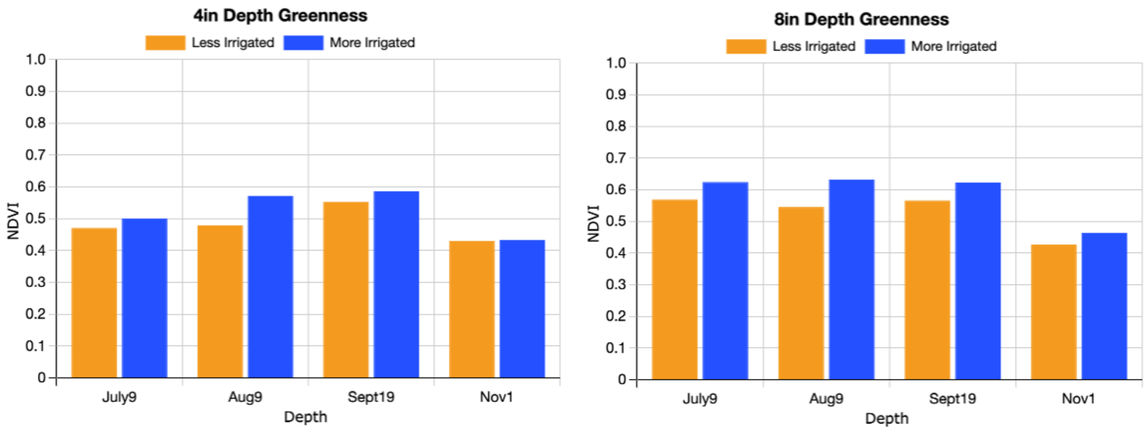



**Figures 15, 16, and 17:** The NDVIs for each specific plant type, by irrigation level and depth.

If only depth is considered, the more irrigated plots typically have a greater NDVI **(Figures 18 and 19).** The 8-inch depth typically has a higher NDVI over the course of the season when compared to the 4-inch. This is consistent with what was found comparing plant types in two different depths. There are also less swings in greenness levels across the 8 inch season, compared to the 4-inch season. This arguably makes the 8-inch plot the more desired depth again.




**Figures 18 and 19:** Bar graph displaying the differences between less and more irrigated plots in two different plot depths.

When implementing a green roof, it is important to consider what type of soil to use. **Figure 20** compares the two different substrates and the two different irrigation levels. Overall, the more frequently irrigated Kansas Buildex® recorded the highest NDVI all season. It is notable that the more irrigated rooflite® substrate performs about the same as the less irrigated Buildex® substrate as indicated by the NDVI values. This suggests that Buildex® is the better substrate to use in this context, since less irrigation is needed to achieve the same NDVI values. This setup will result in a more effective green roof performance and management over time. A previous study on this same experimental green roof supports our findings. Liu et al. (2019) showed that the plants grown in the locally mixed substrate (Kansas Buildex®) showed greater height in the 4-inch depth and greater coverage in the 8-inch depth. This indicates that Kansas Buildex® is the most favorable substrate for a local Great Plains green roof.

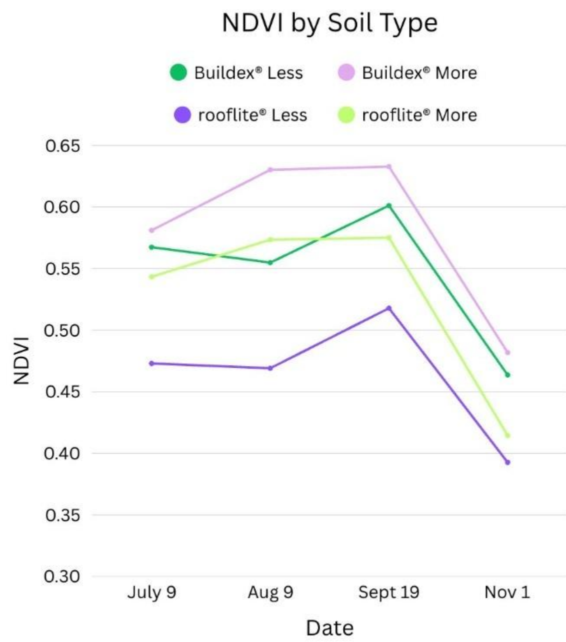



**Figure 20:** Comparing the NDVI by Soil Type

## 3.5 Soil-water-plant interactions in a green roof

Green roof performance is influenced by the interaction of multiple environmental and design-related factors rather than by any single parameter alone. Throughout this study, relationships between substrate depth, irrigation, vegetation cover, soil moisture, and soil temperature consistently appeared across multiple analyses. While each parameter was evaluated individually in previous sections, understanding how these factors interact provides a more complete picture of overall green roof function and long-term performance.

### 3.5.1 Moisture & Temperature

The relationship between soil moisture and soil temperature is one of the most important aspects of green roof performance (Jim & Peng, 2012). Because the water content of soils can change considerably across the growing season, their physical properties shift  in ways that affect how heat is absorbed and stored. A higher water content increases the heat capacity of the substrate, meaning that moist soil can absorb more energy without experiencing large temperature increases (Jim & Peng, 2012). During the day, moist soil absorbs solar radiation and stores heat. At night, this stored heat is released gradually, which helps reduce temperature fluctuations. Jim and Peng (2012) showed that these fluctuations lead to more stable temperature conditions within the soil profile, especially at deeper layers. Dry soil behaves very differently. Without moisture, the substrate heats up quickly when exposed to sunlight and cools down just as rapidly once temperatures drop. This leads to larger temperature swings, which can increase stress on vegetation and allow more heat to pass into the building below. These differences highlight how closely soil temperature is tied to moisture conditions. When moisture is present, temperature changes are moderated. When moisture is absent, temperature extremes become more pronounced. Some studies suggest that there may be an optimal range of moisture where temperature regulation is most effective. Sun et al. (2014) found that too little moisture reduces cooling, while too much moisture may limit how efficiently heat is released. This suggests that management strategies should aim to maintain balanced moisture levels rather than simply maximizing water content. Overall, soil temperature cannot be understood without considering soil moisture. Because management practices influence moisture levels, they also play a key role in determining temperature conditions within the green roof system. Moist soils act as a thermal buffer. Arkar et al. (2019) found that this buffering effect helps stabilize indoor temperatures and improve overall building performance. In contrast, shallow or dry substrates allow heat to move more quickly through the system. This increases temperature variability and reduces the effectiveness of the green roof as an insulation layer.

### 3.5.2 Vegetation Cover, Moisture, & Temperature

One beneficial aspect of green roofs is the range of advantages they provide to both people and infrastructure. A review by Gomes et al. (2019) explores the impact of vegetation, substrate, and irrigation on the energy performance of green roofs. They found that higher irrigation

levels led to smaller energy consumption annually. The authors discuss that, during the summer, if the green roofs are watered 3 mm/day there is a 4.1 times decrease in cooling energy needed. If intensive green roofs are watered 6 mm/day during the summer, there can be a 500% reduction in energy needs.

### 3.5.3 Organic Matter & Vegetation Cover

Organic matter and vegetation cover interact in many different ways that are not completely understood yet. Scientists do agree that the main source of OM is from roots that are decomposed from microorganisms found in the soil. Every year, around a quarter to a half of the total root biomass becomes available to soil microorganisms for conversion into OM. The plant type and location do in fact dictate where the OM is distributed throughout the profile. Changing the plant composition or depth will alter the OM composition of the plots (Parton 1987). Organic matter and vegetation cover are very dependent on each other, making their interactions very important.

## 3.6 Recommendations & Implications

Our goal of this study is to identify the best design parameters in terms of substrate depths, substrate types, irrigation frequency, and plant types in order to implement a successful green roof in the Great Plains region of the United States. After analyzing data from one growing season of continuous monitoring of the green roof as well as its vegetative cover as indicated by UAV-captured images, we suggest two main recommendations for future implementation of green roofs under the same climatic regime. The first recommendation is using an 8-inch depth for substrate. The 8-inch plots achieved a lower variability in soil moisture content compared to the thinner 4-inch sections. Although the thicker substrate sections had lower average daily values for soil moisture content, the larger total substrate volume in the 8-inch compared to the 4-inch plots resulted in a nearly 83% increase in total water volume in the 8-inch sections when calculating using the daily average soil moisture content.

Additionally, the 8-inch sections exhibited lower variability, which means that the 8-inch substrate maintained more stable temperature and moisture conditions over time, while the 4-inch plots were more responsive to short-term environmental changes. Less variability or less significant changes leads to better vegetative cover and health. The substrate depth did not show a significant impact on the OM content. In terms of vegetation, the 8-inch plots led to higher NDVI values overall, regardless of plant or soil type. Because NDVI indicates plant health and density, the higher NDVI in the 8-inch plots suggests that this depth is more desirable for vegetative cover maintenance.

The second recommendation this data indicates is that the local Kansas Buildex® substrate is the better choice when considering design aspects of a green roof. Our data shows that Buildex® has more stable soil moisture throughout the substrate with a slightly lower average moisture content. Buildex® had the higher bulk densities for both more and less irrigated, but the bulk density was still in a reasonable range that should not impede plant growth (>1.8 g/cm$^3$ for sandy soils). This helps explain why Buildex®, despite having the higher bulk density, was still able to perform better in terms of vegetation cover. Buildex® bulk density also decreased more than the rooflite® from the original substrate bulk densities. The NDVI of the less irrigated Buildex® substrate was almost identical to the more irrigated rooflite® substrate. Using Buildex® can save water and energy while still having great vegetative cover. Overall, the Buildex® 8-inch performed better than its 4-inch counterpart.

All of this information is important in order to construct functional green roofs that are less intensive and with lower management. This will also lead to longevity and ease with overall maintenance and labor.

# 4. Conclusion

In this study, we show how design choices, like substrate depth, irrigation, and substrate type, impact soil moisture stability, temperature control, and plant growth. Soil moisture and temperature were both significantly influenced by soil thickness and irrigation schemes. Overall, moisture content and temperature were less variable in the 8-inch, more irrigated substrate plots. While the thicker 8-inch substrates had lower soil moisture content values, the total water content by volume was greater than the thinner 4-inch substrates. Additionally, the substrate types, Buildex® and rooflite®, appeared to have no influence on daily average soil temperatures, but did have some effect on daily average soil moisture. Buildex® maintained a less varied and slightly lower soil moisture content value compared to the alternative rooflite® substrate. Furthermore, future green roof performance with predictive modeling using current and previous day weather and soil conditions proved to be a viable evaluation tool, however, with diminished model performance when handling subjective human irrigation inputs.

Despite our hypotheses that there would be a higher percentage of organic matter and a lower bulk density in the more irrigated plots, the irrigation frequency, as well as substrate depth, did not appear to have a significant impact on soil percent organic matter (OM) or soil bulk density. The primary differences between OM and bulk density values were driven by substrate type. From first installation in 2016 to the study period in 2025, rooflite® had the largest OM change resulting in the highest overall OM content, regardless of depth and irrigation methods. Buildex® maintained a higher bulk density despite having the largest drop from initial bulk density values at installation. However, substrate thickness and irrigation schemes did have a measurable difference in NDVI values and plant mixes. The thicker 8-inch plots had, on average, higher NDVI values with the native mix plants performing better, regardless of substrate depth. Moreover, the 8-inch plots demonstrated less variability in greenness levels throughout the study period. When comparing substrate types for NDVI values, the Buildex® substrate had higher values than rooflite®, with the Buildex® less irrigated plots being comparable in performance to the more irrigated rooflite® plots.

Soil moisture, soil temperature, substrate properties, and plant growth behaviors are all interlaced in highly complex yet simply designed green roof installations. Soil moisture and soil temperature are typically inversely proportional within extensive green roofs due to the relatively thin heat transfer layers. As soil moisture lowers, soil temperature increases. Additionally, substrate properties and how plants grow and behave are crucial to soil moisture and temperature. An increase in substrate water capacity leads to an increase in soil moisture, which ultimately leads to a thicker, more robust vegetative layer. A delicate balance of many parameters in a small, confined space leads to tangible benefits.

Based on our analysis,  two simple recommendations have been made. First, a thicker substrate layer in an extensive green roof is preferred to a thinner alternative. This is due to decreased variability in soil moisture and temperature and increased overall water capacity when comparing 8-inch depths to 4-inch depths. The second recommendation is the use of the Kansas Buildex® substrate in a green roof with a climate equivalent to the Central Great Plains of the United States. The Kansas Buildex® performed better overall in soil moisture and plant NDVI when compared to the rooflite® alternative.

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# 6. Appendices

Appendix A: NRES Capstone Project Soil Sampling Methodology - Organic Matter and Bulk Density Analysis

**Table A1**: List of samples and sample IDs for organic matter and bulk density sampling

| **4-Inch Bed** | | **8-Inch Bed** | |
|---|---|---|---|
| **Sample** | **Sample ID** | **Sample** | **Sample ID** |
| rooflite®, More Irrigated | 4-RM-1 | rooflite®, More Irrigated | 8-RM-1 |
| Kansas Buildex®, More Irrigated | 4-KM-1 | Kansas Buildex®, More Irrigated | 8-RM-2 |
| rooflite®, Less Irrigated | 4-RL-1 | rooflite®, Less Irrigated | 8-KM-1 |
| Kansas Buildex®, Less Irrigated | 4-KL-1 | Kansas Buildex®, Less Irrigated | 8-KM-2 |
| rooflite®, More Irrigated (Duplicate) | 4-RM-2 | rooflite®, More Irrigated (Duplicate) | 8-RL-1 |
| Kansas Buildex®, More Irrigated (Duplicate) | 4-KM-2 | Kansas Buildex®, More Irrigated (Duplicate) | 8-RL-2 |
| rooflite®, Less Irrigated (Duplicate) | 4-RL-2 | rooflite®, Less Irrigated (Duplicate) | 8-KL-1 |
| Kansas Buildex®, Less Irrigated (Duplicate) | 4-KL-2 | Kansas Buildex®, Less Irrigated (Duplicate) | 8-KL-2 |

<-- N

| | | | |
|---|---|---|---|
| 4-KL | 4-RL | 4-RM | 4-KM |
| 4-KL | 4-RL | 4-RM | 4-KM |
| 4-KL | 4-RL | 4-RM | 4-KM |
| 4-RM | 4-KM | 4-KL | 4-RL |
| 4-RM | 4-KM | 4-KL | 4-RL |
| 4-RM | 4-KM | 4-KL | 4-RL |

4 inch

| | | | |
|---|---|---|---|
| 8-RL | 8-KL | 8-KM | 8-RM |
| 8-RL | 8-KL | 8-KM | 8-RM |
| 8-RL | 8-KL | 8-KM | 8-RM |
| 8-KM | 8-RM | 8-KL | 8-RL |
| 8-KM | 8-RM | 8-KL | 8-RL |
| 8-KM | 8-RM | 8-KL | 8-RL |

8 inch

| | |
|---|---|
| K | Kansas Buildex® |
| R | rooflite® |
| L | Less irrigated |
| M | More irrigated |

| | |
|---|---|
| | KL |
| | KM |
| | RL |
| | RM |

**Figure A1:** Plot identification showing sample IDs, with color coding for plots of the same substrate type and irrigation frequency. Same color plots of the same depth were mixed and combined to be one sample

**Materials:**

- 16 sandwich-sized plastic bags
- 16 collection tins
- Marker
- Hand shovel
- Gloves
- 8 Buckets

**Procedure:**

1. Label all plastic bags and tins with Sample IDs before collecting samples
2. Identify the sampling area in each plot based on the sampling location **figure A2** (see below, red signifies duplicate sampling locations). Choose a spot without any plants and clear away any litter. Be aware of cables and monitoring devices
3. Using the hand shovel, dig to a depth of ~3 inches
4. Collect samples from inches 1-3, ensuring that the sample is the same width from top to bottom.
5. Place samples for each sample set (4-KL, 8-RL, etc.) into the same clean bucket and mix
6. Scoop into designated bag and tin
    1. Fill bag approximately halfway
    2. Fill tin to the top
7. Repeat for each sample set

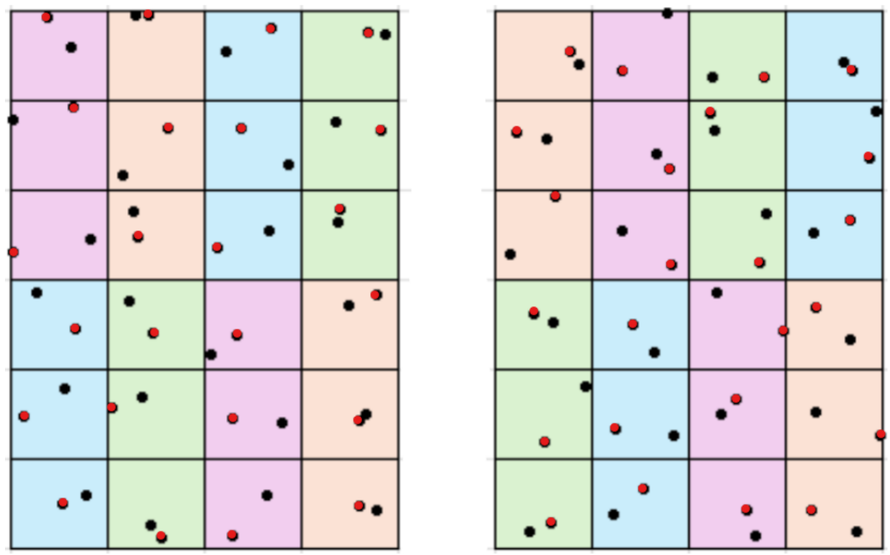

**Figure A2**: Random sampling locations of the 4-inch (left) and 8-inch (right) beds, generated by ChatGPT. Black dots signify the first sampling locations, red dots signify the duplicate sampling locations.