Title
Influence of Sedum Species on Thermal Performance of Green Roofs in a Mediterranean Climate

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Influence of Sedum Species on Thermal Performance of Green Roofs in a Mediterranean Climate

A thesis submitted in partial satisfaction

of the requirements for the degree Master of Science

in Environmental Health Sciences

by

Eden Axelrad

2019

ABSTRACT OF THE THESIS

Influence of Sedum Species on

Thermal Performance of Green Roofs

in a Mediterranean Climate

by

Eden Axelrad

Master of Science in Environmental Health Sciences

University of California, Los Angeles, 2019

Professor Richard F Ambrose, Chair

The use of vegetated roofs (green roofs) is a common method for combatting the urban heat island effect and heat-related health consequences. The performance of green roofs depends on the type and composition of its various components, including plants, substrate, insulation, drainage, or other roof layers, as well as climate. While some studies have looked at vegetation's functional properties in determining thermal effects, none have occurred in Southern California. Because green roof performance is highly dependent on climate, this knowledge gap stands in the way of providing the area with optimally performing designs. This study addressed this knowledge gap by using vegetated roof simulation cells to examine the impacts of two different plant species on thermal properties of a green roof. The plants were two species in the genus *Sedum*, which is the most commonly used taxon in green roofs. Nine cells were used, where 3 cells had *Sedum acre*, 3 cells had *Sedum rubrotinctum*, and 3 cells had bare substrate only. Ambient, soil level, and interior temperatures were collected at 30-minute intervals during the study period, which lasted from March 4th until April 8th. Temperatures were compared afterwards across treatments and location. Both plant species lowered daily maximum temperatures and temperature ranges. However, *Sedum acre* was far more effective, lowering mean daily max temperatures and temperature ranges by 1.6 °C and 1.4 °C, respectively. *Sedum rubrotinctum* lowered both mean daily maximum temperatures and temperature range by 0.5 °C.

The thesis of Eden Axelrad is approved.

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2019

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Introduction

Green roofs have repeatedly shown the ability to impact thermal properties of buildings, but the role of plant species in this impact remains largely undetermined for Mediterranean climates. In order to optimally implement green roofs to combat the effects of climate change, it is imperative to understand the climate-dependent and region-specific roles of plant species. This need is especially urgent for cities in which heat related illnesses and heat related energy demands are high and on the rise. In California, minimum temperatures have been increasing since 1950 and are expected to continue rising (Bohr, 2009). As illustrated by Figure 1, average annual temperatures have exhibited similar trends in Los Angeles County since 1950 (NOAA, 2018). Figure 2 shows that average maximum temperatures in the Los Angeles region are projected to rise by 3.17 °C by the mid 21^{st} Century (2040-2069) and 4.67 °C by the late 21^{st} century (2070-2100) under RCP 8.5 (Hall, 2018). Weather extremes will be exacerbated, with more frequent occurrences of extremely hot days and big rain events (Hall, 2018).

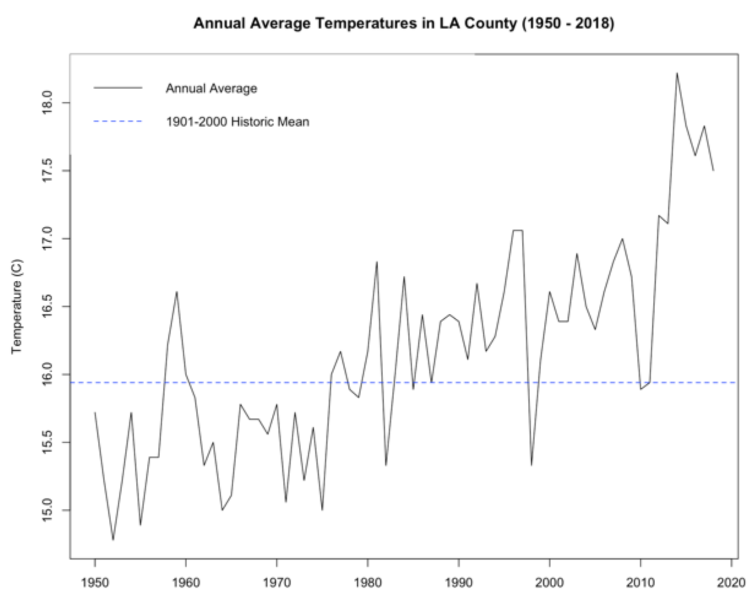


Figure 1. *Annual average temperatures in Los Angeles County from 1950 to 2018. Data source: NOAA National Centers for Environmental information, Climate at a Glance: County Time Series, published May 2019.*

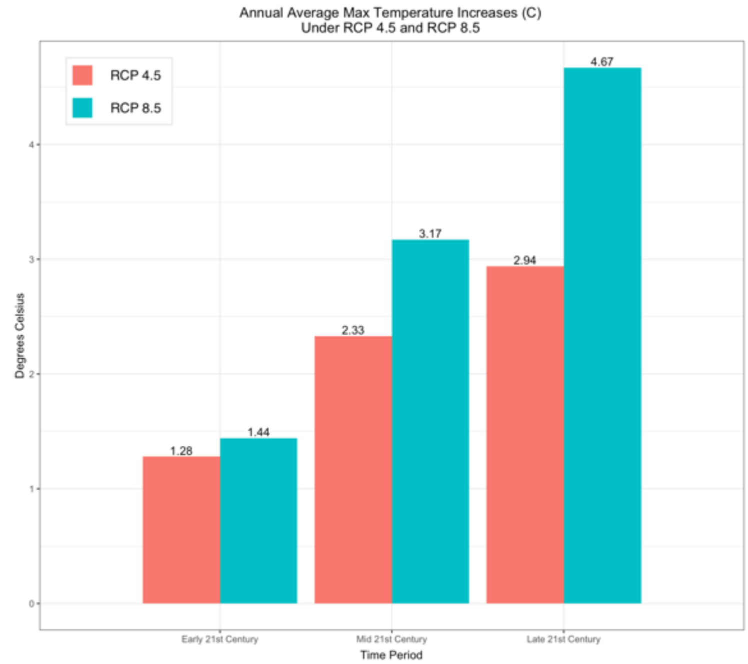


Figure 2. *Annual average maximum temperature increases under RCP 4.5 and RCP 8.5 for the Los Angeles region. Data source: California's Fourth Climate Change Assessment, Los Angeles Summary Report (Hall et al., 2018).*

To cope with heat, the human body can regulate its temperature through perspiration and vasodilation (Kilbourne, 1992). As environments and conditions change, the body will attempt to maintain an internal temperature of about 37 °C (Parsons, 2003). However, excessive heat can lead to adverse health effects, especially in vulnerable populations like the elderly (Sari and Hajat, 2008), or those with respiratory or cardiovascular diseases (Wong et al., 2013). Heat stress can lead to elevated heart rate, loss of water from sweating, and blocked sweat glands (hidromeiosis) (Parsons, 2003). Heat illnesses will occur when heat stress persists and thermoregulation is compromised or insufficient. These include heat stroke, heat syncope, heat exhaustion, heat fatigue, and heat cramps (Parsons, 2003).

When populations are exposed to extreme temperatures, heat stress is capable of leading to broader welfare and economic consequences. A review of European heat waves completed by

Kovats and Hajat (2008) showed that heat waves have substantially contributed to increases mortality rates. A particularly infamous case occurred in France in 2003, where a heat wave increased mortality rates by 60%, leading to nearly 15,000 deaths. During that same period of excessive heat, England experienced a country-wide 17% increase in mortality. The impact to the city of London was most pronounced, with an observed 42% increase in deaths (Johnson et al., 2005). During a 1995 episode in Chicago, hospital admissions increased by 11% overall, with a 31% increase for those over 65 years of age (Semenza et al., 1999). Productivity and labor supply have also been shown to suffer during hot days, eventually leading to lags in economic development (Heal and Park, 2016). Extreme heat has been linked to worse student performances on exams and general decline in cognitive functions. These impacts are most pronounced in regions where access to adaptive technology (like air conditioning) is lacking (Park, 2016).

The effects of extreme heat are further amplified in urbanized areas due to urban heat islands (UHI) - a term used to refer to the temperature disparities between urban centers and adjacent rural regions. Urban heat islands arise from concentrations of impervious surfaces and areas with little or no vegetation. Incoming solar radiation is trapped in cities where there is less evapotranspiration and shading from natural canopies. Average temperatures in large cities can be as much as 3 $_{o}$C hotter than their rural counterparts. Cities are so efficient at trapping heat that at night this temperature discrepancy can rise to more than 10 $_{o}$C (Oke, 1997).

Roofs generally make up about 25% of the urban landscape, which makes green roofs one of the more common methods for combatting the impacts of extreme heat in cities (Akbari et al., 2005). Green roofs include soil and vegetation that insulate buildings and surroundings through evapotranspiration, raised surface albedo, and shade. However, there are additional layers that are important to the overall function of the system. These include filter membranes, drainage layers, waterproofing layers, and roofing membranes. Once installed, green roofs offer many co-benefits including improved storm water runoff management, aesthetic value, noise reductions, air pollution reductions, and ecosystem benefits (Razzaghmanesh and Beecham, 2015).

There are several heat fluxes that play key roles in the energy balance of a green roof (Figure 3), including solar radiation from the sun, short wave radiation that reflects back from the green roof, long-wave radiation leaving the roof, latent heat flux, and sensible heat flux (Ouldboukhitine et al., 2011). Heat fluxes are easily influenced by the design and type green roof elements. This means that variations in soil depth, soil composition, soil water content, plant type, and plant coverage can lead to changes in energy balance. Latent heat refers to the energy required to change a substance's phase, while sensible heat refers to temperature changes within a phase. In terms of green roofs, latent heat is used to describe energy exchanges in soil evaporation and plant transpiration. Sensible heat exchanges occur via thermal conduction – where heat moves from the hotter entity to the cooler one until equilibrium is reached (Fourier's Law). In a green roof, solar radiation will heat the substrate via sensible heat transfer, raising the temperature of the soil, but providing a thermal barrier for the internal (building) space.

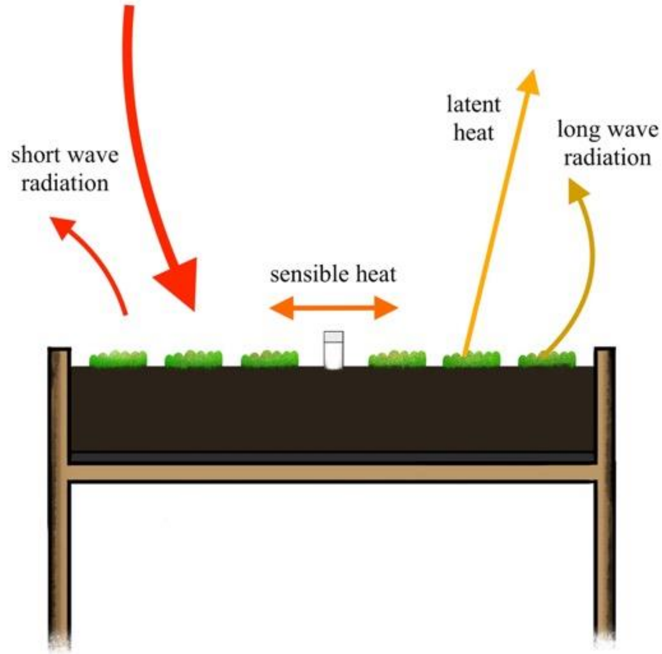


Figure 3. *Main thermal fluxes experienced by green roofs*

Vegetation and green roofs have been shown to reduce urban temperatures in various climates (Alexandri and Jones, 2008; Takebayashi and Moriyama, 2007). They appear to be most effective in hotter climates, where they can significantly reduce cooling-related energy demands during summer months, but even then, variability in the outcomes appears to be large. One study found that energy costs could drop by 32% to 100% on hot days (Susca et al., 2011). Another study completed in a Mediterranean climate found that cooling related energy use could drop by up to 48% for comprehensive applications of green roofs (Niachou, 2001). Similarly, Spala et al. (2008) used simulations to estimate the impact of green roofs on cooling related energy use in an Athens office building. The authors suggested that the building could reduce those energy demands by up to 39%. A study in France used a residential home to examine the thermal impacts of a *Sedum* green roof under various conditions. During summer months, indoor air temperatures below the green roof were found to be 2 °C cooler than the standard roof slab. This corresponded to a 6% reduction in energy use throughout the year. The authors concluded that green roofs can make temperature changes milder and reduce maximum heat (Jaffal et al., 2011).

While cooling effects come from green roofs' ability to lower heat fluxes, they can also lower temperatures by altering the overall surface albedo and radiative forcing. In summer, daily surface temperature ranges for green roofs are estimated to be half the size of black surfaces (Susca et al., 2011). Relative humidity and wind also play crucial roles in determining the success of green roofs because of their impacts on evaporation. Morakinyo et al. (2017) found that green roofs in humid climates performed worse than those in drier climates. In drier climates, increases in soil moisture resulted in larger internal temperature reductions. Because of this, substrate alone can make an impact on thermal properties of buildings. For Bowler et al. (2010), heat gained by a conventional roof was 4.23 times larger than a green roof with substrate and no vegetation.

Despite the level of support for green roofs in scientific publications, there remain incongruities among experimental studies. Eksi et al. (2017) points out that there is disagreement regarding the importance of factors such as plant type, plant cover, and substrate depth. Comparisons between extensive and intensive roof systems tend to show more defined differences, but even then, attributing results to a singular element has proven difficult. This is evidenced by the findings in their experimental study which was completed in Michigan, where extensive *Sedum* green roofs and intensive herbaceous green roofs had different interactions with ambient weather and yielded distinct impacts on thermal properties. The *Sedum* roofs outperformed their herbaceous counterparts in summer months and had more pronounced temperature fluctuations. The intensive herbaceous treatment was more effective in reducing energy demands in winter. However, Eksi et al. (2017) could not definitively say whether plant type or substrate depth was the main influencer. The authors also point out that these results are climate and region dependent, concluding that a similar study in the southern portion of the United States could yield other findings.

It is safe to say that green roofs can impact thermal properties of buildings, but the role of plant species in a Los Angeles climate is still undetermined. The Environmental Affairs Department for the City of Los Angeles released a green roof resource guide in which they stated that "although there is a substantial amount of guidance available on plant selection for green roofs, little of it is directly applicable to climatic conditions in Los Angeles" (LA County Environmental Affairs Department, 2007). They added that "information on the performance of specific species is not currently available for Los Angeles". Similarly, Schweitzer and Erell (2014) completed a green roof study in Israel after which they concluded that "there are many barriers to the implementation of [green] roofs in Israel and other Mediterranean countries with year round or seasonal hot, dry climates". The authors added that further research is required for these types of environments. A more recent study describes the ongoing issue by commenting that "plants are mostly selected for their survival potential and not for their ability to provide valuable ecosystem services. In essence, many existing green roofs could be underperforming with regards to insulating against incoming solar radiation, and reducing air temperatures around buildings" (Vaz Monteiro et al., 2017).

While some research on plant species and thermal impacts is beginning to surface, existing studies mostly utilize simulation models or have taken place in temperate, sub-tropical or tropical climates and cannot be extended to Los Angeles (Vaz Monteiro et al., 2017; Zhao et al., 2014; Jim et al., 2012; Liu et al., 2012). These unknowns stand in the way of optimizing green roofs' ability to reduce heat demands, urban heat islands, and heat related health impacts in the area. Los Angeles is currently lagging behind other big cities in terms of green roof coverage, legislation, and incentive programs. The uncertainty around thermal benefits could be a contributing reason. Additionally, Los Angeles is subject to harsher climatic hazards and the number of people exposed to these hazards is extremely high. The western portion of the contiguous United States has experienced greater temperature rises than the global average (Spencer et al., 2008), and Los Angeles County is also the most populous County in the United States. This further justifies the need for addressing existing knowledge gaps in green roof systems for the region.

This study aimed to shed light on the role of vegetation in green roof thermal performance in a Los Angeles climate. The study looked at variability across two different succulents, *Sedum rubrotinctum* and *Sedum acre*, in green roof simulation cells. Succulents, and in particular those in the *Sedum* genus, are one of the most commonly used taxa in green roofs. They have been shown to possess the best characteristics for cooling – such as higher albedo, thicker leaves, and larger coverage (Schindler et al., 2019). They are also able to store water, tolerate heat, and survive extended periods of time with little or no precipitation (Getter and Rowe, 2008). *Sedum rubrotinctum* has survived in a greenhouse for 2 years without water and *Sedum acre* has survived up to 88 days without water (Teeri et al., 1986; VanWoert et al., 2005). Additionally, a recent study completed in Israel identified *Sedum* species as ideal green roof plants for a Mediterranean climate (Schindler et al., 2019). The authors compared typical roofs, *Sedum* green roofs, and green roofs with both *Sedum* and annual plants. Results indicated that in summer months, green roofs with only *Sedum* species provided the largest reduction in interior temperatures. However, critical knowledge gaps remain. Is there variability in the thermal performances of green roofs across different *Sedum* species? If so, which one would be ideal for a Los Angeles climate? This study utilizes green roof cells in to address these knowledge gaps and test the hypothesis that thermal performance will in fact vary across *Sedum* species.

Materials and Methods

Location and Climate

The study was conducted in Los Angeles at the University of California, Los Angeles (UCLA) campus. The site was a concrete slab measuring approximately 6 meters by 9 meters. Los Angeles has a Mediterranean climate with dry summers and mild winters. The study period began on March 4th, 2019 and ended on April 8th, 2019. Typical springtime temperatures for Los Angeles are highs of 18 to 24 °C and lows of 7 to 16 °C. Average rainfall during spring months (March through May) is 25.4 cm.

The UCLA weather station was used for collecting ambient weather and meteorological conditions throughout the study. The weather station is located approximately 40 meters west of the test site on the same roof and collects data every minute. During the study period, the station recorded a maximum air temperature of 28.3 °C, minimum air temperature of 8.3 °C, and mean air temperature of 15.7 °C (Figure 4). The mean diurnal temperature range was 8.3 °C. The daily mean wind speed ranged from 0.21 to 13.33 kilometers per hour (kph) with a study period average of 7.07 kph and a max gust of 43.45 kph. It rained during 3 of the study days, accumulating a total of 3.2 centimeters of rain. The mean relative humidity for the study period was 58.12% with a maximum of 86.90% and minimum of 17.07%.

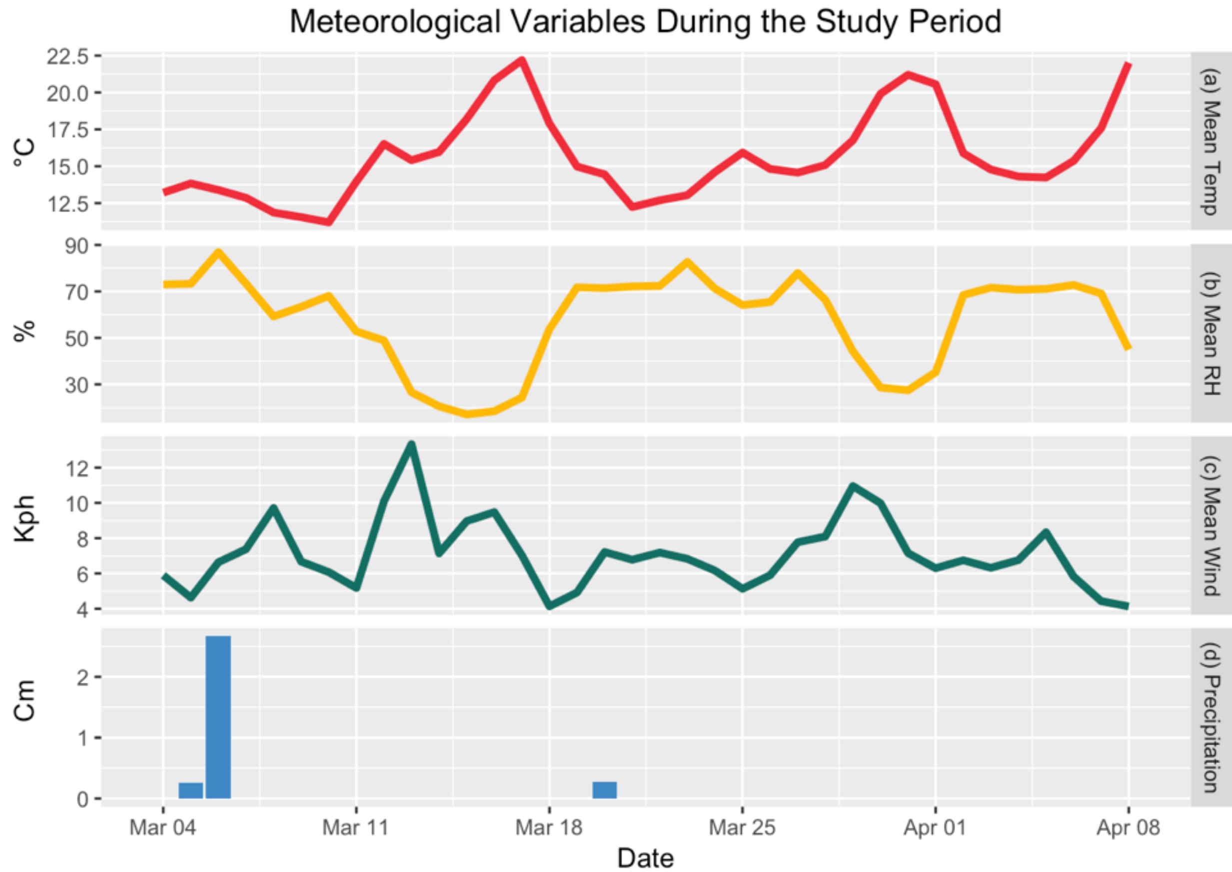


Figure 4. *Meteorological data for the study period - measured by the UCLA weather station. The panels include (a) mean daily temperature in °C, (b) mean daily relative humidity in %, (c) mean daily wind speed in Kph, and (d) precipitation in cm.*

Cell Construction

The cells were designed to replicate a generic southern California roof that has been retrofitted with an extensive green roof. They were constructed from plywood and contained an insulation layer, roofing membrane, drainage layer, root and moisture fabric, and substrate, as seen in Figures 5 and 6.

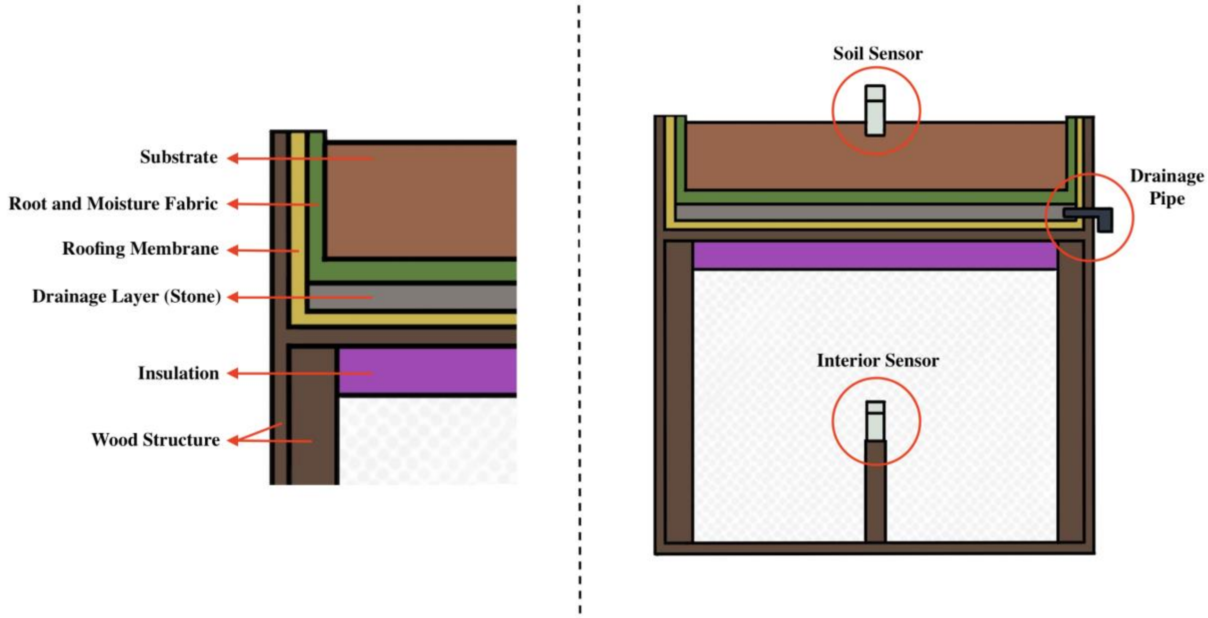


Figure 5. *Schematic of test cell showing a cross-section and detailed view of all layers. From top to bottom they are: substrate, root and moisture fabric, drainage stone, roofing membrane, plywood, and insulation.*

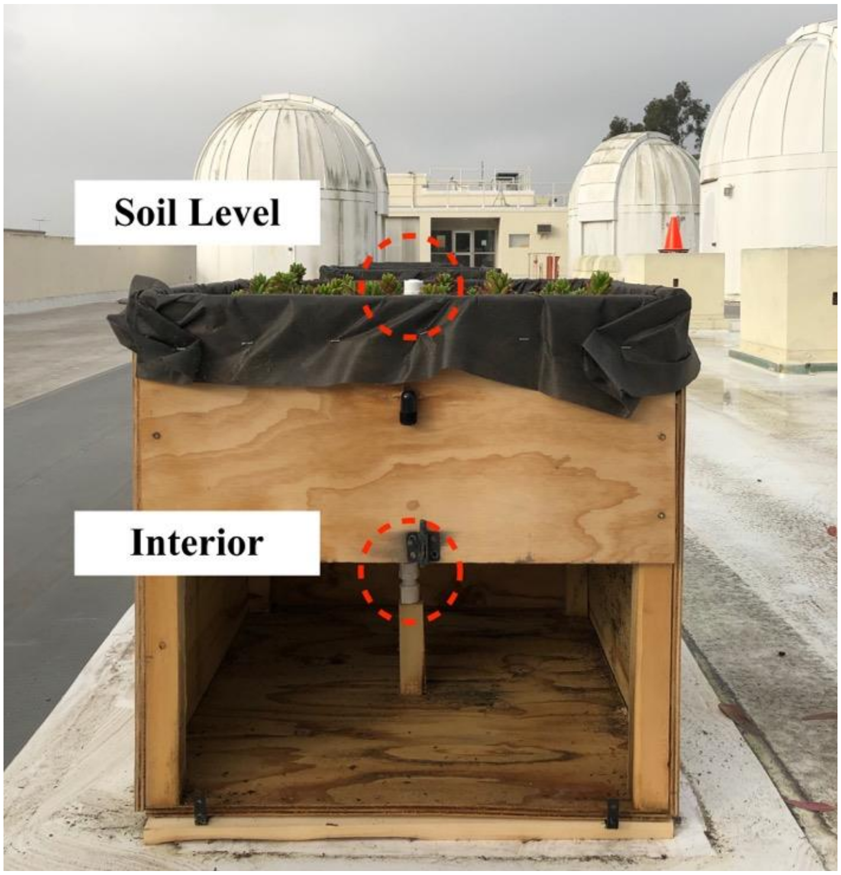


Figure 6. *A test cell with the access panel removed. Soil level sensor and interior sensor are highlighted.*

Each cell measures 61cm wide, 61cm tall, and 61 cm long. The wood structure of the green roof test cells was constructed using 1.27cm thick plywood panels and four wooden posts. The panels and posts were assembled using exterior wood screws. A 15cm space was created at the top of each cell for the green roof layers, including soil and vegetation. A 15cm post was secured to the center of the cell's floor as a mounting spot for the interior sensor. Each cell has one side panel that served as an access point for the sensor and was constructed with two 61cm x 30.5cm pieces of plywood. To construct the access panel, one of the 61cm x 30.5cm pieces was secured to the top portion of the cell in order to finish off the planter box depression. The bottom piece was then locked in place with two L-brackets and a window lock. This made it possible to access the interior sensor without compromising the integrity of the soil and vegetation. A roof sealant was also used during the main construction of the cell in order to seal every gap and joint.

Once the wood structure of the cell was completed, a staple gun was used to add the insulation to the underside of the top plywood panel. The insulation was 8.89 cm thick with an R-13 insulation rating. R-13 insulation is recommended for residential and non-residential buildings in Southern California (ASHRAE 90.1, 2016). Roofing membrane, consisting of asphalt underlayment and an adhesive waterproof flashing membrane (FortiFlash), was added to the top planter box portion of the cell . This membrane acted as the main waterproofing layer.

To provide adequate water drainage for each cell, a 90-degree PVC elbow was added at the center of the rear side panel. The end facing the interior of the cell was covered with mesh in order to avoid any blockage. After the PVC elbow was installed, a layer of stone approximately 2.5 cm deep was added on top of the roofing membrane. The drainage pipe was completely covered by the drainage stone layer. A layer of root and moisture fabric was added on top of the drainage stone, and substrate was added over it. The commercial planting substrate used for this project was an organic soil composed of pumice, sand, bark fines, recycled forest products, dehydrated poultry manure, and hydrolyzed feather meal. This substrate was used because it is specifically designed for succulents and cacti. Approximately 12 cm of soil were added to the top of each cell. Finally, in order to weatherproof the cell, a minimum of three coats of a weatherproofing urethane spray were added to each exterior panel of the green roof cell. This provided protection from UV rays and moisture.

Experimental Setup and Data Collection

Two different temperature loggers from Embedded Data Systems (EDS) were used for the study. The interior sensors recorded temperature, while the sensors that sat at the soil level recorded both temperature and relative humidity. The interior sensor has an accuracy of +/- 1.0 °C and the exterior sensor has an accuracy of +/- 0.5 °C. Sensor housing was constructed from PVC. Each sensor fit between a cap and a male adapter which protected the sensor but allowed for easy access. Interior sensors were mounted in the center of the cell compartment at a height of 18cm off the bottom of the cell. Substrate sensors were placed in the center of the cell at soil level (Figure 6). The data loggers collected temperature (and relative humidity at soil level) every 30 minutes, which resulted in 1,680 records per logger over the study period. This interval of data collection provides reasonable temporal resolution, consistent with Schindler et al. (2019).

Nine cells were constructed with identical structure and substrate. Three cells were planted with *Sedum rubrotinctum* (treatment 1, cells 1 – 3), three were planted with *Sedum acre* (treatment 2, cells 4 – 6), and three control cells had no vegetation and only substrate/soil (cells 7 – 9). The treatment and location of each cell is shown in Figure 7, with pictures of each treatment in Figure 8. The cells were evenly spaced from each other and far enough away from the roof edge and each other to avoid shadow interference. *Sedum rubrotinctum* (commonly known as jelly bean or pork and beans) does well in full sun and drought conditions, grows quickly, and is easily propagated. It can reach heights of 10 to 18 cm and blooms in spring. The leaves are fleshy with coloring ranging from green to red. *Sedum acre* (commonly known as gold moss or stonecrop) is a perennial plant that flowers in June or July. It is a fast-growing ground cover with yellow to greenish color. It can grow to a height of 5 to 10 cm and does well in full sunlight conditions. Both plant species were potted in fairly high density to ensure adequate coverage before data collection. The plants were grown in even rows with approximately 4 cm of spacing between them. The vegetation was given several weeks to establish and grow before data collection began. The data collection period began on March 4, 2019 and lasted until April 8, 2019 for a total of 36 days.

Cell Number	Treatment
1	Sedum rubrotinctum
2	Sedum rubrotinctum
3	Sedum rubrotinctum
4	Sedum acre
5	Sedum acre
6	Sedum acre
7	Bare Substrate
8	Bare Substrate
9	Bare Substrate

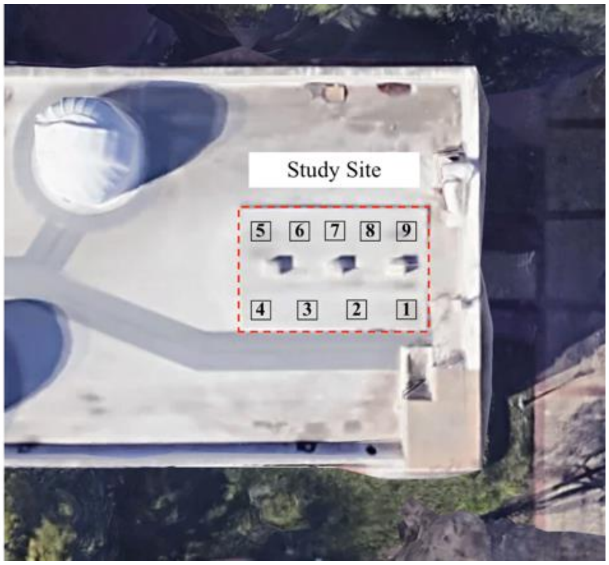


Figure 7. *Location and treatment type of each cell*

Figure 8. *Pictures of cells from each treatment group in the study*

Analysis

Analysis for this study was completed using the programming language R, with R Studio. Two sets of data were used to analyze the temperature by treatment. The first data set utilized a raw version of all obtained sensor records, while the second used treatment averages for each sample. The averaged data was created by taking the mean of each treatment group at each temperature recording. The averaged data were taken for *Sedum rubrotinctum*, *Sedum acre*, and bare substrate temperatures. Additional comparisons of plant species were completed using a "difference score" - generated by subtracting bare substrate from treatment temperatures at each sensor recording, using the averaged data. The difference score allows the results to focus on the influence of plant species by controlling for ambient weather like temperature, wind, and humidity. Difference scores were plotted both over the study period and by hour for *Sedum rubrotinctum* and *Sedum acre.* These plots were created to identify patterns over the entire study period and also over each day. Temperatures for each treatment were analyzed by time of day and also at specific day times through-out the study period. This was completed in order to examine periods in which peak differences occurred. Daily temperature ranges and max daily temperatures were also analyzed. Linear models for treatment against bare soil and loess regressions for difference score against bare soil were also used to examine relationships.

Ambient weather data obtained from the UCLA weather station was trimmed down to the study period. A subset was used by selecting only ambient readings that matched sensor timestamps.

Results

Temperature for the interior sensor was plotted over the study period for each treatment using the averaged data in order to assess differences between treatments (Figure 9). Each treatment shows regular diurnal fluctuations, but the differences between treatments appears most noticeable during daily peaks in hot periods. For example, on March 17th and March 31st, *Sedum acre* was over 2 ºC cooler than bare substrate. Results for interior sensor temperature differences are shown in Figure 10, where zero (no difference) is shown by the blue line and the mean difference is depicted by a red dashed line.

For both *Sedum rubrotinctum* and *Sedum acre*, most readings were close to the mean difference but there were many readings that were far from the mean. These excursions were both positive and negative, with a regular pattern. To understand the basis for this pattern, the difference scores were plotted by hour instead of sample (Figure 11). The plots revealed a pattern in which cells with plants had higher temperatures during the colder morning hours, and lower temperatures during the warm late morning to early evening period.

Positive peak differences occurred at 8:00 AM for both treatments, where *Sedum rubrotinctum* and *Sedum acre* were on average hotter than the bare substrate by 1.4 ºC and 1.2 ºC, respectively. It was surprising to find that treatment groups with plants were warmer in the morning, so the observation was further explored by filtering the data to show only morning hours (7:00 AM to 9:00 AM) and overlaying ambient temperatures on top (Figure 12). The plots revealed that differences were greater when ambient temperatures were higher. This effect was most pronounced between March 12th and March 18th when ambient temperatures were highest and relative humidity was lowest for the study period.

Negative peaks for *Sedum rubrotinctum* occurred at 1:00 PM where it was 0.6 ºC cooler than bare substrate (Figure 11). For *Sedum acre* the negative peak occurred at 3:00 PM where the interior sensor was on average 2.0 ºC cooler than the bare substrate. Throughout the study period, 36.6% of *Sedum rubrotinctum* samples were cooler than bare substrate, with 30.2% being hotter and 33.2% being equal. In contrast, 80.6% of *Sedum acre* observations were cooler than bare substrate, with 10.8% being hotter and 8.6% being equal.

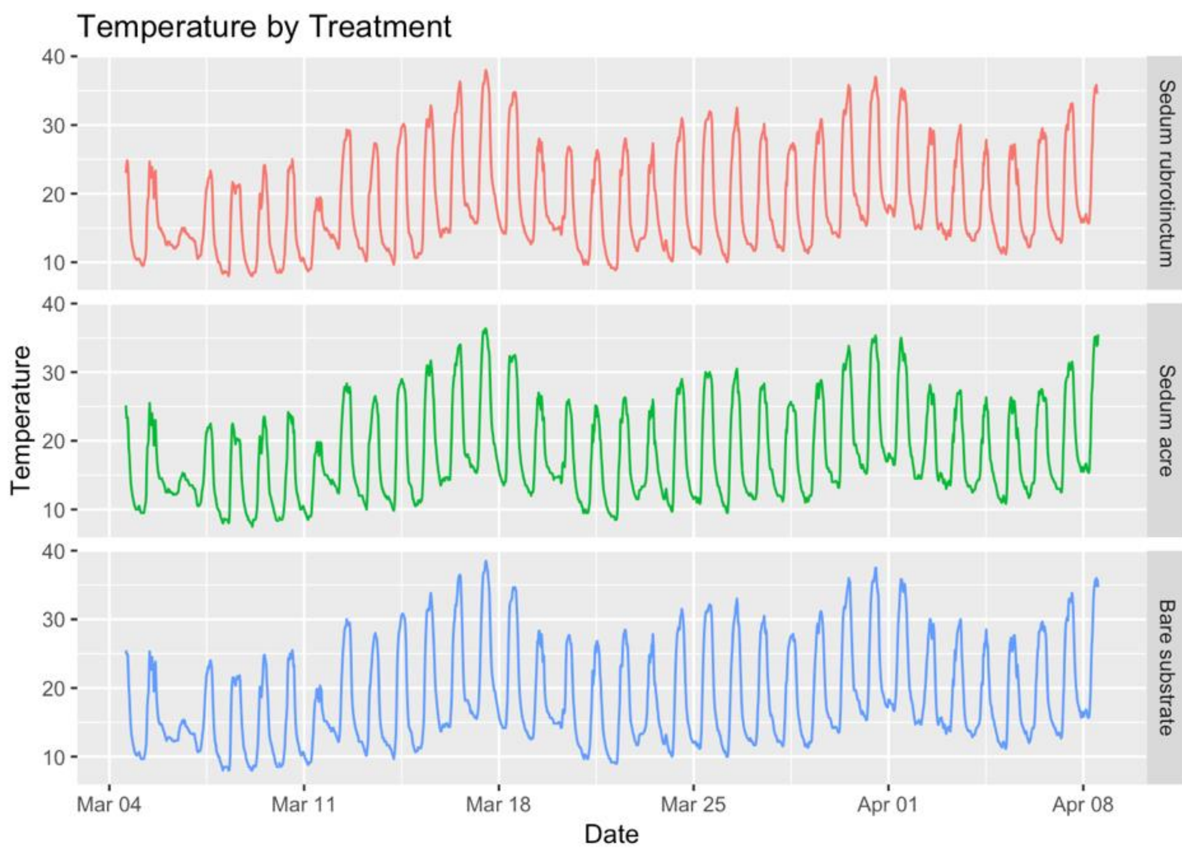


Figure 9. *Temperature by treatment plotted over the study period*

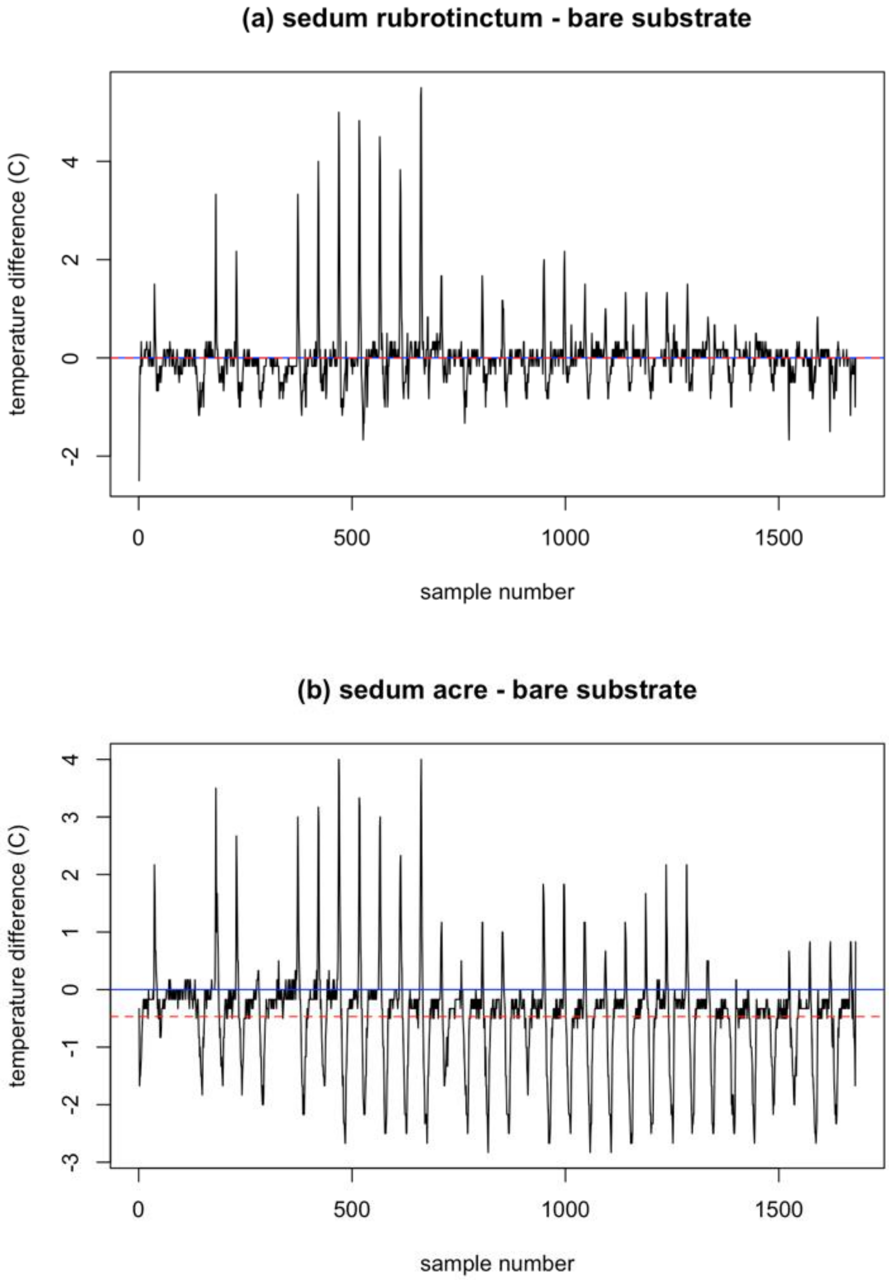
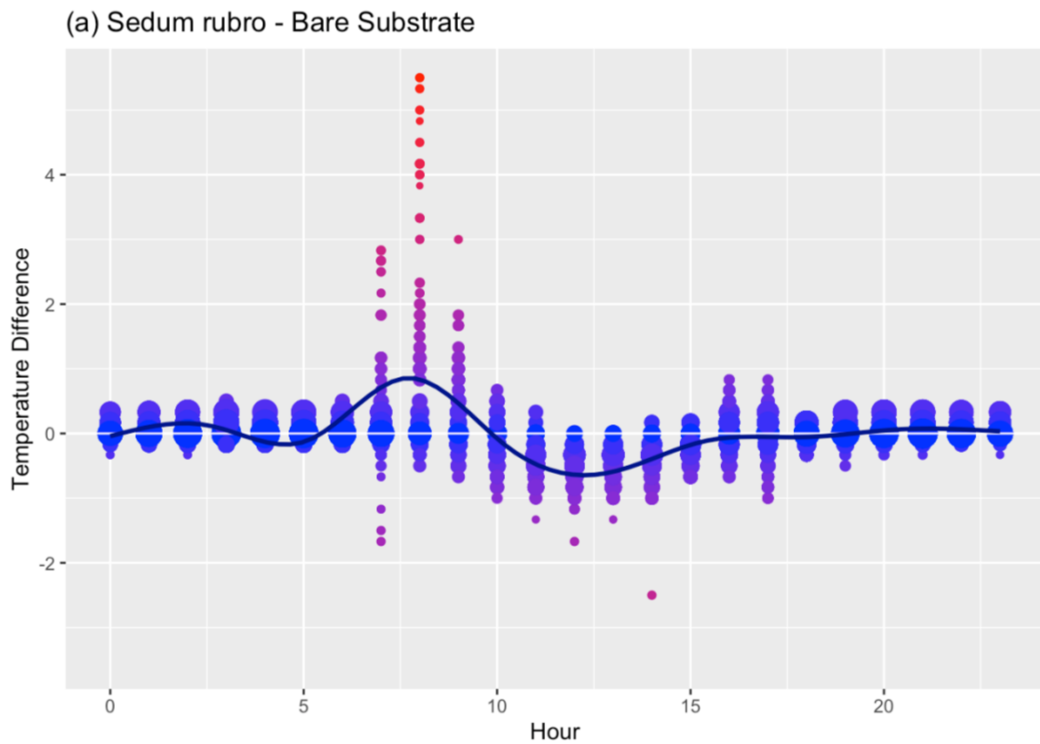


Figure 10. *Temperature difference between Sedum species and bare substrate. (a) Sedum rubrotinctum. (b) Sedum acre. Each point represents the difference between the Sedum species and the bare substrate. Zero (no difference) is depicted by the solid blue line and the mean difference is shown with a dashed red line.*



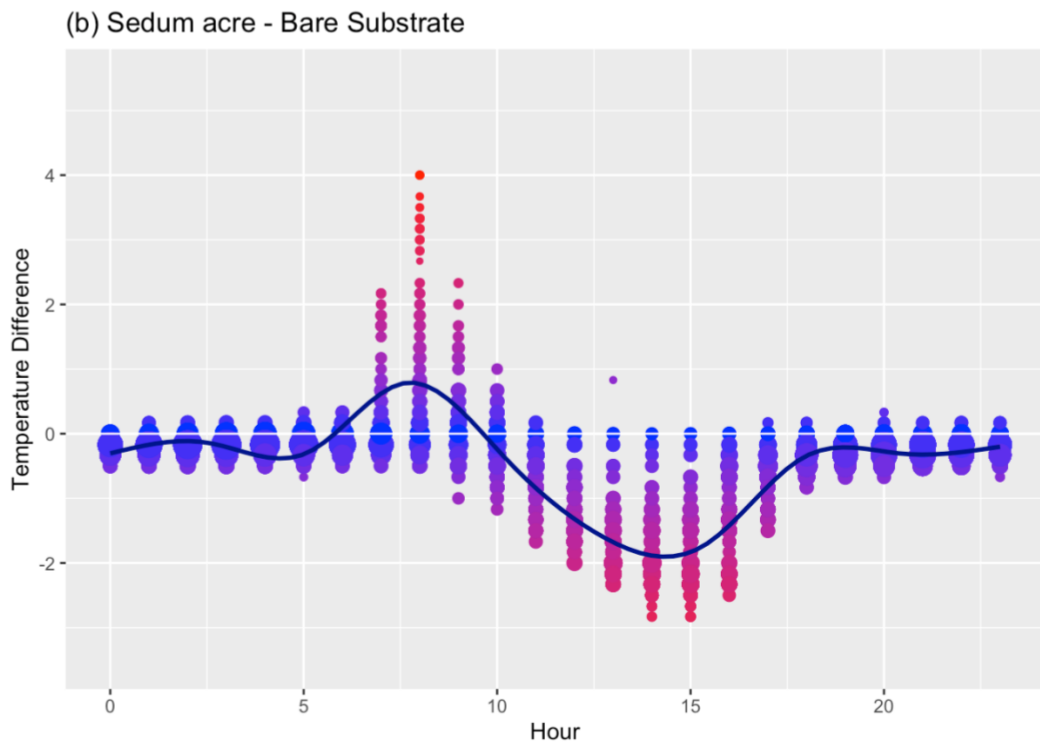
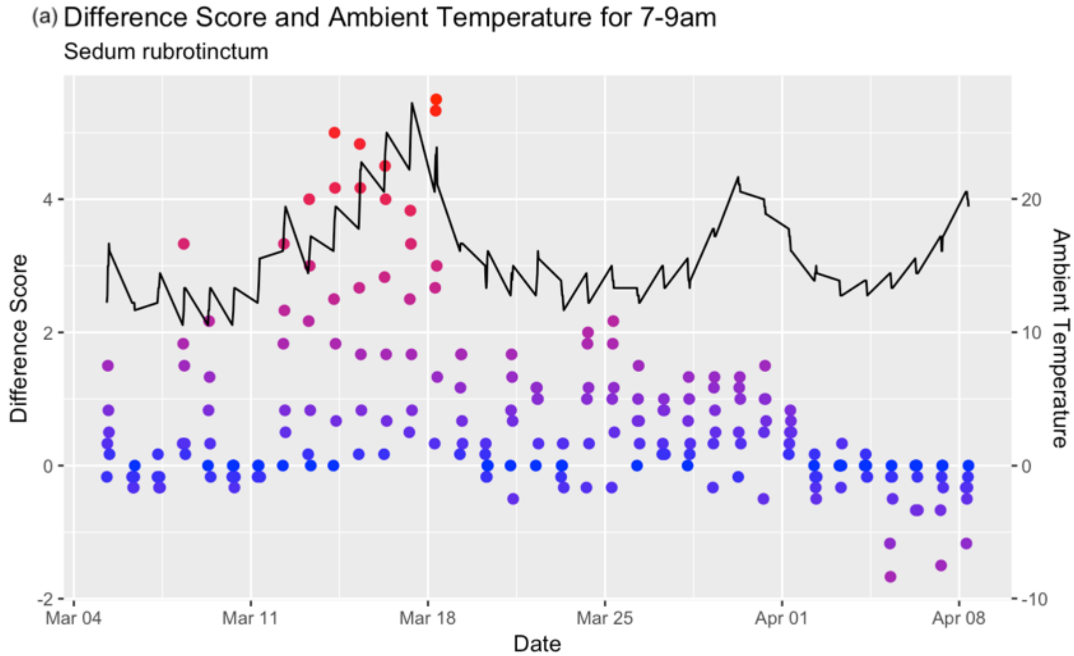


Figure 11. *Temperature differences between Sedum species and bare substrate plotted by hour of day. (a) Sedum rubrotinctum. (b) Sedum acre. The size of each point depicts the frequency of occurrence (or density) and the color shows degree of difference. A dark blue trendline illustrates the predicted linear model.*



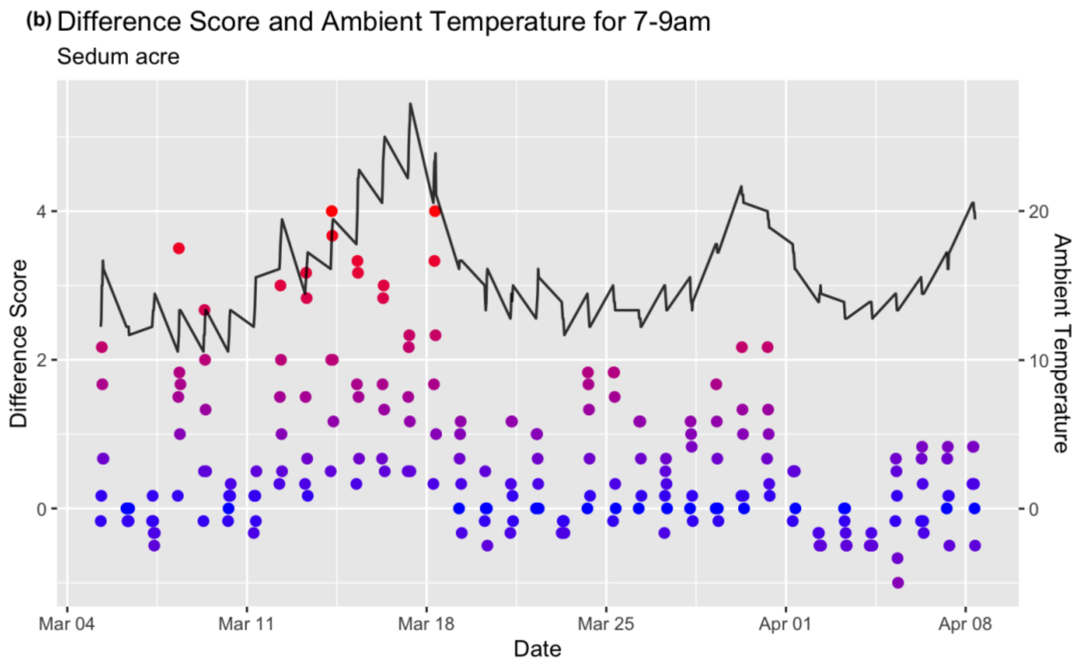


Figure 12. *Difference score filtered for morning period (7-9am) for Sedum species with ambient temperature overlaid on top (shown with a black line). (a) Sedum rubrotinctum. (b) Sedum acre.*

Hourly temperature averages by treatment were plotted in Figure 13. Max daily temperature was reached at 1:00 PM for all treatment groups, and minimum daily temperatures were reached at 5:00 AM for all treatment groups. Differences in temperature among treatment groups at 5:00 AM were relatively smaller, with larger differences occurring around maximum daily temperature.

Both treatment groups had lower max temperatures in over 90% of the study days when compared to the bare soil. Average maximum daily temperature for *Sedum rubrotinctum* was 29.1 ºC, *Sedum acre* was 28.0 ºC, and bare substrate was 29.6 ºC. Both treatment groups were found to be significantly different than bare soil (at the $\alpha = 0.05$ level), but *Sedum acre* exhibited a much larger reduction of 1.6 ºC compared to the 0.5 ºC reduction of *Sedum rubrotinctum*. Maximum temperature reached during the entire study period was 38.0 ºC for *Sedum rubrotinctum*, 36.3 ºC for *Sedum acre*, and 38.5 ºC for bare substrate. *Sedum rubrotinctum* and *Sedum acre* had lower minimum temperatures in over 13.8% and 88.9% of the study days when compared to the bare soil, respectively. Average minimum daily temperature was 11.6 ºC for *Sedum rubrotinctum* and 11.3 ºC for *Sedum acre*. Only *Sedum acre* was found to be significantly different than bare soil (at the $\alpha = 0.05$ level).

Daily temperature ranges (DTR) were calculated for each treatment group and plotted over the study period (Figure 14). Average DTR for *Sedum rubrotinctum* was 17.5 ºC, *Sedum acre* was 16.6 ºC, and bare substrate was 18.0 ºC. Both treatment groups were found to be significantly different than bare soil at the $\alpha = 0.05$ level. Compared to the bare substrate, *Sedum acre* was able to lower average DTR by 1.4 ºC during the study period.

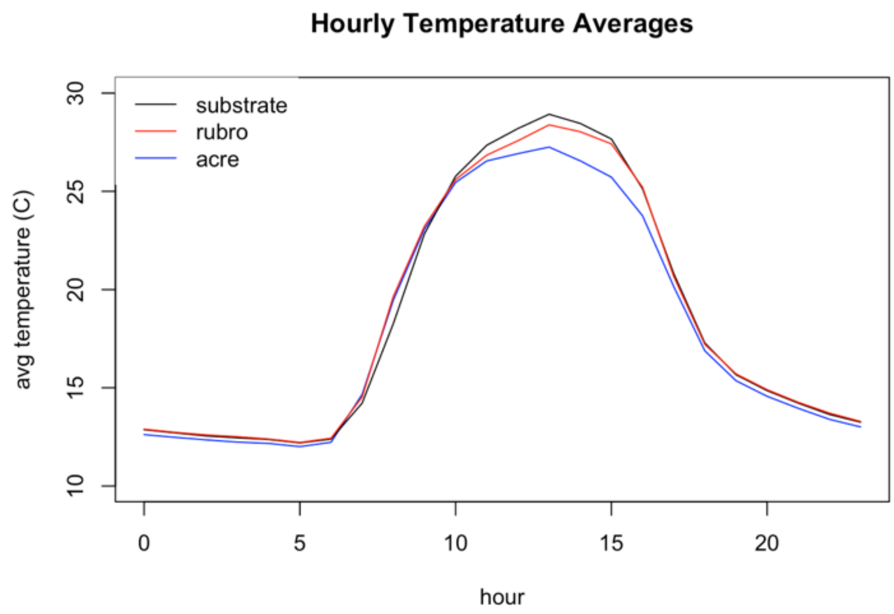


Figure 13. *Averaged hourly temperatures for all treatment groups plotted over the study period*

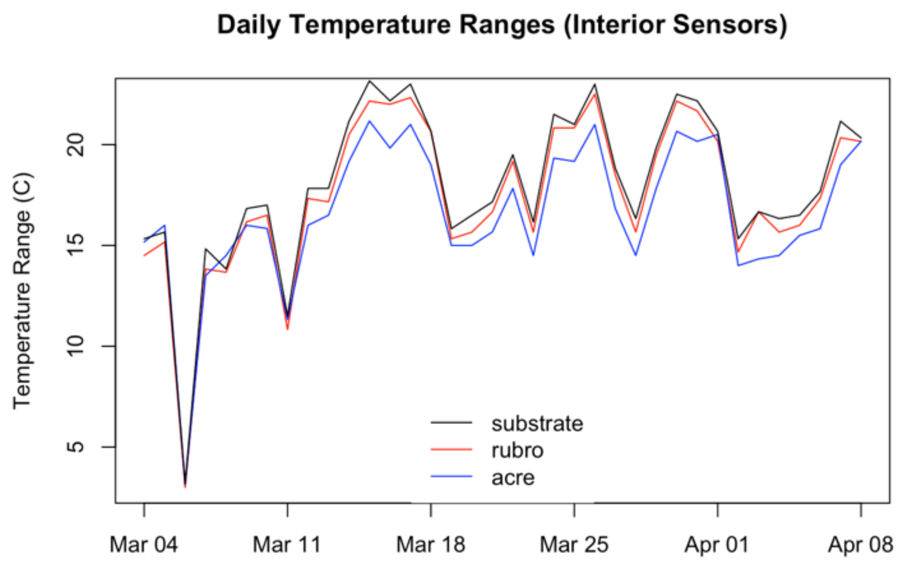


Figure 14. *Daily (diurnal) temperature ranges for all treatment groups plotted over the study period*

Linear models were created by regressing treatments against bare substrate (Figure 15) in order to examine degree and direction of treatment effects. A trendline with a slope (coefficient) farther away from 1 shows greater treatment effects. The linear model for *Sedum rubrotinctum* has an intercept of -0.22, coefficient of 1.01 and a standard error of 0.002. The linear model for *Sedum acre* has an intercept of -0.65, coefficient of 1.06 and a standard error of 0.003. These models suggest that the influence of *Sedum acre* on temperature is greater, and that it provides a larger temperature reduction compared to the other treatment. Temperature differences were regressed against bare substrate using a loess method (Figure 16). The loess regressions for both treatments indicate increased effects after 20 ºC; however, it is much stronger for *Sedum acre*.

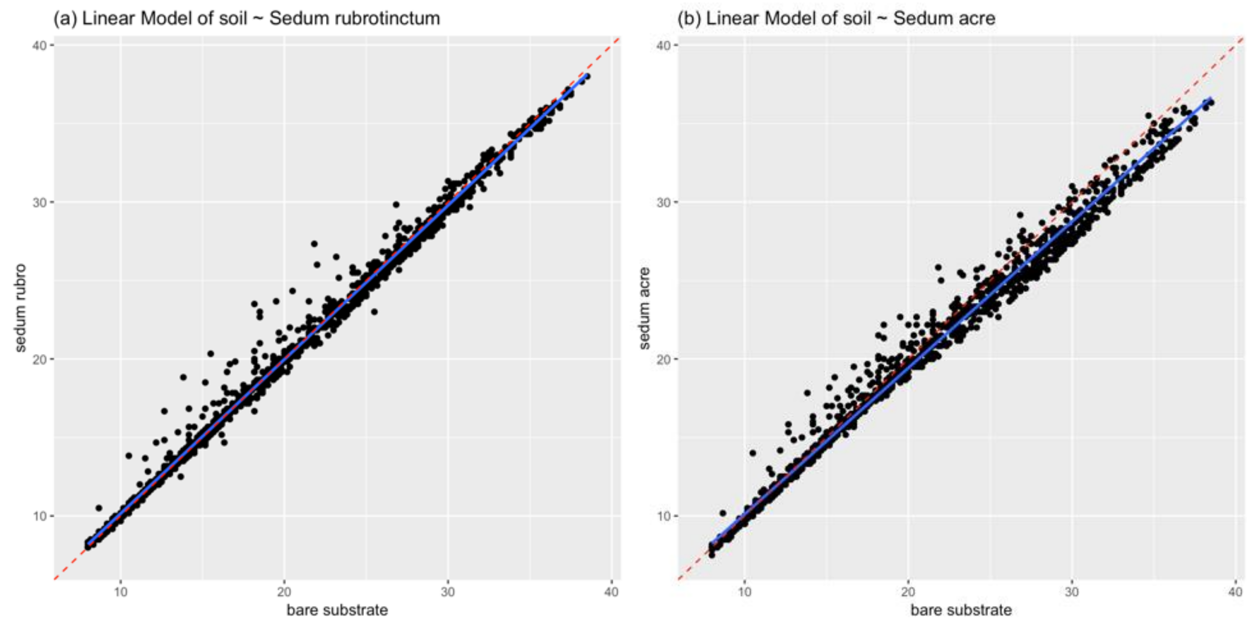


Figure 15. *Linear regression of Sedum species temperature and bare substrate temperatures. (a) Sedum rubrotinctum. (b) Sedum acre. The blue line represents the fitted linear model, and the dashed red line is a reference for a slope of 1*

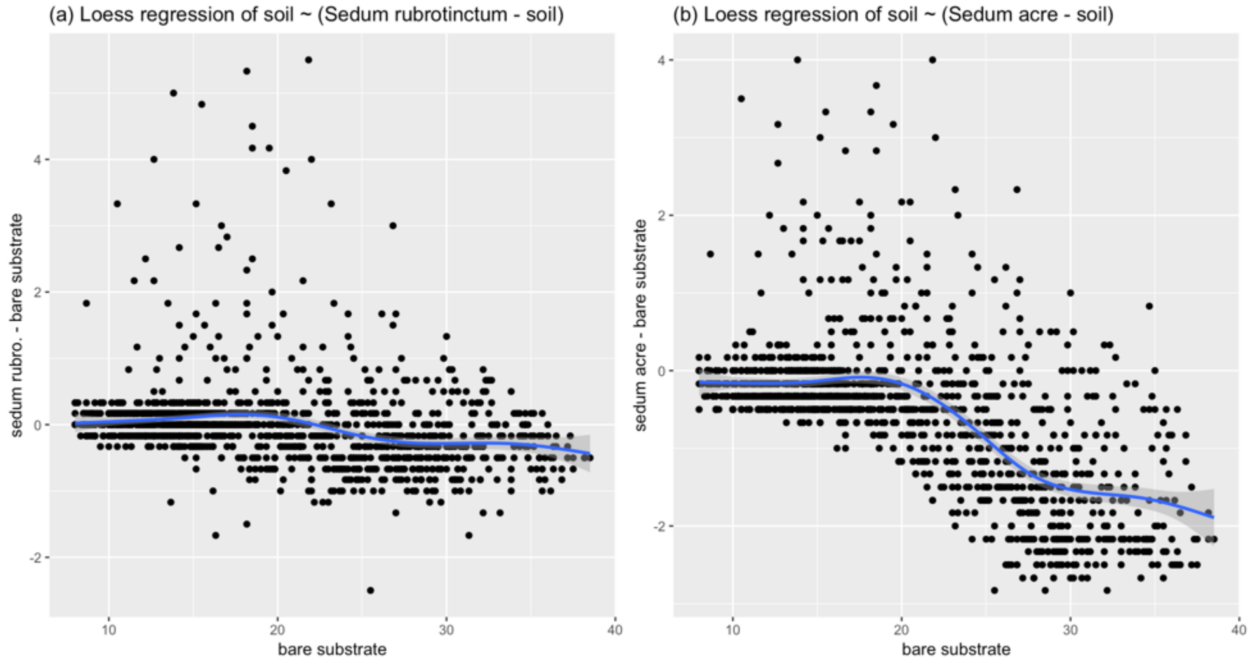


Figure 16. *Loess regression of bare substrate against difference score for Sedum species. (a) Sedum rubrotinctum. (b) Sedum acre. The blue line represents the fitted model, with surrounding gray area showing the standard error.*

Discussion

In this study, both plant species were able to achieve significant reductions in the interior sensor's daily temperature range and maximum temperatures compared to bare substrate. However, there were varying levels of insulation and cooling achieved by the different plant species – even within the same genus. Overall, *Sedum acre* was more effective at reducing temperatures in comparison to the bare substrate cells, which in turn led to significantly smaller diurnal temperature ranges and max temperatures. The findings show that plant selection plays a critical role in the thermal performance of green roofs in Mediterranean climates. They also allow cities like Los Angeles to implement informed, evidence-based green roof legislation and incentive programs – effectively mitigating many of the regions' most dire climate driven issues.

The difference in albedo and reflectivity properties of the plants could have contributed to the observed outcomes. This conclusion is reached because of the significant difference in spectral reflectivity among the two studied species, and because of the observed pattern of temperature differences by hour. The albedo score for *Sedum acre* is 0.26, which was the highest albedo score among the 21 species tested by Lundholm et al. (2015). *Sedum rubrotinctum* is assumed to have a much lower albedo score. The color profile of *Sedum rubrotinctum* changes under certain conditions, like full sun and low water. The tips of the succulent leaves turn reddish in hue during these types of stresses – which were observed during the study period. This change may lead to a drop in reflectivity or albedo of the plant. No known albedo or reflectivity score was identified for this specific species, but similar species have been shown to have reflectivity scores somewhere in the 0.10 to 0.18 range (Lundholm et al., 2015; Zhao et al., 2014). *Sedum spurium*, a succulent commonly referred to as "red carpet", was found to have a solar reflectivity score of 0.14 (Zhao et al., 2014). Furthermore, Zhao et al. (2014) concluded that reflectivity was the main driver for reducing net radiation gained by green roofs in their simulated model study. They found that there was an average of 20% difference in net radiation gained between the species with the highest and lowest reflectivity. The authors also found that there was no difference in net radiation gained during the night time. This is consistent with the temperature by hour trends observed in this study. However, they found that plant species only had a significant impact on net radiation in mixed and/or cool climates, but not warm or hot climates. Since Los Angeles is located in a warm climate, the findings in this study appear to contradict those found in Zhao et al. (2014).

Because solar reflectivity has been hypothesized to be an important factor in a plant's ability to reduce interior temperatures, plant coverage could have played a role in the observed results. There was about 50% plant coverage by the start of the study period. A higher planting density or longer growth period may have yielded more prominent results. Yaghoobian and Srebric (2015) show that increasing plant coverage reduces substrate temperatures and energy demands. They found that the difference in solar radiation received by the substrate between no vegetation and full vegetation coverage can be around 32%. However, the authors also wrote that soil and plant albedo in their study were 0.12 and 0.11, respectively. This suggests that differences could be even larger for vegetation with higher reflectivity.

Data for this study was collected in spring. Although spring temperatures in Los Angeles can be quite warm, summer is undoubtedly the time period of most interest when discussing heat related adaptation measures. Summer temperatures in Los Angeles typically reach 28 ºC while the average max temperature in March is around 21 ºC. Data analyzed in this study depict a positive correlation between day time interior temperatures and temperature reductions. Given this trend, temperature reductions could be even larger during summer months. However, additional data will need to be collected during summer to see if this speculation is true.

Testing cells provide valuable insight into the relationships between green roof design and outcome effects, but how these effects translate to real buildings is complex and largely undetermined. A study completed in Pomona, California by Pablo La Roche (2009) used green roof testing cells to measure differences between insulated green roofs, non-insulated green roofs and conventional roofs. The cells were slightly larger and contained a window, but otherwise utilized very similar construction to the ones presented in this paper. La Roche followed up his test cell study by measuring the effects of a green roof on an actual building located in Tijuana, Mexico. The author compared predicted interior temperatures to the recorded temperatures and found that the model was very accurate (within 2.2%) during cloudy days. However, during sunny days the difference ratio grew to over 21%. He hypothesized that this discrepancy could arise from various differences in variables such as surface to volume ratio, window size and orientation, and wall construction. It is also important to note that the locations of the test cells and real building were not the same, and that the follow-up study consisted of only six days. Schweitzer and Erell (2014) also utilized similarly constructed green roof testing cells for their study. The only major difference was the addition of water bottles to the inside of the cell in order to better mimic the thermal behavior of larger spaces. The authors concluded that results gained from testing cells are suggestive but not directly translatable to actual buildings.

This study confirms that green roof plants should be selected based on their functional abilities, and that significant thermal differences exist even within the same genus and life form. This information is vital for a city like Los Angeles that suffers from extreme heat, air pollution, urban sprawl, and water quality issues. The performance of green roofs can have a profound impact on human health and energy demands in the region, and these findings help Los Angeles move passed existing implementation barriers. Currently, southern California is far behind other states and countries when it comes to green roof coverage, legislation, and incentivization. For a city that desires to set precedent in terms of climate action, green roofs must be utilized.

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