ASSESSING THE THERMAL PERFORMANCE OF GREEN ROOFS AND THE INFLUENCE OF SOLAR PANELS

by

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Bachelor of Science
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DEDICATION

This is dedicated to my friends and family who have graciously dedicated their time, labor, and moral support to the construction and launch of this research installation.

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I would like to thank the many friends, relatives, and supporters who have made this happen. My advisor, Dr. Houser, for helping with the conception and construction of the installation and advising me through my course work. My professors, Dr. Dann and Dr. Maggioni, for their support and advising on various aspects of this whole process. To my colleagues, Alia Gholoom, Jeremy Johnston, Travis Richardson, and Giorgio Barchitta, for helping install, manage, and collect data from the installation. To Samantha Cooke, Geography and Geoinformation Science Department Manager, for assisting in all purchases and budget management. Special thanks to Eco Roof, LLC and Robbie Shannahan for donating the vegetated green roof products and for offering assistance throughout the planning and construction process. This project was supported by the GMU Office of Sustainability's Patriot Green Fund and the Dominion Foundation Grant for Higher Education.

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LIST OF ABBREVIATIONS

Averagely Insulated Roof TR4
Carbon Dioxide .... CO_2
Combined Sewer Overflow .... CSO
Ethylene Propylene Diene Methylene Rubber .... EPDM
Green Roof on an Averagely Insulated Roof .... GR
Mean Relative Difference .... MRD
Non-Vegetated .... NV
Oriented Strand Board .... OSB
Particulate Matter .... PM
Polyvinyl Chloride .... PVC
Poorly Insulated Roof TR0
Solar Reflectance Index .... SRI
Tukey’s Honestly Significant Difference Test .... HSD
Ultraviolet .... UV
Vegetated .... Veg
Well Insulated Roof .... TRL

ABSTRACT

ASSESSING THE THERMAL PERFORMANCE OF GREEN ROOFS AND THE INFLUENCE OF SOLAR PANELS

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Approximately 25% of city area is roof, traditionally made up of darker materials with low albedos. Cool roofs are designed to have higher albedos and range from white membranes to green roofs. Green roofs have the added benefit of mitigating stormwater, improving air quality, and insulating the building envelope. Since green roofs cost a premium over other materials, it is important to assess which type will meet the desired performance goals. Dark asphalt shingles, black and white membranes, and three depths of green roof soils were assessed for their thermal performance in terms of surface temperatures and the temperature underneath the roofing materials from March 2018-March 2019. A research green roof was installed on a parking garage at the George Mason University Fairfax, VA campus, and included replicate trials that were also outfitted with solar panels above the green roof. Temperature data revealed that green roofs (1) reduced surface temperature and below material temperatures compared to the

darker roofing materials; (2) performed similarly to a white polyvinyl chloride (PVC) membrane cool roof; (3) did not perform different thermally when depth was increased; and (4) found that vegetation presence reduces surface temperatures of green roofs but does not notably impact temperatures beneath the growing media. Regular observations and photo records revealed that solar panels promote vegetation growth for longer throughout the year, in addition to increased surface coverage and vegetation density, which has the potential to increase the performance benefits of green roofs. Due to limitations of small-scale testing and the influence of ambient air temperatures below the tested trials, future full-scale observations are recommended.

CHAPTER ONE: INTRODUCTION

1.1 Green Roof Design and Construction

Green infrastructure offers the ability to reduce the environmental impact of development in urban areas and is defined by American Rivers as "an approach to water management that protects, restores, or mimics the natural water cycle… [and is] effective, economical, and enhances community safety and quality of life." Green infrastructure as an alternative to traditional construction methods is primarily used for stormwater management by preventing and encouraging infiltration and retention of runoff. In addition, green infrastructure has shown to improve urban air quality, promote biodiversity, reduce the heat island effect, promote human mental and physical well-being, and increase property values (US EPA, 2015). There are many forms of green infrastructure, ranging from pervious sidewalks to rain

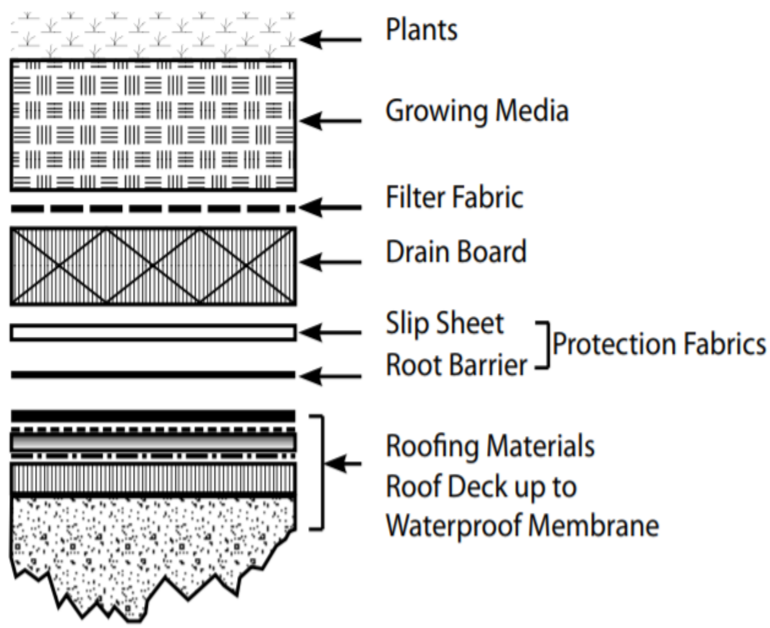


Figure 1: Depiction of the typical layers of a vegetated green roof. Retrieved from https://eco-roofs.com/eco-roofs-brochure/.

gardens, each filling a specific niche in a multifaceted approach to reduce the impact of urban development. One form, and the focus of this research, is green roofs.

Green roofs are installed on the rooftop of a structure as either a retrofit on existing buildings or included in the design and construction of new buildings in lieu of traditional building materials (Vacek et al., 2017). Green roofs are composed of a water-tight liner and root barrier, drainage layer, filter component, growing media, and a mix of extreme weather-tolerant vegetation, typically sedums (Vacek et al., 2017). Figure 1 depicts a standard cross-section of a green roof installation.

The liner holds the growing media and allows for storage of water up to a set capacity, where the excess enters the building's gutter system for discharge, facilitated by a drainage layer. Additional water storage could inundate the plants and add additional weight to the system. The growing media can be comprised of inorganic substances, such as rock wool, or include a mix of organic and inorganic substances, referred to as engineered soil (Vacek et al., 2017). Since roofs experience relatively extreme thermal and hydrological conditions, vegetation is chosen based on its ability to withstand the conditions that can be experienced on roofs. Sedums are most frequently used in green roof installations as they can tolerate more extreme heat and

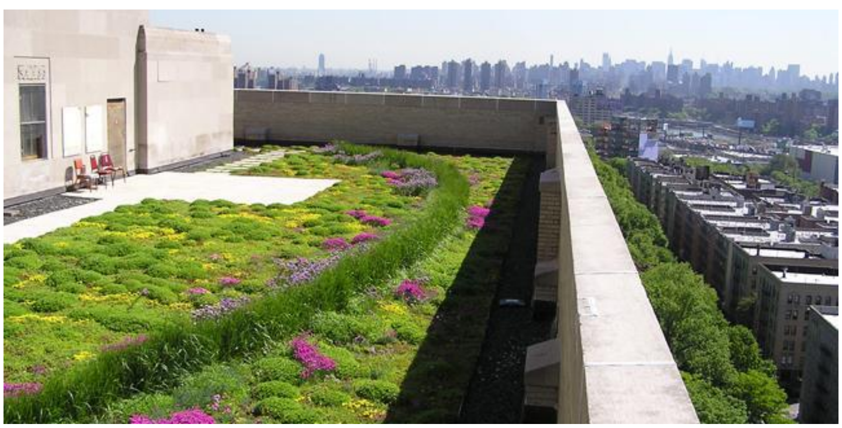


Figure 2: A typical intensive green roof with a mix of various sedum and grass species. Retrieved from https://greencitygrowers.com/blog/green-roofs-on-every-building/.

drought conditions and do not require deep substrate for below ground biomass (Durham et al., 2007). Other varieties of plants can be used but will require additional irrigation throughout the summer and potentially a deeper substrate (Snodgrass and Snodgrass, 2006).

Traditional roofing materials, such as shingles, require occasional repairs due to precipitation, rain, and ultraviolet (UV) rays. Because of this, traditional roofs often have a life expectancy of 17-30 years (General Services Administration, 2011). Retrofitting or using green roofs in the initial construction reduces maintenance and replacement frequency as the installation protects the building from the environment and has an expected life expectancy of 40 years or more (General Services Administration, 2011).

Green roofs come in a variety of types and depths, depending on the installation goals. Intensive green roofs have a depth of 6” or greater and can support trees, shrubs, and grasses (Carter and Keeler, 2008). This method generally requires irrigation and fertilization and is overall more labor and infrastructure intensive than extensive systems. Intensive installations can also experience loads greater than what most existing buildings are engineered to withstand. Intensive green roofs can be a great tool for new construction; however, these heavier systems with deeper substrate can be difficult to use as a retrofit on existing structures. The immense weight of these green roofs can, and have, resulted in catastrophic failure of structures since the full biomass and saturation weights were not taken into careful consideration. A green roof installation under construction on a market in Latvia collapsed following a storm event in 2013 due to the oversaturation and underestimation of the potential load (Yurek, 2013). Since the structure was not engineered to withstand the realized load, 54 people were killed and many more injured (Yurek, 2013).

In contrast to intensive installations, extensive green roofs generally range from 3-6" and contain sedum and grass plant varieties (Carter and Keeler, 2008). Even though these systems are unable to store and reduce as much stormwater as the intensive systems, they are more broadly utilizable as they are cheaper and can make an excellent retrofit on existing structures.

Green roofs that are 3-6" deep carry a relatively large upfront cost with a premium around $10-$13 per square foot over traditional asphalt roof installations (General Services Administration, 2011). With this in mind, it is very important to consider the depth when designing an installation. If a shallower depth can provide the desired level of performance, it may be favored over a deeper installation that is heavier and more expensive.

Green roofs offer many benefits to the building on which it is installed and to the surrounding community. Benefits can be broken into three categories: air quality, stormwater, and thermal performance.

1.2 Green Roofs-Air Quality

Green roof vegetation has shown to remove air pollutants, improving ambient air quality, through direct and indirect processes. The vegetation intakes gaseous pollutants, while also promoting dry deposition, reducing airborne particulate matter, and improving air quality (Pugh et al., 2012). Uptake of gaseous pollutants and undergoing photosynthesis sequesters Carbon Dioxide (CO_2) in the biomass of green roof plants

(Getter et al., 2009). Getter et al. quantified this effect with an extensive green roof system containing a sedum mix and found that the system stored an average of 275g of carbon per m^2 over a two-year period.

In addition to sequestering air pollutants, leaf surface area promotes dry deposition of particulate matter (PM), which primarily comes from anthropogenic activities (Karagulian, 2015). PM poses a serious health risk to humans with prolonged exposure, like that of living in cities (World Health Organization, 2016). Elevated levels of PM are linked to increased rates of respiratory and heart conditions, cancer rates, and premature death (Fraser, 2011). Viecco et al. (2018) examined dry deposition rates of commonly-used green roof species and showed that sedum varieties can significantly reduce peak and overall concentrations of PM in urban areas, similar to the rates seen through the use of street trees.

1.3 Green Roofs-Stormwater

Urban development traditionally required the transition from a permeable landscape dominated by vegetation to an impervious grey-scape dominated by concrete, asphalt, and roofs. This transition is accompanied by an alteration of the waterscape where water is no longer allowed to be absorbed by the ground and is instead funneled into the sewer system and directly into local tributaries (Frazer, 2005). Increased impervious area leads to pollutants being washed directly into waterways, resulting in a greater total volume and more drastic peak of stormwater, and leading to increased flooding and erosion (US EPA, 2003). In addition, cities with antiquated sewage systems generally experience combined sewer overflows (CSO) where stormwater combines with sewage during extreme storm events and the untreated mix is then delivered directly into waterways. These occurrences pose a health risk to humans and aquatic life and can lead to economic losses (US EPA, 2004).

Green roofs, like most green infrastructure, can help reduce these impacts during storm events by retaining stormwater, preventing it from becoming runoff and entering the sewer system (Banting et al., 2005). With roof space representing around 25% of cities, there is a strong potential to reduce total runoff by more than 60% and peak discharge by over 80% through the use of green roofs (Akbari, 2001; Zhang et al., 2015).

1.4 Green Roofs-Thermal Performance

Green roof thermal performance can be broken down into several aspects: albedo, surface temperatures and the heat island effect, and the impact it has on buildings. Figure 3 shows the relative impacts that green

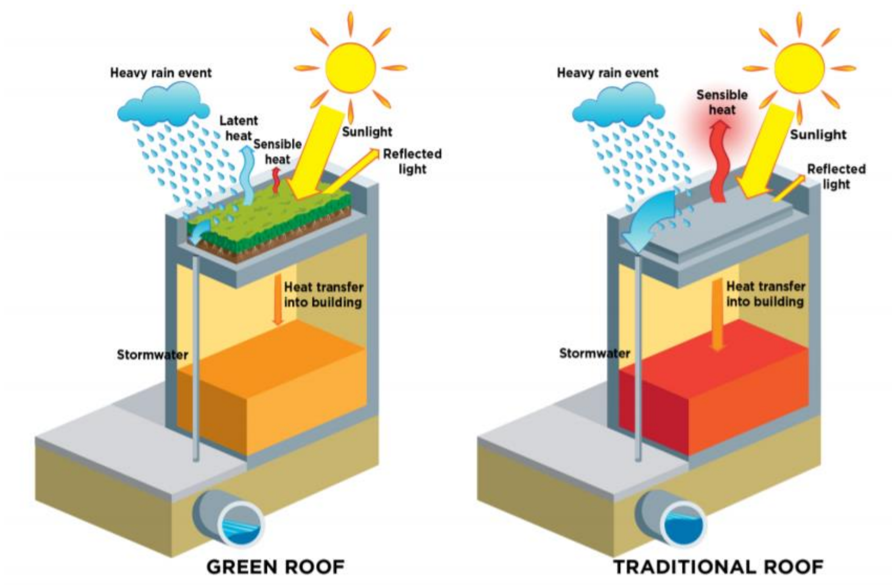


Figure 3: Heat exchange and water runoff interactions of a green roof versus a traditional roof. Retrieved from https://www.epa.gov/sites/production/files/2018-09/documents/greenroofs_casestudy_kansascity.pdf

roofs can have on thermal and stormwater interactions compared to traditional roofing materials.

1.4.1 Albedo

Traditionally, roofing materials are made of darker materials such as black shingles and membranes such as EPDM. Darker surfaces have a lower albedo; absorbing solar radiation and generating heat that impacts a building's interior and contributes to the heat island effect (Razzaghmanesh, 2016). Albedo refers to the percentage of solar energy reflected by a surface where higher albedo contributes to lower surface temperatures (Liang et al., 2012).

Table 1: Albedo, emittance, and solar reflectance index (SRI) of commonly used roofing materials. Retrieved from http://danieloverbey.blogspot.com/2015/11/the-difference-between-reflectance-and.html.

Solar Performance of Roofing Materials

Material	*Albedo (%)*	*Emittance (%)*	*SRI*
White asphalt shingles	21	91	21
Black asphalt shingles	5	91	1
White granular-surface bitumen	26	92	28
Red clay tile	33	90	36
Red concrete tile	18	91	17
Unpainted concrete tile	25	90	25
White concrete tile	73	90	90
Galvanized steel (unpainted)	61	4	37
Aluminum	61	25	50
Siliconized white polyester over metal	59	85	69
Polyvinylidene fluoride (PVDF) white over metal	67	85	80
Black EPDM	6	86	-1
Gray EPDM	23	87	21
White EPDM	69	87	84
T-EPDM	81	92	102
Chlorosulfonated polyethylene (CSPE) synthetic rubber	76	91	95

Table 1 shows the albedo level of some common roofing materials used in residential and commercial applications. In comparison, green roofs typically have an albedo of 70-85% when fully vegetated (Gaffin et al., 2005).

Cool roofs, as defined by the U.S. Department of Energy, are simply roofs that are "designed to reflect more sunlight and absorb less heat than a standard roof." During the summer, traditional roofs can experience temperatures of 150°F or more, whereas cool roofs under the same conditions can stay over 50°F cooler (Konopacki et al, 1998; Gartland; Miller et al., 2004; Konopacki and Akbari, 2001). Cool roofs range in materials and design from lightly colored membranes to green roofs, depending on installation goals and the engineering of the structure.

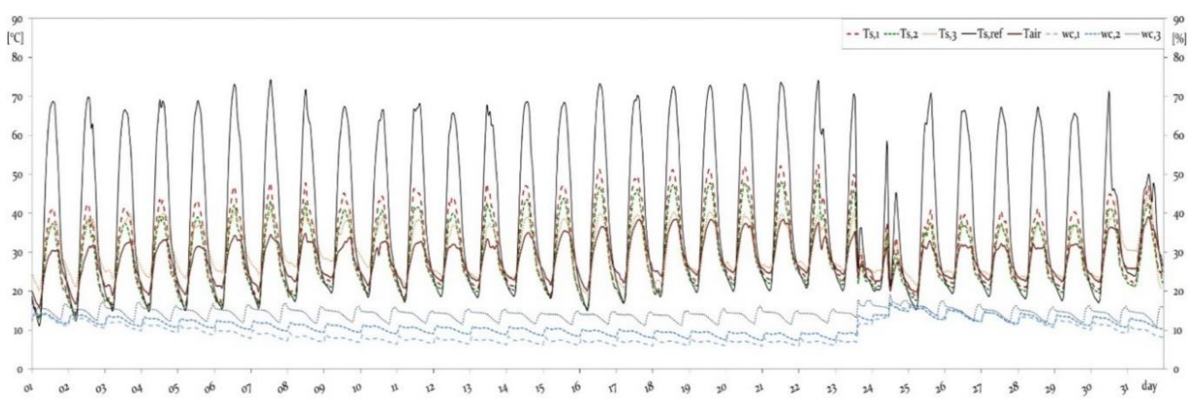


Figure 4: Figure from Bevilacqua et al. (2017) showing surface temperature variability compared to a reference roof in Southern Italy, July 2015. The dashed red, green, and yellow lines represent three different green roof plots while the solid black line represents a bituminous reference roof.

1.4.2 Heat Island Effect and Surface Temperature

The higher albedo of green roofs allows for the potential to reduce surface temperatures compared to traditional roofs (General Services Administration, 2011). Figure 4 depicts the surface temperatures of several green roofs and a traditional reference roof in Southern Italy. This study conducted by Bevilacqua et al. (2017) showed that the reference roof generated surface temperatures 2-3 times that of green roofs. On top of lower surface temperatures, green roofs act as an additional layer of insulation, combining to reduce the energy exchange through the roofing layers that impact the interior of the building envelope (Gagliano et al., 2017).

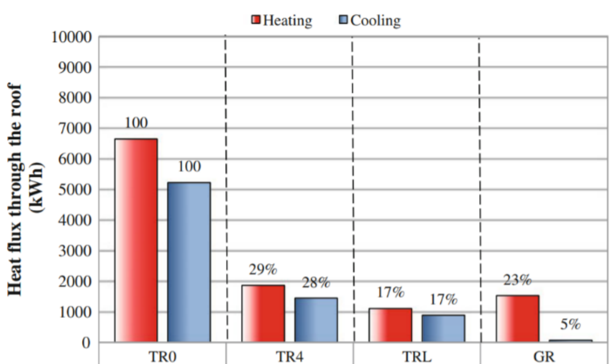
Urban areas often experience a phenomenon known as the heat island effect where cities are several degrees warmer than surrounding areas due to a lower overall albedo (Gaffin et al., 2010). The shift from a vegetation-dominated landscape to one of buildings and roads is the primary reason for this (US EPA, 2014). Green roofs help mitigate the heat island effect by reflecting the solar radiation that would otherwise be absorbed by the roof of buildings. In addition, green roofs undergo evapotranspiration, absorbing ambient heat and lowering the roof top surface temperature (Gaffin et al., 2010). This reduction of surface temperatures can result in an energy savings for the building it is installed on, in addition to reducing the heat island effect when installed on a city-wide scale (Jaffal et al., 2012; Bass et al., 2017).

1.4.3 Impact on Buildings

The higher albedo, evapotranspiration, and added insulation that green roofs provide reduce the energy exchange between a building and the roof, thus reducing air conditioning and heating demands (Jaffal et al, 2012). This reduction in energy demand saves money and reduces CO_2 and other pollutant generation from fossil fuels, thereby improving air quality (General Services Administration, 2011).

The overall cooling impact can range drastically depending on location, building construction, and green roof design. One study showed that green roofs in New York could reduce cooling costs anywhere from 1-20%,[9] while a study in Athens, Greece showed a potential energy savings of 2-44% (Rosenweig et al., 2006; Niachou et al., 2001).

Figure 5 shows the heat flux through several roof scenarios from Gagliano et al. (2017). Their findings indicate a heat flux reduction of 6% during heating and 23% during cooling with the addition of a green roof on an averagely insulated roof. This reduction grows to 77% and 94%, respectively, when an averagely insulated roof outfitted with a green roof is compared to a poorly insulated roof.



	TR0	TR4	TRL	GR
Heating	6653	1866	1107	1528
Cooling	5229	1447	889	66

Figure 5: Heat flux through various roofing scenarios with varying insulation levels and a green roof. Retrieved from Gagliano et al. (2017).

Although a well-insulated roof performed better than the green roof scenario during heating periods, the green roof out-performed during cooling periods.

With the push for green energy, roof tops may soon become a valuable commodity in cities. Currently, a building owner must choose between a green roof system or energy generation with photovoltaic cells. There is potential, however, to optimize the space by combining the systems. Solar panels can offer shade to the green roof, reducing the extremes that can tax the vegetation and the need for an irrigation plan during the drier summer months (Hui and Chan, 2011). Green roofs may also increase energy production of the photovoltaic cells by contributing to a lower panel operating temperature, increasing their efficiency (Hui and Chan, 2011).

In order to help justify the additional cost premium of green roofs, it is important to quantify the cost savings of various green roof installation depths and types. As described above, there are several components that contribute to the overall monetary savings that green roofs provide over time.

This study is designed to examine the thermal impact to buildings and surface temperatures that various green roof types have, compared to common roofing materials. In addition, this study examines potential thermal co-benefits of various green roof installation depths with and without the addition of solar panels.

CHAPTER 2: METHODOLOGY

2.1 Site Description

A green roof research installation was constructed and launched on the Fairfax, VA campus of George Mason University, located at 38.834961° N 77.306712° W. The installation was launched April 2017 on the top floor of Rappahannock Parking Deck, an exposed 4-story concrete structure near the northeast corner of campus with no shading by abutting structures or trees. This location allowed for easy access to the installation while also replicating the extreme conditions that are found on roofs. The structure is outfitted with a concrete barrier wall around the perimeter that is 4 feet high for pedestrian and vehicle safety, abutting the installation on the Northern and Western sides. The Eastern and Southern perimeters of the installation were outfitted with steel safety rails to discourage unauthorized access and protection from vehicular traffic.

Table 2: Weather data recorded from March 2018-February 2019.

	Temperature (°F)			Solar Radiation (w/m^2)	Rain (Inches)
Month	High	Average	Low	Peak	Cumulative
January	66.9	33.4	5.7	555.3	0.81
February	80.8	42.8	11.8	689.6	4.10
March	78.6	40.0	27.9	677.4	1.76
April	85.6	52.0	30.7	777.5	4.26
May	91.4	71.1	51.4	806.9	7.54
June	93.4	73.9	53.8	909.8	5.28
July	96.6	77.4	59.4	921.4	11.19
August	95.9	78.6	62.1	912.9	4.61
September	94.1	73.3	55.6	715.3	6.67
October	88.9	59.8	34.0	582.5	2.72
November	74.1	44.6	25.7	439.8	6.86
December	66.2	40.9	25.2	390.1	6.56

An Ambient Weather WS-1001 weather station was installed on site to record accurate ambient weather data every 10 minutes during the study period. The station was pole mounted 4 feet above the surface of the table to minimize the impact of surface temperatures from the installation. Table 2 displays the observed weather data during the study period and Figure 6 shows the monthly average diurnal cycle of ambient air temperature and solar radiation.

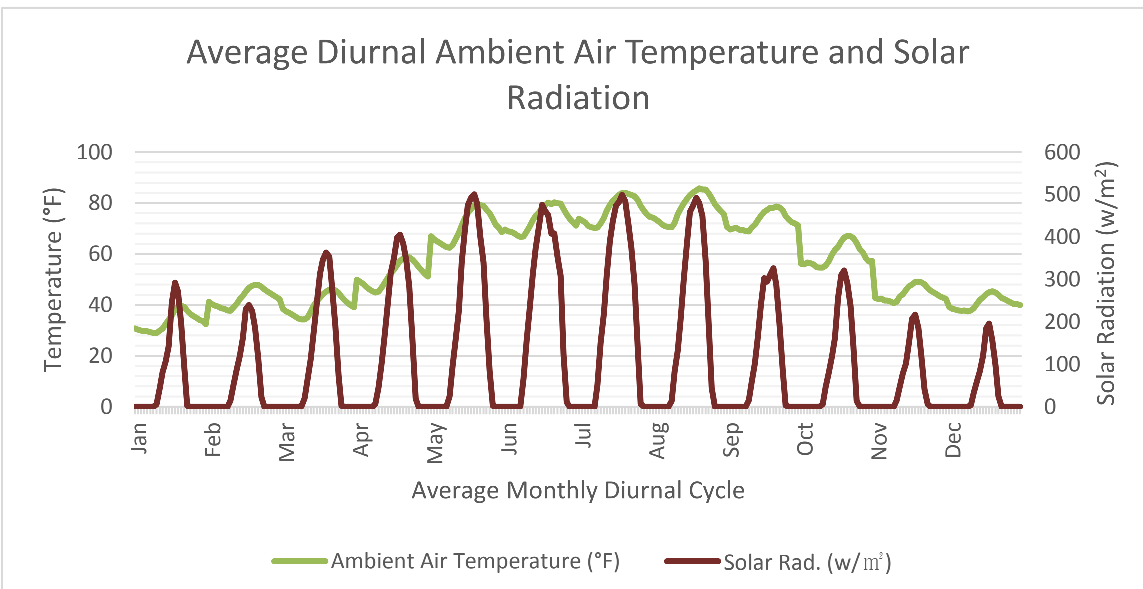


Figure 6: Average diurnal ambient air temperature and solar radiation recorded from March 2018-February 2019.

2.2 Experimental Design

2.2.1 Installation Construction

Two “tables” were constructed as shown in Figure 7. Each table was framed using lumber and enclosed in PVC trim board to promote installation longevity and to reduce thermal noise. Each table is 8 feet wide by 15 feet long, each housing 15 2’x2’ PVC boxes. The surface of each box is 3 feet above the parking deck surface, 1 foot below the height of the surrounding wall. The tables were fitted with a skirt to enclose the area beneath each table, reducing the impact of ambient air temperature by limiting air exchange. The concrete structure aided in temperature regulation under the tables, as the concrete was able to store energy during the day and release it at night, thus reducing temperature fluctuations under the table.

Figure 7: George Mason green roof installation during the Summer of 2017.

The parking garage surface is gently sloped towards the middle of the structure to aid in water runoff, which attributed to the installation having a slope of roughly 1 degree. Each box houses a roofing material and has a drain located on the downhill side that empties into a bucket placed underneath for runoff collection. Each roofing material is fitted with two temperature sensors: one on the surface and one on the bottom (for green roof applications) or attached to the underside (for residential and commercial materials) of the component.

The northernmost table was equipped with a photovoltaic array of SP50P 50W 12V Poly panels that were fixed at approximately 45° facing East. The solar panels were mounted on a horizontal pole 30" above the table, ensuring that the panels do not interfere with the vegetation growth. Each of the solar panels were 2'x2' to match the size of the boxes. Electricity generated from the panels was stored on two deep cycle marine batteries and was used to power the weather station, data loggers, and a Wi-Fi extender. The installation was not connected to any external power source.

2.2.2 Roofing Materials

This study was designed to compare traditional roofing materials and green roof products that are versatile and readily available. Three common traditional roofing materials were selected: black asphalt shingles, white PVC membrane, and a black EPDM membrane. Asphalt shingles are

Figure 8: Eco-Roofs, LLC's pre-vegetated green roof system. Retrieved from https://eco-roofs.com/eco-roofs-brochure/.

most common in residential applications, while the membranes are more indicative of commercial applications. The white PVC membrane represents a cool roof, which aims to reduce rooftop temperatures by increasing the albedo over that of darker roofing materials. The roofing materials were mounted to oriented strand board (OSB), typical of that used as roof sheathing. The green roof products that were chosen are manufactured by Eco-Roofs, LLC and shown in Figure 8. The product is composed of a specially designed plastic tray that is 1 foot by 2 foot and 3.3 inches tall with a series of holes and canals for drainage. The tray contains engineered growing media and vegetation that can be assembled easily to meet installation goals. Additionally, the 4” and 6” depths are outfitted with a coconut coir “basket” that the engineered soil is placed in. This additional layer acts as a filter fabric and increases the depth of the product from 3.3” to 4” or 6”. Green roof systems generally require an additional drainage layer; however, this is built into the tray itself, reducing the installation labor and expenses (Eco-Roofs, LLC).

For each depth of green roof product being tested, one trial was established without vegetation and three with vegetation on each table. The trial with bare soil acts as a control to assess the additional impact of vegetation.

The following trials were conducted on each table:

a. black asphalt shingles;
b. white PVC membrane;
c. black EPDM membrane;
d. 3.3” deep extensive green roof product with growing media;

e. 4” deep extensive green roof product with growing media and coconut coir;

f. 6” deep extensive green roof product with growing media and coconut coir;

g. 3.3” deep extensive vegetated green roof with sedum mix;

h. 4” deep extensive vegetated green roof with sedum mix and coconut coir;

i. And 6” deep extensive vegetated green roof with grasses and coconut coir.

Figure 9 indicates the layout and orientation of the installation.

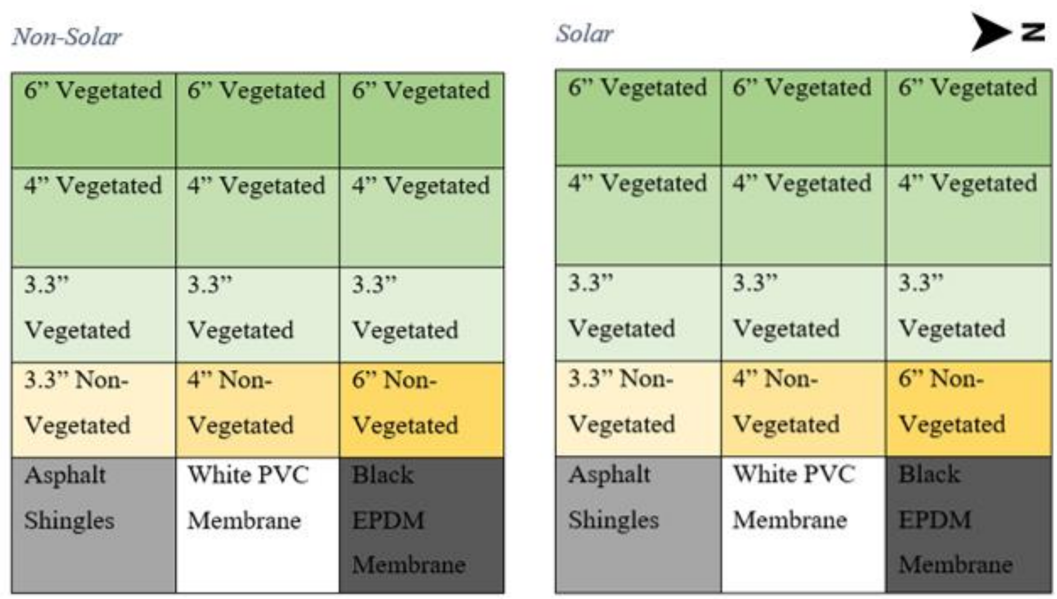


Figure 9: Layout and orientation of the two installation tables.

2.2.3 Vegetation

Eco-Roof, LLC utilizes pre-vegetated sedum “mats” that are grown using sedum clippings. Using already established and rooted vegetation provides instant coverage and benefits instead of waiting for the vegetation to become established (Eco-Roofs, LLC). The 3.3” and 4” depth products included a mix of *Sedum album, Sedum spurium,* and *Sedum hybridum*. These trials, in addition to the bare soil trials, were weeded regularly throughout the growing season, as typically recommended by the manufacturer.

The grass species supplied for the 6” deep product included plugs of *Calamagrostis Karl Foerster* and *Panicum Shenandoah*. Irrigation is generally recommended when using grasses on green roofs as they are not able to withstand the same conditions as the sedum mixes are able to. For this study, irrigation was not utilized, which resulted in the grasses dying at the end of Summer, 2017. Once this occurred, weeding no longer continued in order to allow for a vegetation layer of weeds for comparison to the non-vegetated control. Sedum varieties from the neighboring trials, in addition to native plants, were noted growing throughout the season, although not identified.

2.2.4 Data Collection

Two waterproof DS18B20 temperature sensors were installed on each trial. The first sensor was placed on the immediate surface of the medium, recording surface temperature at the interface of the medium and of the air. The second sensor was placed on the underside of the OSB for the traditional materials and against the bottom of the tray for the green roof trials, recording bottom temperature. The temperature sensors at each table were wired into an Arduino UNO board that recorded and stored the data. Data was collected from March 1, 2018 to January 31, 2019 for the non-solar table. Temperature was recorded every 15 minutes throughout the study period.

Due to errors from wiring and data storage, temperatures from the following seasons and trials were omitted from the analyses:

a) February 2019 for all trials, non-solar table
b) Winter and Fall data for EPDM, non-solar
c) Winter data for 6” non-vegetated, non-solar
d) Solar table data.

2.3 Data Analyses

2.3.1 Non-Solar Trials

Surface and bottom temperature data was pre-processed for recording errors. Sensor and wiring errors were recorded as the maximum and minimum recordable temperatures and were removed. The primary errors were identified and listed above.

Temperature data was then averaged by trial type and by seasons to reduce the impact of environmental and vegetation variability. Seasonal averages were used to compare performance and months, grouped as follows:

- Winter: December-January
- Spring: March-May
- Summer: June-August
- Fall: September-November

$$\text{MRD\%} = \frac{T_i - T_{ref}}{T_{ref}}\, x100$$

Equation 1: Percent Mean Relative Difference

Mean Relative Difference (MRD) was calculated using Equation 1 where *T* represents temperature in degrees Fahrenheit as either surface or bottom, *i* represents trial being compared, and *ref* represents the reference roofing material. For relative comparisons, the asphalt shingles were used as this reference. The seasonal MRD to asphalt shingles is then graphed to compare thermal performance of surface and bottom temperatures.

A one-way anova test is used for each season and for top or bottom temperature to test if there is a statistical significance between trials. If found to be significant, a Tukey's honestly significant difference test will be conducted to identify the significance between trial types.

To create a time series of surface and bottom temperatures, data will be averaged by trial type and by month. Monthly data will be averaged by day and within hour to create an average monthly diurnal cycle for March-January when data was collected.

2.3.2 Solar Trials

Solar data was assessed for errors and, due to wiring and sensor errors, was not able to be utilized, with an overwhelming majority of readings being deemed as errors. Because of this, a quantified assessment of the impact of solar panels on green roof thermal performance was not able to be conducted.

Throughout the data collection period, however, images and observations were made of the differences identified between the two tables. These images and observations will be assessed for differences and compared with the quantified comparisons of the non-solar trials to create predictions of what the effect would be on thermal performance. This will create a strong basis for future research and serve as a “proof of concept.”

2.4 Hypotheses

The hypotheses being tested by this study:

H1: The thermal performance of vegetated green roof products is greater than that of standard dark commercial and residential roofing materials, as measured by surface and below material temperatures.

H2: Thermal performance of vegetated green roofs will be similar to that of "cool" roofs.

H3: Thermal performance of vegetated green roofs perform better as growing media depth increases.

H4: Vegetated green roofs have a greater thermal performance than that of growing media alone.

H5: Green roof installations implemented with solar panels exhibit greater thermal performance than those implemented without solar panels.

CHAPTER 3: RESULTS

3.1 Non-Solar Trials

A one-way anova test was conducted for each seasonal MRD in relation to asphalt shingles for top and bottom temperatures in order to determine if there was a statistical difference between trial types throughout the year. Appendix A shows the sample sizes and results for each test. Each season and sensor location was found to be significant (p-value <.05) indicating that there was a significant difference between trials on the non-solar table. To determine if there was a significant difference by season between two trials, testing the hypotheses, a Tukey's honestly significant difference test (HSD) was conducted. Table 3 reflects these values where a significant difference (p-value <.05) is indicated in bold.

Table 4 shows the average seasonal surface and bottom temperatures recorded for each trial. Seasonal MRD to asphalt shingles is shown in Figure 11 for the top sensors and Figure 12 for the bottom sensors. The MRD indicates relative performance as a percent temperature (°F) difference between a material and that of asphalt shingles, whereas a negative percentage indicates the material being compared was cooler than the asphalt shingles. The shingles were chosen as the reference as there were few sensor errors and that there was limited variability that could have been caused by vegetation or soil parameters.

Table 3: Results of Tukey's Honestly Significant Difference test.

Top Sensors	PVC Membrane				EPDM Membrane				3.3" Non Vegetated				4" Non Vegetated			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Asphalt	0.361	**0.001**	**0.001**	**0.001**		**0.001**	**0.001**		**0.014**	**0.006**	**0.001**	**0.001**	**0.032**	**0.001**	**0.001**	**0.001**
PVC Membrane						**0.001**	**0.001**		0.839	0.069	**0.043**	0.899	0.899	0.403	0.562	0.899
EPDM Membrane										**0.001**	**0.001**			**0.001**	**0.001**	
3.3" Non Vegetated													0.899	0.899	0.899	0.899

	6" Non Vegetated				3.3" Vegetated				4" Vegetated				6" Vegetated			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Asphalt		0.130	**0.001**		**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.009**	**0.001**
PVC Membrane		**0.002**	**0.042**		**0.035**	0.899	**0.002**	**0.035**	**0.039**	0.899	0.574	**0.001**	**0.001**	0.727	**0.001**	0.737
EPDM Membrane		**0.001**	**0.001**			**0.001**	**0.001**			**0.001**	**0.001**			**0.001**	**0.001**	
3.3" Non Vegetated		0.899	0.899		0.538	**0.003**	**0.001**	**0.004**	0.487	0.060	**0.001**	**0.001**	0.083	0.899	**0.022**	0.361
4" Non Vegetated		0.682	0.899		0.448	0.054	**0.001**	**0.044**	0.487	0.370	**0.003**	**0.001**	0.084	0.899	**0.001**	0.789
6" Non Vegetated						**0.001**	**0.001**			**0.002**	**0.001**			0.354	**0.027**	
3.3" Vegetated									0.899	0.899	0.496	0.372	0.899	0.207	**0.001**	0.649
4" Vegetated													0.899	0.698	**0.001**	**0.004**

Bottom Sensors	PVC Membrane				EPDM Membrane				3.3" Non Vegetated				4" Non Vegetated			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Asphalt	**0.001**	**0.001**	**0.001**	**0.001**		0.695	0.882		**0.001**	**0.001**	**0.001**	**0.001**	**0.018**	**0.001**	**0.001**	**0.001**
PVC Membrane						**0.001**	**0.001**		0.899	**0.001**	**0.001**	**0.001**	0.309	**0.001**	**0.001**	**0.001**
EPDM Membrane										**0.004**	**0.001**			**0.002**	**0.001**	
3.3" Non Vegetated													0.837	0.899	0.899	0.826

	6" Non Vegetated				3.3" Vegetated				4" Vegetated				6" Vegetated			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Asphalt		**0.001**	**0.001**		0.227	**0.001**	**0.001**	**0.001**	0.899	**0.001**	**0.001**	**0.001**	0.899	**0.001**	**0.001**	**0.001**
PVC Membrane		**0.001**	**0.011**		**0.030**	**0.001**	**0.005**	**0.002**	**0.001**	**0.015**	0.570	**0.001**	**0.001**	**0.001**	**0.002**	**0.001**
EPDM Membrane		**0.003**	**0.001**			**0.003**	**0.001**			**0.001**	**0.001**			**0.001**	**0.001**	
3.3" Non Vegetated		0.899	0.365		0.289	0.899	0.508	0.899	**0.007**	0.525	**0.003**	0.899	**0.007**	0.899	0.656	0.899
4" Non Vegetated		0.899	0.380		0.899	0.899	0.521	0.746	0.260	0.632	**0.004**	0.899	0.263	0.899	0.669	0.899
6" Non Vegetated						0.899	0.899			0.607	0.767			0.899	0.899	
3.3" Vegetated									0.811	0.585	0.635	0.899	0.814	0.899	0.899	0.899
4" Vegetated													0.899	0.899	0.487	0.899

Table 4: Average seasonal daily surface and bottom temperatures by trial.

Average Seasonal Daily Surface Temperature (°F)									
Season	Asphalt	PVC	EPDM	3.3" NV	4" NV	6" NV	3.3"Veg	4" Veg	6" Veg
Winter	35.89	35.25		34.88	35.09		34.89	34.43	34.43
Spring	58.10	55.68	59.53	56.83	56.40	56.92	55.33	55.76	56.27
Summer	84.91	80.52	87.29	81.86	81.34	81.99	78.63	79.62	83.30
Fall	61.31	59.26		59.56	59.29		58.35	57.63	61.81
Average Seasonal Daily Bottom Temperature (°F)									
Winter	35.80	34.04		34.41	35.02		34.73	35.41	35.47
Spring	57.14	52.98	56.29	55.01	54.82	54.65	53.75	54.10	54.50
Summer	83.13	76.56	82.25	79.88	79.84	79.52	77.41	77.62	78.79
Fall	60.67	57.22		58.52	58.88		57.88	58.31	61.13

3.1.1 Vegetated Green Roofs Versus Asphalt Shingles and EPDM Membrane

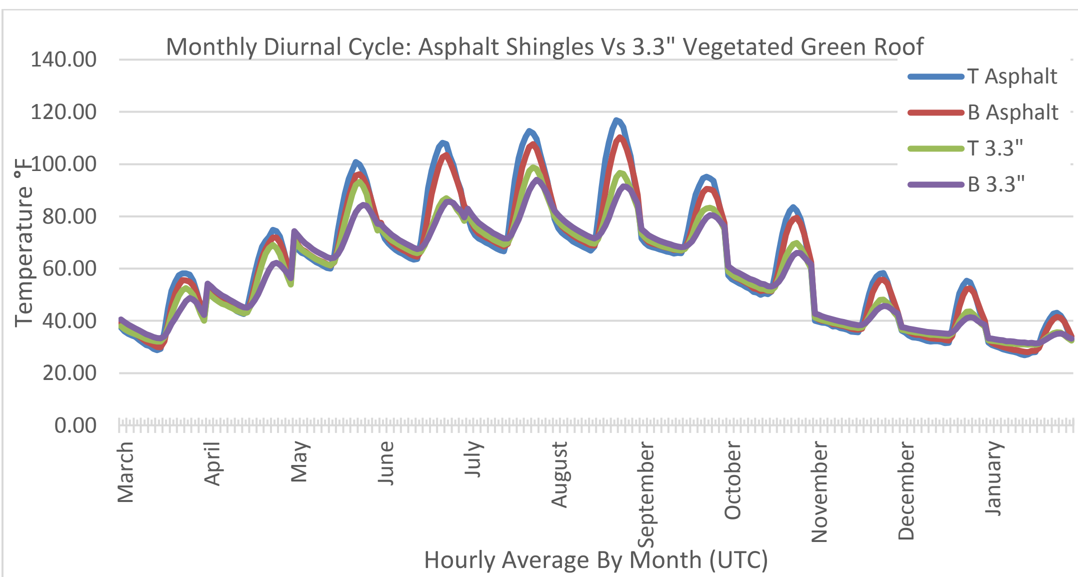


Figure 10: Average monthly diurnal cycles for asphalt shingles and 3.3" vegetated green roof trials.

Vegetated green roof surface temperatures were significantly different (p-value<.05) compared to the asphalt shingles and EPDM membranes for all seasons. During the Winter and Spring, green roof surface temperatures were 2-4% cooler than the shingles. This difference increased to 4-7% during the Summer and Fall for the 3.3” and 4” green roof trials. The 6” vegetated green roof was also cooler than the shingles by 2% during the Summer; however, the surface temperature was warmer during the Fall. Surface MRD for EPDM were approximately 2.5% warmer during the Spring and Summer than the shingles, noting that Winter and Fall measurements were omitted from this analysis for EPDM. Summer surface temperature of the shingles averaged at 84.9 °F, while the 3.3” and 4” green roofs averaged at 78.63 and 79.62 °F, respectively.

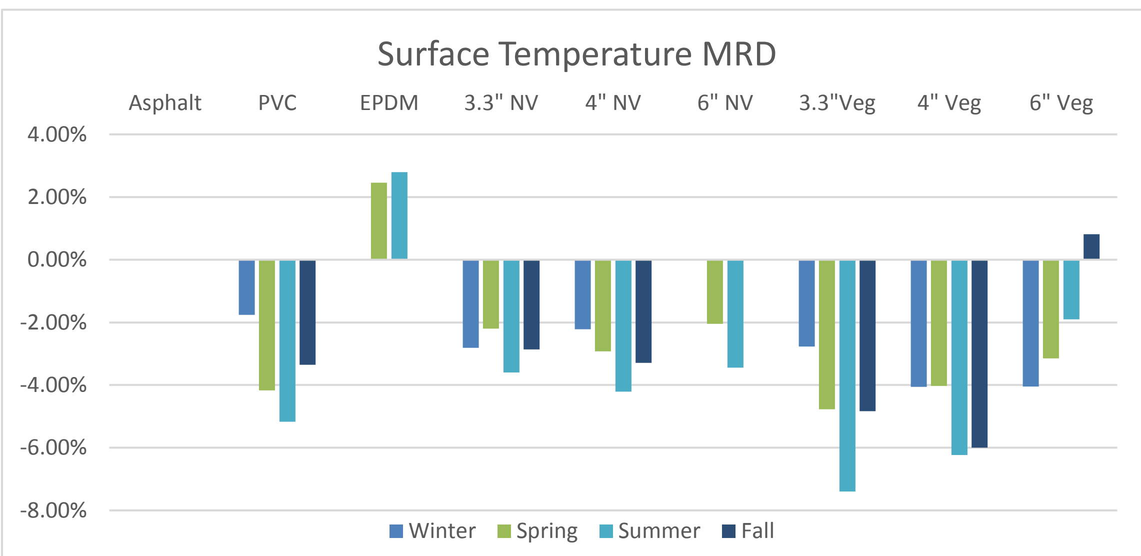


Figure 11: Seasonal surface MRD compared to asphalt shingles.

The maximum surface temperature recorded for the shingles was 149.23 °F on 7/3/18 while EPDM reached 157.66 °F. The 3.3” and 4” vegetated green roof trials all remained at or under 130 °F when this extreme was recorded. The first week of July experienced the highest ambient air temperatures of the observation period with temperatures reaching 96 °F two days in a row. In addition, Solar Radiation reached 744 w/m^2 on 7/3/18. July tied with May for highest hourly average peak solar radiation at 500 w/m^2.

Bottom MRD for vegetated green roof trials during the Winter were 1-3% lower than shingles, increasing to 4.5%-7% cooler during the Spring and Summer. Bottom MRD was significant between all vegetated green roof depths and the dark roofing materials with the exception of Winter. During the Summer, shingles averaged at 83.13°F while vegetated green roofs averaged between 77.41°F-78.79°F.

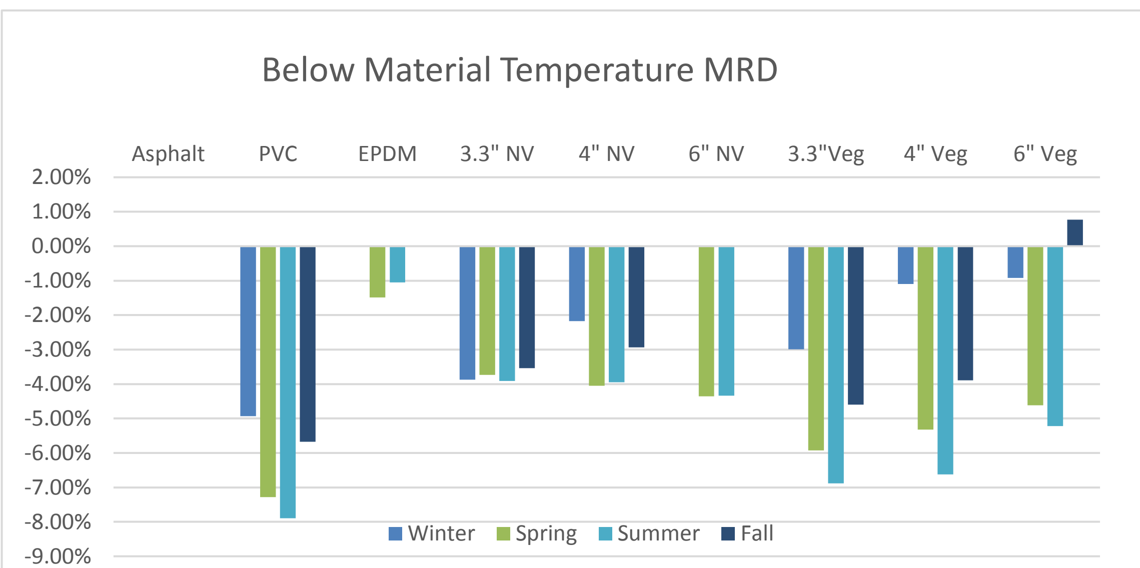


Figure 12: Seasonal bottom MRD compared to asphalt shingles.

Figure 10 compares the surface and bottom average diurnal cycle per month for asphalt shingles and 3.3” vegetated green roofs. Temperatures for shingles were consistently higher than the green roof, with this difference growing notably during the Summer and Fall months.

3.1.2 Vegetated Green Roofs Versus PVC Membrane

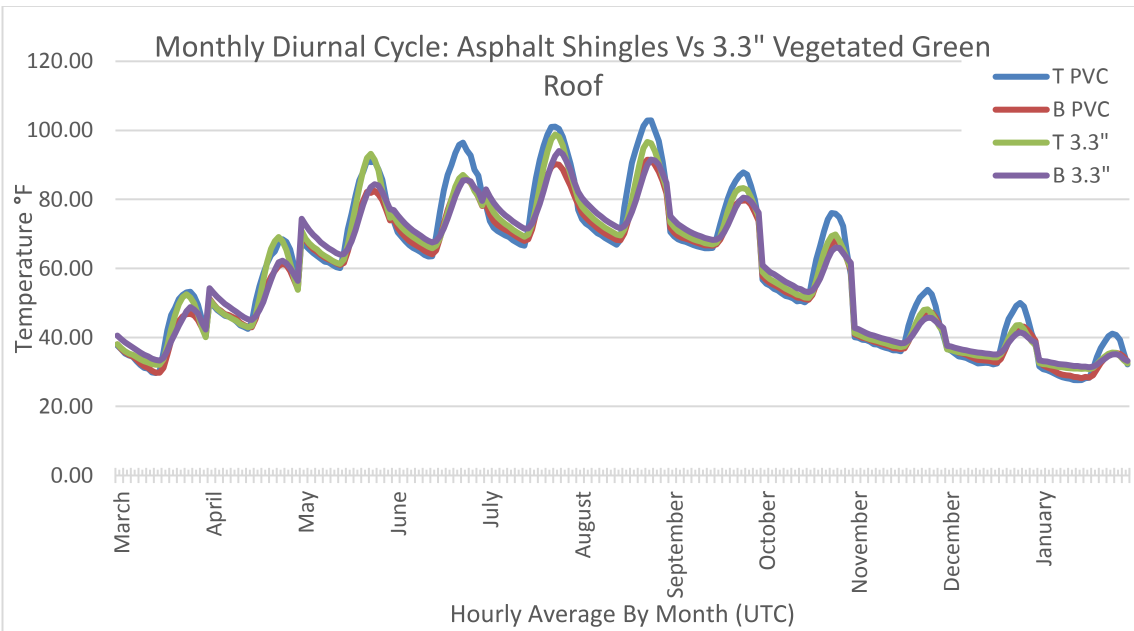


Figure 13: Average monthly diurnal cycles for white PVC membrane and 3.3" vegetated green roof trials.

During the Winter, vegetated green roof surface temperatures were all significantly different than the PVC membrane. None were significant during the Spring, 3.3” and 6” for Summer, and 3.3” and 4” for the Fall. Both the 3.3” and 4” vegetated green roofs remained cooler than the PVC membrane, with MRD generally being 1-2%

different. Summer surface temperatures represented the greatest difference with green roofs reaching cooler temperatures by 2°F.

Bottom temperatures were all significantly different with the exception of the 4” vegetated green roofs during the Summer. From Spring to Fall, MRD of bottom temperatures for the 3.3” and 4” trials were again within 2% of the PVC membrane; however, they were 2% warmer. This difference increased during the Winter when the vegetated green roofs stayed up to 2°F warmer than the PVC membrane.

The diurnal cycles between the PVC membrane and 3.3” green roof appear to be very similar, even overlapping, in Figure 13. When compared with Figure 10, the 3.3” vegetated green roof temperatures more closely resemble that of a cool roof than that of a dark roof.

3.1.3 Green Roof Performance by Depth

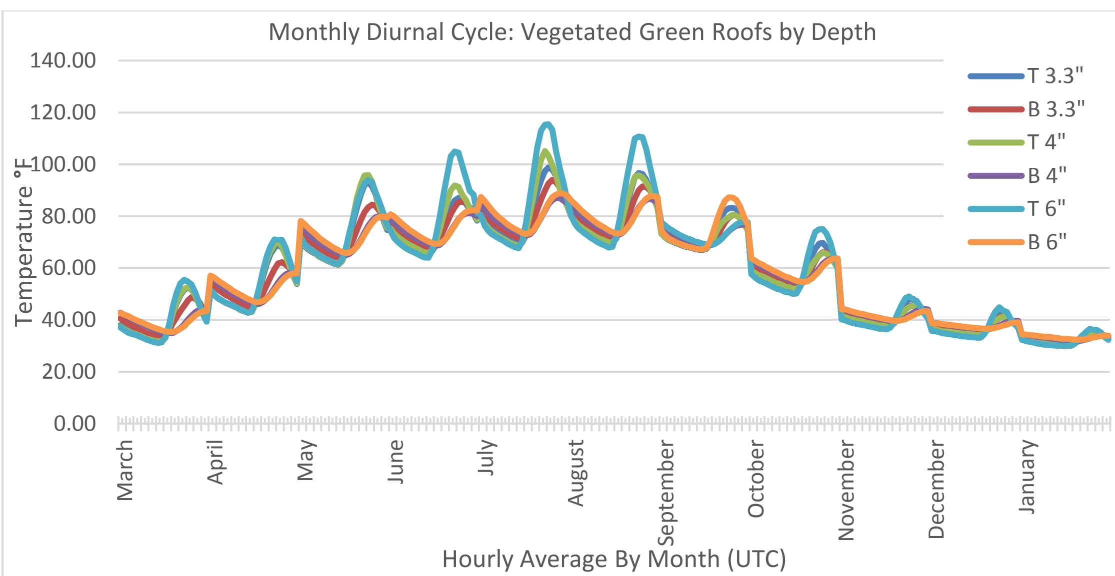


Figure 14: Average monthly diurnal cycles for vegetated green roof trials.

There was no significant temperature difference for surface or bottom temperatures of the non-vegetated green roof trials. Average seasonal temperatures were within 1°F difference for the three depths of non-vegetated green roof trials.

A similar pattern was observed for the vegetated trials. MRD was not significantly different on the surface with the exception of 3.3” and 4” when compared to 6” during the Summer and again for 4” to 6” during the Fall. There was no significant difference for bottom temperatures of the vegetated green roof trials. Surface and below temperatures respectively remained within 1°F across all depths with the only exceptions being for the 6” depth trials during the summer and Fall when this increased to 4°F warmer than the other vegetated trials.

Figure 14 shows the diurnal cycles of the different depths of green roofs frequently overlapping, with the only exception being the surface temperatures for the 6” trials during the Summer. During the winter, differences were indistinguishable by depth.

3.1.4 Vegetated Green Roof Versus Non-Vegetated

Surface temperatures for all non-vegetated trials were significantly different than the vegetated trials during the Summer. In addition, Fall temperatures were significant with the exception of when compared to the vegetated 6” trials. Half of the Spring comparisons for 3.3” and 4” trials were also significant. In contrast, no winter surface temperatures were found to be significant. During the Summer, surface temperatures of the non-vegetated trials averaged 81.83°F while the vegetated 3.3” and 4” trials averaged at 78.63°F and 79.62°F, respectively.

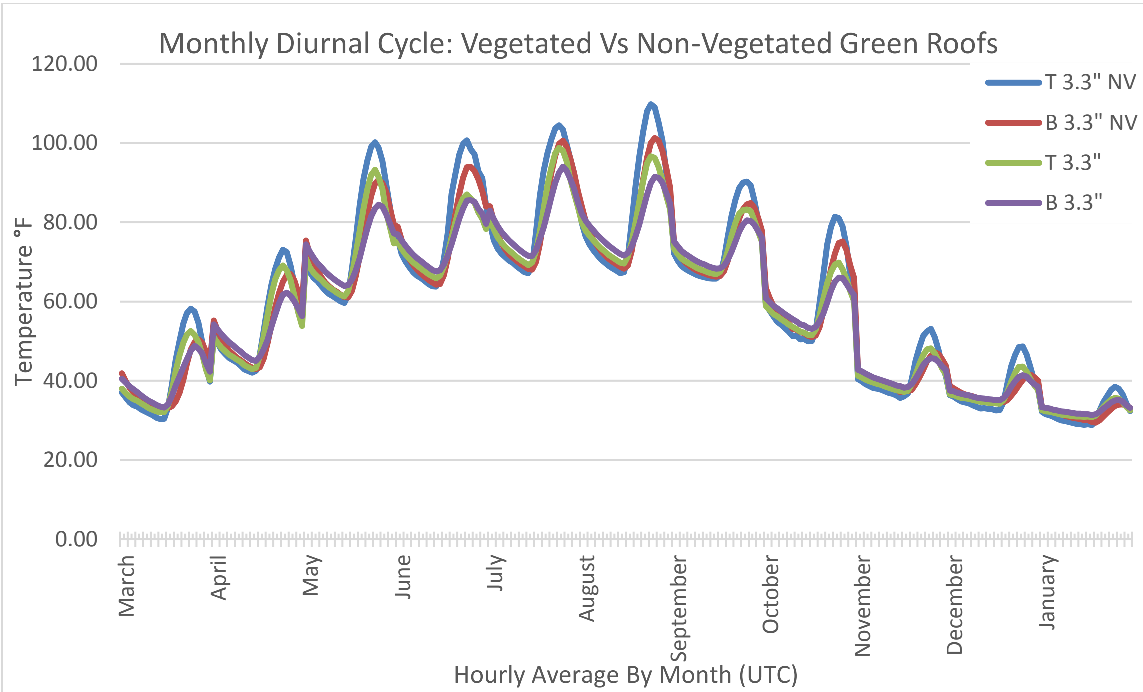


Figure 15: Average monthly diurnal cycles for 3.3" non-vegetated and 3.3" vegetated green roof trials.

Bottom MRD was not significant between vegetated and non-vegetated trials with the exception of 3.3" and 4" non-vegetated compared to 4" vegetated during the summer and 3.3" non-vegetated compared to 4" and 6" vegetated trials. During Winter, Spring, and Fall, the average below temperatures for vegetated trials was 1°F cooler than the non-vegetated trials. During the Summer, this difference grew to about 2 °F, except for the 6" vegetated trials that averaged closer to 1°F cooler.

Figure 15 shows the difference in temperatures between the 3.3" vegetated and non-vegetated green roof trials. During the Winter, diurnal averages were very similar in contrast to the Summer months when this difference grew for surface temperatures.

3.2 Solar Vs Non-Solar Trials

Due to sensor and wiring errors for the trials equipped with solar panels, quantified data was not usable for comparisons. Observations throughout the course of the experiment were noted and photographic records made. Figure 16 compares the vegetated green roof trials on the non-solar and solar tables from May 2018-March 2019.

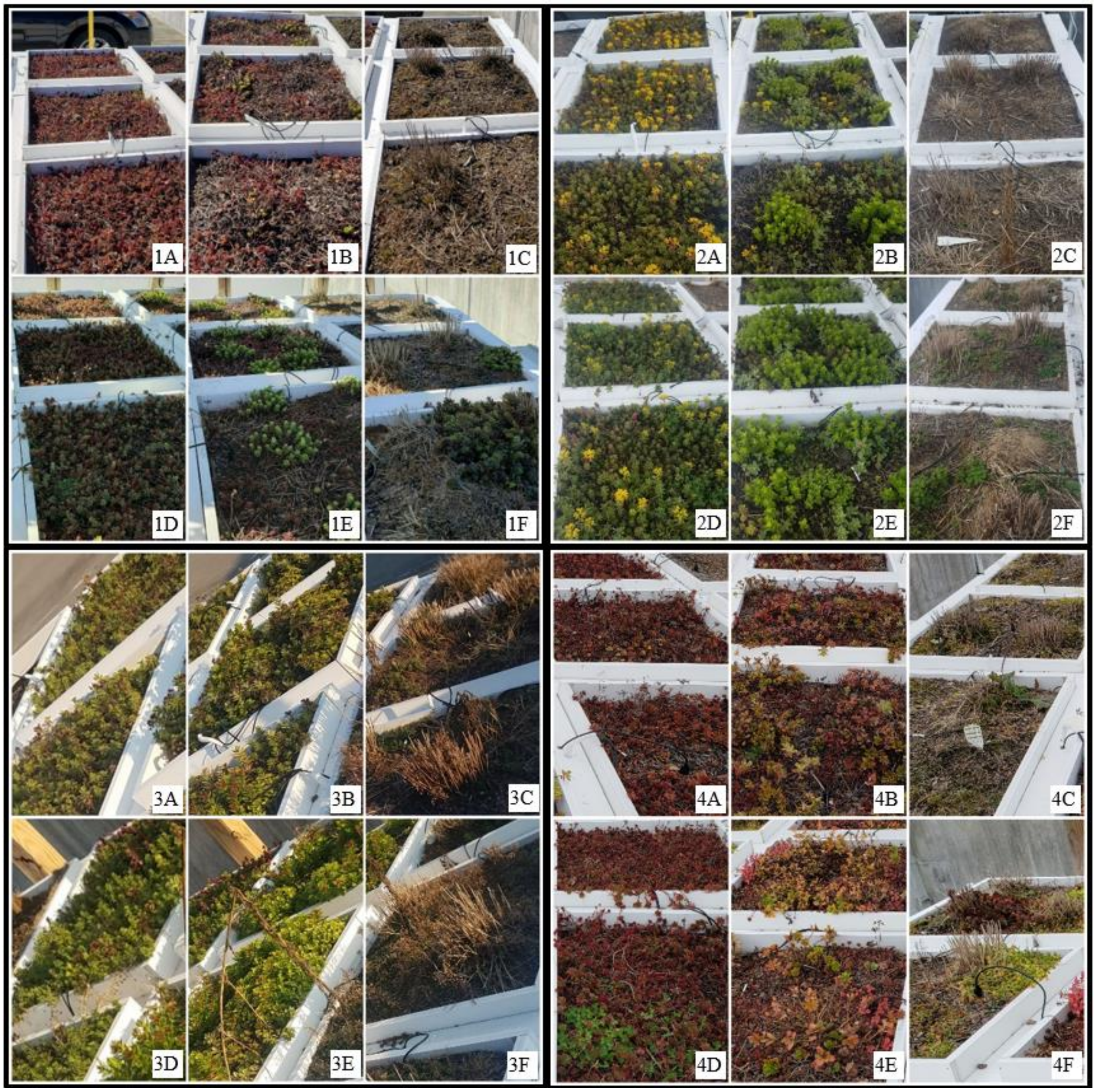


Figure 16: Photos from 3/23/19 (1), 5/8/18 (2), 7/29/18 (3), 11/19/18 (4) of vegetated green roofs: 3.3” non-solar (A), 4” non-solar (B), 6” non-solar (C), 3.3” solar (D), 4” solar, and 6" solar (F).

3.2.1 Spring

During the cooler months, the sedums took on a red color, turning green when temperatures began to rise. During March, the 3.3” and 4” vegetated green roof trials on both tables had a cover of thin red vegetation. The non-solar table had a few stems of green vegetation interspersed for these depths, while the trials equipped with the solar panels had a thin cover of green for the 3.3” and several dense green clumps for the 4” trials. The solar 6” depth had a few small clumps of green vegetation around the dead stumps of the grasses, while the non-solar table only contained the dead stumps. In May, green vegetation was more prolific and appeared denser than in March on both tables. The 3.3” depths appear to have very similar vegetation coverings for both tables. The 4” solar equipped trials appeared to have more surface coverage and denser groupings than the non-solar trials. Similar to March, the 6” depths for the non-solar table did not have notable live vegetation, while the solar equipped trials did, growing marginally over the season. A mix of sedum species and other vegetation started to grow around the grass remnants in the 6” deep trials during the Spring of 2018 and was left to grow, while the other trials were weeded. Observations throughout the Spring noted that the trials equipped with solar panels flowered earlier in the season than their non-solar counterparts.

3.2.2 Summer

During the Summer, vegetation in the 3.3” and 4” solar equipped trials appeared to be slightly denser, with deeper green tones than the non-solar trials. Vegetation cover in all 6” trials appeared to be minimal during the Summer months. This installation was installed during early Spring of 2017; by early Fall, the grasses in all of the 6” depth trials had died and were left in place in anticipation of them re-growing in 2018 when this observation period took place. Since they didn’t grow back, the remnants were left as other research was being conducted where a major disturbance of removing the stumps would have been disruptive.

3.2.3 Fall

Through the Fall, it was noted that vegetation for the solar trials remained greener and denser longer than the non-solar table, mirroring the effect seen in the Spring. By late Fall, nearly all vegetation in 3.3” non-solar trials had turned red, while its solar counterparts had clumps of green still remaining. For the 4” depth, there were green and yellow vegetation in addition to the red; however, there was less red and more yellow and green for the solar trials. 6” trials continued this trend, whereas the solar trials had a few clumps of dense green vegetation while the non-solar trials had sporadic and less dense vegetation coverage.

CHAPER 4: DISCUSSION

<u>4.1 Non-Solar Trials</u>

The greater surface and bottom temperatures observed for the black shingles and EPDM membrane over those of the green roofs are attributed to the lower albedo and vegetation. The green roof trials were able to reflect solar radiation and undergo evapotranspiration, resulting in lower surface temperatures. During the Winter and Spring, this difference was lower than during the Summer, when the vegetation had increased surface coverage and when ambient air temperatures and solar radiation increased. The maximum surface temperatures experienced during the first week of July exemplify the capacity for vegetated green roofs to reduce surface temperature extremes by 20-30 °F, greatly reducing the potential impact of roofs on the heat island effect. Bottom temperatures mirrored this effect with MRD to the black shingles increasing drastically from Winter to Summer. The lower bottom temperatures are due to the combination of reduced surface temperatures and the boundary layer created by the growing media for the green roof trials. These cooler bottom temperatures represent a greatly reduced impact on a building's thermal envelope.

Throughout the year, peak bottom temperatures of the shingles were greater than the surface temperatures of the green roofs, indicating the significant performance benefits of the green roofs. Minimizing the extreme temperature peaks during the

Summer will reduce electrical demand for air conditioning and promote comfort for individuals inside the building. Peak Summer temperatures experienced during daytime “business hours” offer the largest potential benefit to building managers as green roofs have the potential to reduce energy costs and promote inside comfort over black shingles and EPDM roofing materials.

When compared with the white PVC membrane, these differences are harder to distinguish. The PVC membrane, representing cool roofs, did exactly that. When compared to traditional black roofs, the PVC membrane performed similarly to the vegetated green roofs. During the Winter when vegetation was sparse, there was little to no surface thermal difference observed between the two. For bottom temperatures, all green roof depths stayed warmer than the PVC, likely due to stored solar energy during the day releasing at night or by trapping in energy that is escaping the underlying concrete structure. This effect helps insulate a building during the Winter months, reducing the energy required to heat a building. For the remainder of the year, surface and bottom temperatures of the green roof trials remained within 2°F cooler than the PVC, representing a minimal performance advantage during the warmer months. Since the performance of the white PVC membrane was very similar to that of the vegetated green roofs, ample justification of the premium costs to install a green roof over another cool roof method may not be plausible. For some building managers who make their decision based solely on thermal performance, white PVC membranes and other cool roofing methods may be more financially attractive than a vegetated green roof.

No significant difference was found in the surface temperatures between the non-vegetated green roof depths. Due to the bare growing media, little to no difference was expected as the dark surface was nearly identical across the trials. In addition, for the vegetated 3.3” and 4” depths, surface temperatures were not significantly different between the two. Although a different sedum mix was used in each depth, similar surface coverage and vegetation density was observed, likely performing similarly for solar reflection and rates of evapotranspiration. The 6” vegetated green roof did perform differently than the 3.3” and 4” trials due to the grasses dying. Since the grasses were not irrigated, the extreme conditions experienced did not support a more susceptible vegetation and it is therefore recommended that it be watered in the future. In an attempt to maintain some kind of vegetation, the 6” trials were not weeded as the other trials were. The plants that did establish, however, were not able to cover enough of the surface to have the same impacts as the already established sedum mixes. Because more growing media was exposed in the 6” trials, the surface temperatures reached several degrees warmer than the other vegetated trials during the Summer and early Fall. For both the non-vegetated depths and the vegetated depths, there was no significant bottom difference by depth. This indicates that a 6” vegetated green roof has nearly an identical impact on the building envelope as a 3.3” depth green roof, assuming there is no surface temperature difference, and therefore may not be worth the additional costs. Since the grasses were not alive during the observation period, there may still be an impact of the increased vegetation and biomass, as surface temperatures may be reduced drastically enough to create a bottom temperature difference. This effect can be seen between the 4” vegetated and non-vegetated trials, where the bottom temperatures averaged over 2°F cooler during the summer when vegetation was present. Therefore, thermal performance by depth was inconclusive for the 6” depth used in this study, but no difference found between a 3.3” and 4” deep vegetated green roof installation.

During the Summer, when temperatures and solar radiation were highest, all vegetated green roofs had significantly lower surface temperatures than the non-vegetated trials due to the higher albedo. Spring and Fall roughly followed this effect, although there were some trials that were not significant. There was no significance identified during the Winter, when vegetation covered the least amount of the surface and was not as dense. Since the albedo would then be similar between the vegetated and non-vegetated trials, it makes sense that surface temperatures were similar during the cooler months. Bottom temperatures were almost completely all non-significant between the vegetated and non-vegetated trials, showing that vegetation offers minimal potential to reduce the thermal impact on buildings above what the presence of growing media alone has.

It is important to note that the bottom temperature sensors were impacted by the air temperature under the table. The tables were constructed with “skirts” to enclose the space under the table in an effort to reduce the impact of wind and to help regulate the temperature through the energy storage capacity of the concrete structure; however, this may not have been enough. Installing the trials directly on a building’s roof or by heating or cooling the area under the table to minimize the impact of ambient air quality would be beneficial in the future. The George Mason University installation allows for strong comparisons between roofing materials but does not allow for direct quantification and monetization of the benefits as this conditioned building envelope is not present to assess heat flux and measurements of energy consumption.

4.2 Non-Solar Trials

The solar panels appeared to have a profound impact on the green roof vegetation throughout the year. In the Spring, the solar-equipped trials began to turn green and flower earlier in the month than the non-solar trials. This effect was mirrored in the Fall when the solar trials stayed green later into the season. This is believed to have been caused by the solar panels emitting stored sensible heat and re-radiating long wave radiation from the installation and the concrete parking deck back down toward the trials. This effect was shown by Barron-Gafford et al (2016), where solar panels were shown to keep nighttime soil temperatures several degrees warmer. Further research of this effect on green roofs is warranted as there is a potential to extend the growing season for green roof vegetation.

During the Summer, the solar panels appeared to promote surface coverage and vegetation density. This is likely caused by the shading provided by the panels. This shade reduces surface temperatures, raising soil moisture levels and effectively mitigating the severe drought conditions experienced on green roofs (Schindler et al., 2016). Reducing the surface temperatures should therefore increase the thermal performance of green roofs similar to how the presence of vegetation performed better than bare growing media.

Observed during the routine weeding and through allowing whatever vegetation to grow in place of the grasses in the 6” vegetated trials, it became apparent that colonizing species and weeds were more prolific on the solar table. The difference in temperature conditions from the solar panels may have contributed to this, as well as the introduction of seeds. Birds were often observed perched on the solar array, defecating on the panels and the roofing materials below. This is believed to be one of the main sources of seeds and colonizing species that made it onto the installation on the top floor of a parking deck.

In all, the solar panels promoted a longer growing season and increased vegetation density and surface coverage. Keeping green roofs greener beyond the average growing season may increase evapotranspiration rates, promote stormwater storage and mitigation, and improve air quality, in addition to reducing the heat island effect and thermal impacts on buildings.

CHAPTER 5: CONCLUSIONS

Previous research has demonstrated the ability for vegetated green roofs to reduce heat flux, reduce the heat island effect, and reduce energy demands from air conditioning and heating buildings. In addition, previous studies have shown that solar panels can be combined with green roof setups to reduce peak Summer temperatures. Few, however, have assessed traditional dark roofing materials, cool roofing materials, and various green roof depths side-by-side with and without being outfitted with a photovoltaic array. This study set out to test three different roofing materials: black asphalt shingles and EPDM membrane, both having a very low albedo, and a white PVC membrane representative of a higher albedo "cool roof." These traditional materials were compared to three depths of a commercially available, pre-established, and extensive green roof products that can be installed relatively anywhere the load can be supported by the building. These included 3.3", 4", and 6" depth vegetated green roof trials and a control for each trial that was left as bare growing media. Each were established as 2'x2' trials and replicated to include a photovoltaic array. The installation was constructed on the George Mason University campus in Fairfax, VA, on the roof of a four-story concrete parking deck. The observation period was from March 2018 through March 2019, with February omitted from the analyses due data collection errors. Each trial for the non-solar table was assessed for surface temperature and the temperature beneath the material to assess thermal performance. To assess the performance of the addition of solar panels, images and observations taken over the course of the study period were analyzed to identify differences between vegetated green roofs equipped with panels and those that were not.

Data collected for the trials without solar panels indicated that vegetated green roofs can average per day as much as 7% cooler than asphalt shingles, just shy of 10% for EPDM membranes on the surface and underneath. During one notable afternoon in July, the vegetated green roofs were cooler than asphalt shingles and EPDM by 20°F and 30°F, respectively. This enforces the findings of previous research and supports the hypothesis that vegetated green roofs out-perform dark roofing materials in terms of thermal performance.

Since the white PVC cool roof is designed to have a higher albedo than traditional darker materials, and therefore lower temperatures, it performed similarly to the green roofs, as expected. The green roof managed to stay mildly cooler during the Summer, but the opposite was observed during the Winter, when the bottom temperatures of the green roof were slightly warmer than that of the cool roof, reducing the energy needed to heat the building. In all, thermal performance over the year was very similar for the PVC membrane and vegetated green roofs.

The assessment of performance by green roof depth yielded surprising results as there was no significant performance difference identified with an increase in green roof depth. This did not support the hypothesis but highlights the potential for building managers to utilize shallower and cheaper green roofs while achieving the same thermal performance. Since there was no irrigation of the vegetation throughout the period, the grasses in the 6” depth died during the establishment period the year prior to observations. The manufacturer recommends supplemental irrigation during the Summer, when temperatures are hottest and the growing media driest to avoid this kind of die off. Because of this, it is important to note that there may still be an effect of green roof depth on thermal performance and it is worth further study.

The vegetation did significantly affect the surface thermal performance of the green roofs, as the bare soil trials averaged 2-3°F warmer than the 3.3” and 4” vegetated trials during the Summer months. This supported the hypothesis that performance would increase; however, below temperatures did not support this as the bottom temperatures were not significantly different based on the addition of vegetation. This indicates that the additional insulation barrier that the growing media provides outweighs the impacts of the vegetation alone on the building envelope.

Based on images and observations made of the two tables throughout the observation period, the addition of solar panels appears to promote a longer growing season with greater surface coverage and increased vegetation density. In addition to shading likely reducing surface temperatures, the more robust vegetation will further improve the thermal performance of surface temperatures as indicated by the performance of vegetated versus non-vegetated on the non-solar table.

CHAPTER 6: LIMITATIONS AND FUTURE RESEARCH

Several limitations and sources of error were identified following the construction and installation of the green roof "tables." Although the tables were designed to reduce the influence of wind and ambient air temperature underneath the trials, it became apparent that this could have been further reduced. Installing trials directly on a roof that has a heated and cooled interior, or artificially conditioning the air beneath the tables and insulating the installation, would help with this aspect in the future.

Irrigation was avoided during the observation period due to parallel research that was examining stormwater quality from the installation. Because of this, the grass in the 6" deep vegetated green roofs died, which could be avoided in future research.

Sensor and wiring errors became a huge limitation during the study as several lines of sensors that were wired together began consistently logging errors due to water short circuiting them. Protecting the wires from water and other physical interactions is strongly recommended. In addition, birds were noted on several occasions "pecking" at the surface sensors and wires, potentially requiring a deterrent or further sensor anchoring to limit bird interference.

In order to detect sensor errors, weekly data assessments should be conducted. Combing through the data regularly will help the researchers identify any errors so that a remedy can be made in a timely fashion.

APPENDIX A

Anova: Single Factor
Spring Surface MRD
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
T PVC	91	-3.57219	-0.03925	0.001415
T EPDM	90	2.203811	0.024487	0.001717
T 3.3" NV	91	-1.97797	-0.02174	0.001063
T 4" NV	91	-2.39756	-0.02635	0.001631
T 6" NV	90	-1.44259	-0.01603	0.002054
T 3.3"	273	-4.03538	-0.04434	0.002028
T 4"	273	-3.59828	-0.03954	0.002294
T 6"	273	-2.6762	-0.02941	0.001785

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.301751	7	0.043107	24.6586	3.26E-30	2.022315
Within Groups	1.255182	718	0.001748			
Total	1.556933	725				

Anova: Single Factor
Spring Bottom MRD
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
B PVC	91	-6.64352	-0.07301	0.001578
B EPDM	90	-1.03145	-0.01146	0.001015
B 3.3" NV	91	-3.35142	-0.03683	0.001086
B 4" NV	91	-3.45717	-0.03799	0.001521
B 6" NV	90	-3.39084	-0.03768	0.003257
B 3.3"	273	-3.40985	-0.03747	0.001756
B 4"	273	-4.55883	-0.0501	0.003297
B 6"	273	-3.98927	-0.04384	0.004161

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*

Between Groups	0.184542	7	0.026363	11.93344	1.92E-14	2.022315
Within Groups	1.586197	718	0.002209			
Total	1.77074	725				

Anova: Single Factor

Summer Surface MRD

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
T PVC	91	-4.60961	-0.05066	0.000612
T EPDM	72	2.018026	0.028028	0.001021
T 3.3" NV	91	-3.18279	-0.03498	0.000828
T 4" NV	91	-3.71475	-0.04082	0.001197
T 6" NV	89	-3.0972	-0.0348	0.001539
T 3.3"	273	-6.45299	-0.07091	0.002077
T 4"	273	-5.50647	-0.06051	0.001886
T 6"	273	-1.64525	-0.01808	0.001219

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.511091	7	0.073013	55.98006	1.52E-63	2.022662
Within Groups	0.911684	699	0.001304			
Total	1.422775	706				

Anova: Single Factor

Summer Bottom MRD

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
B PVC	92	-7.12899	-0.07749	0.000759
B EPDM	72	-0.72875	-0.01012	0.00034
B 3.3" NV	92	-3.56896	-0.03879	0.000567
B 4" NV	92	-3.58275	-0.03894	0.00068
B 6" NV	92	-4.95228	-0.05383	0.011144
B 3.3"	276	-4.81932	-0.05238	0.00117
B 4"	276	-5.94136	-0.06458	0.001492
B 6"	276	-4.67039	-0.05077	0.001701

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.228074	7	0.032582	14.25939	2.14E-17	2.022495

Within Groups	1.617746	708	0.002285			
Total	1.84582	715				

Anova: Single Factor
Fall Surface MRD
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
T PVC	91	-2.95846	-0.03251	0.000465
T 3.3" NV	91	-2.66304	-0.02926	0.001555
T 4" NV	91	-2.99866	-0.03295	0.001138
T 3.3"	273	-4.41565	-0.04852	0.001484
T 4"	273	-5.39486	-0.05928	0.002151
T 6"	273	-3.65114	-0.04012	0.001804

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.060459	5	0.012092	8.439007	1.06E-07	2.230708
Within Groups	0.773743	540	0.001433			
Total	0.834203	545				

Anova: Single Factor
Fall Bottom MRD
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
B PVC	91	-5.22306	-0.0574	0.00107
B 3.3" NV	91	-3.34276	-0.03673	0.001106
B 4" NV	91	-2.73499	-0.03005	0.000784
B 3.3"	273	-3.40534	-0.03742	0.001276
B 4"	273	-3.24824	-0.03569	0.001824
B 6"	273	-2.92765	-0.03217	0.002155

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.043698	5	0.00874	6.382992	8.98E-06	2.230708
Within Groups	0.739368	540	0.001369			
Total	0.783066	545				

Anova: Single Factor

Winter Surface MRD

SUMMARY

Groups	Count	Sum	Average	Variance
T PVC	57	-1.03345	-0.01813	0.000606
T 3.3" NV	54	-1.60258	-0.02968	0.001671
T 4" NV	50	-1.39839	-0.02797	0.002461
T 3.3"	147	-2.27695	-0.04647	0.00303
T 4"	159	-2.4137	-0.04554	0.004946
T 6"	159	-2.84782	-0.05373	0.003364

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.050322	5	0.010064	3.802025	0.002342	2.243113
Within Groups	0.820614	310	0.002647			
Total	0.870936	315				

Anova: Single Factor

Winter Bottom MRD

SUMMARY

Groups	Count	Sum	Average	Variance
B PVC	59	-3.10242	-0.05258	0.001919
B 3.3" NV	51	-2.27005	-0.04451	0.001566
B 4" NV	50	-1.57974	-0.03159	0.001486
B 3.3"	150	-1.11927	-0.02239	0.0026
B 4"	159	-0.48455	-0.00914	0.004628
B 6"	159	-0.48746	-0.0092	0.005756

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.089245	5	0.017849	5.951363	2.84E-05	2.243113
Within Groups	0.929738	310	0.002999			
Total	1.018983	315				

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BIOGRAPHY

Andrew Sachs graduated from Loudoun County High School, Leesburg, Virginia, in 2013. He received his Bachelor of Science from George Mason University in 2017. He was employed as the Sustainability Living Learning Community coordinator, interned with the Mason Water Forum, and served as the Undersecretary of Sustainability during his undergraduate career at GMU. He is currently employed as a Superintendent, overseeing the completion of multiple residential construction sites in the Northern Virginia area.