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The Seasonal Effects of Photovoltaic Cells on Sedum Eco Roof Substrate Moisture

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The seasonal effects of photovoltaic cells on sedum eco roof substrate moisture

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The seasonal effects of photovoltaic cells on sedum eco roof substrate moisture

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Abstract

This paper investigates a combined PV eco roof system and analyzes the soil moisture levels in front of the panels and directly underneath the PV Cells on an experimental ecoroof platform in Portland, Oregon. The purpose of the study was to examine how PV Cells create differences in the moisture level of the soil on the ecoroof. Four moisture sensors were set in different quadrants in four experimental testbeds, and the moisture level data was recorded from October 18th, 2018 to September 10th, 2019. The study found that in with heavy rainfall, the front of the testbed displayed more moisture, possibly because of the rain shading effect of the panels. In the dry periods, the moisture level behind the panels was higher, possibly because of the shading of the PV cells allowed for the retention of water through slowed evaporation. Combined system green roofs and PV cells deserve more research. Future work should be repeated in multiple

locations with different irrigation systems and plants to determine if these findings are applicable on a larger scale.

1.0 Introduction

Portland, Oregon, has embraced solar technologies and green roofs, which can be seen from the Ecoroof Standard in the 2035 plan (“Central City 2035 – Ecoroof Standard”). Ecoroofs are a type of green roof that typically needs little maintenance. The policy to have eco-roofs on Portland buildings has been in place since 2011, which requires all city-owned facilities and roof replacements over 500 square feet to have ecoroofs installed (“Case Study: City of Portland, Oregon Ecoroofs Incentive”). Forty percent of the city ecoroofs can have mechanical equipment installed, which includes PV Cells. There are many benefits of having photovoltaic cells in a combined system with green roofs, the main ones being that the green roof cools the PV cells, making them more efficient, and the PV cells provide shading for parts of the green roof (“Central City 2035 – Ecoroof Standard”). This paper will investigate PV cells affect green roof moisture dynamics. How does having a PV system on top of a green roof affect the moisture levels directly behind the panels compared to the front? It is predicted that the PV cells will affect the moisture directly underneath the cells.

2.0 Advantages and Disadvantages of a Combined Solar and Green Roof System

This research will investigate soil moisture in combined systems, but it is also crucial to understand why combined systems should be studied and are valuable in urban environments in the first place. This section is dedicated to understanding the pros and cons of combined PV-green roof systems.

2.2.0 Advantages of a Combined System

PV and green roofs have a large benefit of the green roof, cooling the PV cells leading to more energy output. A reduction in the urban heat island effect and the overall benefits that green roofs provide for are additional benefits.

2.2.1 Potential Benefits from the Green Roof

Green roofs are a large part of the benefit of having a combined system. Hydrological and air quality gains are aspects of green roofs. Popularity for green roofs has risen over the last ten years (Dinardo 2016). Green roofs can retain water during storm events causing a delay of entry to combined stormwater and wastewater systems meaning that wastewater treatment plants will have more time to process fallen rainwater, reducing the system burden. In Portland, rainfall retention in the winter can be 12% and 42% in the summer, with extreme retention as low as 0% in the winter, as high as 85% in the summer (Spolek 2008). Through the city of Portland's incentives from 2008 to 2011, 8 acres of green roofs have managed an average of 3.3 million gallons of stormwater each year ("Case Study: City of Portland, Oregon Ecoroofs Incentive"). Garrison reasons that a green roof policy should be implemented on the basis that they would be beneficial with their connection with improved air quality (Horowitz et al. 2012). Through transpiration, plants circulate air and pull certain pollutants into their leaves through microscopic openings in a process called stomata. Plants also take carbon dioxide, sunlight, and water to produce oxygen, air, and sucrose. In Yang's article, "Quantifying air pollution removal by green roofs in Chicago," intensive green roofs, including trees, shrubs, and grasses, removed ozone, nitrogen dioxide, and PM10 particulates (Yang et al. 2008). Green roofs have the potential to increase air quality in urban environments and reduce system pressure on combined urban wastewater treatment.

2.2.2 Heat Island Effect

Green roofs can have a positive impact on mitigating the urban heat island effect. The urban heat island effect is when an urban area experiences warmer temperature than the surrounding rural areas. According to the Environmental Protection Agency, “Heat islands can affect communities by increasing summertime peak energy demand, air conditioning costs, air pollution and greenhouse gas emissions, heat-related illness and mortality, and water pollution.” (“Heat Island Effect”). Roofs with a combined system could reduce sensible heat flux by 45% (Scherba et al. 2011). Sensible heat flux is the transfer of energy-related to changes in temperatures. Green roofs reducing the heat island effect was also encouraged by the Natural Resources Defense Council’s research on reducing climate change in Southern California (Horowitz et al. 2012).

2.2.3 Optimization

The large benefit of having a PV cell and green roof combined system is that the green roof creates a microclimate that cools the immediate area around the vegetation, which is beneficial to the solar panels since it allows them to run more efficiently, resulting in more power output (“Central City 2035 – Ecoroof Standard”; “Stormwater Management Manual”). In a 2011 Hong Kong study their urban combined system resulted in 8.3% more electricity than having PV cells alone on a roof (Hui et al. 2011). Butler and Orians found in their 2011 Massachusetts study that their vegetation on their green roof reduced the temperature of the soil by a maximum of 44° Celsius. Chemisana and Lamnatou found the combined system not only increased the maximum power output of their solar panels but that the PV modulus protected the plants from high irradiances (Chemisana et al. 2014). Overall, having a combined system is a benefit to the PV modules.

2.3.0 Potential Disadvantages of a Combined System

Cons of having a combined system include the capital cost associated, application of installing a combined system, and the space required for installation.

2.3.1 Financial Capital

The major con to installing combined system roofs is the cost associated with the initial installation, maintenance, and the environmental cost over the lifetime of the panels. Statler's research paper focused on the costs of combined systems versus separate systems in Portland, OR. A 2014 cost analysis of the ecoroof incentive by the city of Portland found that the median installation costs, "range from approximately \$6.00 per square foot for single-family residences up to \$15.55 per square foot for institutional installations." ("Cost Analysis for Portland Ecoroof Incentive"). Statler found that the best return on investment came when older buildings installed green roofs alone, but newly constructed buildings built combined systems (Statler 2017). The ecoroof standard for the city of Portland referenced that, on average, ecoroofs can cost approximately 4% more to maintain than a standard roof ("Central City 2035 – Ecoroof Standard"). Contrary to this, a typical roof needs replacement every 20 years, while an ecoroof only needs replacement every 40 years, in such a way that these costs may balance out, dependent on the amount of time the building is inhabited ("Central City 2035 – Ecoroof Standard"). In extreme weather events, the plants may die, although sedum are resilient, replacing plants that have died or have been taken over by weeds is an unpredictable maintenance cost [1]. Finally, there may be a cost barrier to lower class residential citizens who wish to utilize the technology. Despite praise for Portland's incentive, citizens can be deterred if they do not fall into a high enough tax bracket to have tax credits be useful. ("Investment tax credit for solar power"). Combined PV ecoroof systems can be a high initial investment

monetarily and environmentally, but if the design is optimized and the initial costs can be paid, the long-term return and reward are high.

2.3.2 Environmental Cost

There can be an initially high environmental cost of installing a new PV-green roof system. Lamnatou studied the overall environmental impact and costs of combined PV-green roof systems in 2015, using the ReCiPe method, which ultimately looks at the damage to human health, the ecosystem, and resource availability in the long-term (Lamnatou et al. 2015a). The research focused on systems in Spain, despite mixed conclusions, Lamnatou found that the PV system had a high initial impact, but combining it with a green roof reduced the impact long-term due to the high performance from the cooling effects of the green roof (Lamnatou et al. 2015a). Initial impacts can be mitigated by buying locally when possible and using sustainably sourced materials when possible in the PV construction.

2.3.3 Application

Not all buildings have the load capacity on the roof to support a green roof and/ or PV system (green roofs are typically the heavier of the two). The City of Portland's Stormwater Management Manual says when installing an ecoroof, "The load-bearing capacity of the roof must be evaluated by a licensed professional, and the design must comply with building code requirements." p.106 ("Stormwater Management Manual"). Having combined systems installed may not be feasible for residential houses and older commercial buildings.

2.3.4 Space Required

The space required to have both a green roof and a PV system could be competitive, in Hui's article there was a stated concern that in using both technologies, they are competing for

available roof space (Hui et al. 2011). However, in Lamnatou and Chemisana's 2015 article, they praise the combined system for having a better utilization of space compared to using each system separately (Lamnatou et al. 2015b). It may be up to design and location to determine if the combined system is saving space as opposed to each competing for space.

Some of the benefits include increased energy output from the solar panels, while the panels may potentially protect the green roofs from harsh sun, reduced heat island effects in urban areas, and improved water management. Cons associated are an initial cost barrier, initial steep environmental impacts from the PV system, not being applicable for all roofs, and spacing. In the long-term, the combined system is an excellent method for saving costs and improving the urban environment.

3.0 Thesis Question

How do photovoltaic cells on greens roofs impact soil moisture in Portland, Oregon, across seasons? To address this question, this research evaluates the effects of shading and rain shadow on the moisture levels behind the panels compared to the moisture levels in front of the panels.

4.0 Hypothesis

It is predicted that the moisture level underneath the PV cells will differ from the moisture level in front of the cells. The PV cells may stop rain and water from reaching the soil underneath the panels, and the sunshade may affect the evapotranspiration of the soil moisture when there is substantial sunlight.

5.0 Why this Work is Needed

Multiple PV-green roof research papers reference the benefit to the green roof having a PV module on it, without direct research to support the claim of the specifics of how it improves the

green roof. Frequently in research papers, the benefit of not having direct light on the vegetation is mentioned, but less on how the soil hydrology changes with the addition of solar panels, which can affect the plants. The information about how shade and moisture affect the green roof in the combined system can be used to alter the setup of future systems for optimization and maximum benefit.

6.0 Material and Methods

This section will review the set of the combined system testbeds and how data will be collected.

6.1 Experimental setup:

Data used in this research was collected from PV panels and green roof test beds on the Science Research and Teaching Center (SRTC) Building at Portland State University (PSU), Portland, Oregon. There are four testbeds, each with four SolarWorld 175-Watt photovoltaic panel (see Figures 1 and 2). The dimensions of each PV panel are 0.8 m by 1.6 m; all are south-facing. Panels are spaced 0.3m apart. Each panel has an Enhance M210 Microinverter with a maximum power output of 210 watts. Each test bed is approximately 3.8 m by 4.7 m. In each corner, there is a drain plug (See Figure 4). The setup is had 16 cm of soil cover, a root barrier, and a water-resistant membrane. The two primary plants used in the green roofs are Sedum Album and Sedum Floriferum (see Figure 2). The sedum was chosen for their previous successful use in green roofs, their shallow root system, and their resiliency. In the summertime the green roofs were irrigated using a spray irrigation system with sprayers located in each corner of each bed.

Figure 1. PSU STRC PV-Green Roof Experimental Setup's Front (Looking South East)

Figure 2. PSU STRC PV-Green Roof Experimental Setup from Behind (Looking Southwest)

6.2 Collection of Moisture Data:

A soil moisture sensor collected moisture data (Decagon EC-5, see Figure 7). The moisture sensor reports the percentage of moisture. These sensors determine moisture content based on dielectric permittivity of the material, there was a 2.5 cm sensing radius (Figure 7). The sensor data was then correlated to volumetric moisture data. The moisture data was recorded every minute for a year and stored by a data logger (Campbell scientific, CR1000, see Figure 6). The moisture data set was condensed and averaged out by the day. There were four dielectric-based soil moisture sensors in each quadrant of each PV-green roof testbed (see Figure 5).

Figure 3. Dimensions of PV-Green Roof Test bed

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199 Figure 4. Approximate Sensor Locations

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201 Figure 5. Data Collection Box

Figure 6. Example of a Dielectric-based soil moisture sensors

Precipitation data was compared to the moisture data to see rainfall events and how those events correlate to the moisture levels. The precipitation data were used to observe when the testbeds were irrigated by looking at spikes in moisture without a rainfall event. The rain data was collected from the National Oceanic and Atmospheric Association's (NOAA) National Centers for Environmental Information (NCEI) Portland Airport database [12].

6.3 Modeling of Shading Effects:

Modeling the sunshade in Google Sketchup was chosen over using light sensors because light sensors would be too complex. Light sensors would require too many sensors being added without a good understanding of how the spacing between the panels might affect the shading. The slits and spacing between each panel create pockets of light that shift throughout the day. Google Sketchup has a feature for the position of the sun at different times of the day, year, and at specific time zones (Portland is GMT-7). The simplified experiment set up was modeled, and then pictures of the shading behind the panels by the sunlight were taken at hourly intervals through three dates from sunrise to sunset. The pictures of each panel for a day were layered at eighty percent transparency over one another in Microsoft Publisher to create a combined image. The combined image shows areas that received the most amount of sunlight in the brighter areas and the least in the darkest areas of the picture. The PV Cells face south-west, a google map image of Portland was imported to Google Sketchup, and the model was placed directly on top

of where their placement was on the map to ensure accuracy with solar direction. A second story behind the panels could have created potential additional shading, so the section of the building directly behind the panels was modeled for accuracy (See Figure 8). An example of what the model looks like before modeling at 100% opacity can be seen in Figure 9.

Using the model, a rain shadow area will also be estimated. A rain shadow is when there is no rain hitting a section of sedum because the PV Cells will be blocking it. The rain shadow estimation will be made by drawing lines directly down from each corner of the PV Cells. The wind would change the area of a rain shadow, but since this is not a water model, that effect will not be taken into consideration.

Figure 7. Shading Model Set-up

Figure 8. The Shadows on the Model without Layering

The analysis of soil moisture and information on the testbeds is still being conducted as of August 28, 2020.

7.0 Effects of Combined Systems to Consider

The following considers different aspects that affect the performance of combined PV-green roof systems. Understanding the possible effects is essential for comprehending the parameters of this research. Discourse about green roofs requires local adjustments, such as tilt angle, for example, since how the sun is captured differs in different latitudes and longitudes in the world. For example, the optimal tilt angle for Hong Kong or Spain might not be ideal for the Pacific Northwest. Plant type will vary based on the yearly weather of the location as well.

7.1 Plant Type

Plant types for green roofs vary widely and significantly affect the overall success and resiliency of the roof. For the sake of this paper, only sedum green roofs will be observed, although roofs

with other types of vegetation are commonplace. Butler found that the sedum helped reduce water loss from the soil and the fact that sedum, such as *Sedum album* has a shallow root system, and high growth makes it a perfect candidate for green roofs (Butler et al. 2011). Each species of sedum has differences in growth rate, drought tolerance, leaf shape, and root depth (Butler et al. 2011). *Sedum Album*, *Sedum Rupestre*, *Sedum Sexangulare*, and *Sedum Spurium* are commonly used on green roofs, but the small differences can create changes in overall performance. An experiment in the research of a PV-sedum roof versus a PV-gazania roof showed that the sedum roof led to 2.21% more efficiency than the gazania attributed to the higher irradiance received on the PV cells with the Sedum (Lamnatou et al. 2015b). Schroll's experiment theorized that the plant selection would primarily affect the retention of water during storm and dry weather events (Schroll et al. 2011). Having a variety of plant species could potentially maximize benefits green roofs provide.

7.2 Substrate

Substrate is the material that vegetation is planted in. The substrate for an ecoroof is placed above a waterproof membrane and root barrier. According to the City of Portland's Stormwater Manual, a growing medium minimum of 4 inches is required (Schroll et al. 2011). Water holding capacity should be a consideration to capitalize on stormwater retention (Schroll et al. 2011). Jahanfar discussed sections where water cumulates, such as in front of the solar panels, where small temporary pools can be created (Jahanfar et al. 2018). Lamnatou's analysis of PV-green roof research mentions that a thicker soil substrate leads to a higher reduction of heat fluctuations from the building, and soil that is less dense can have good insulator effects as well, which can leave to money saved with reduced heating and cooling (Lamnatou et al. 2015b).

7.3 Solar Panel Tilt, Spacing & Height

When setting up the PV system, there are many factors to take into account; some are the tilt or angle at which the solar panels are facing the sun, the spacing in between each panel, and the placement height off the roof. Jahanfar analyzed the shading effects of PV-green roof combined systems by observing plant growth at two different heights of 0.6 m and 1.2 m (Jahanfar et al. 2018). The research found that the native forbs and grasses' growth was 47% greater with the 1.2 m modulus, but they noted that when the modulus is up that high, there is not the cooling effect that makes the combined system optimal (Jahanfar et al. 2018). Statler's research was explicitly designed to find an optimum tilt angle in Portland, OR, and was found to be 36° (Statler 2017). The article also pointed out many of the PV systems in Portland are more than 10° off from the proposed optimal angle (Statler 2017). For panels that are in areas with a significant seasonal difference, the optimal tilt angles range from 18° in the summer and 69° in winter (Statler 2017). One concern that was not found in the articles was the spacing in between each solar panel. Light filters in between the panels, which may affect the growth and health of the plants behind the panels.

7.4 Plant Protection: Moisture Level/ Shading

Several articles suggest that having PV panels on green roofs may be beneficial to the plants because of the shading, but none of them analyzed this effect quantitatively, just qualitatively. The Ecoroof standard for the City of Portland states, "Solar panels and ecoroofs are compatible with each other. Solar panels provide shade for the plants and protect them in inclement weather. The ecoroof helps cool the solar panels. Solar should be installed with breaks between panels to allow rainwater and light to reach the plants." (p.1) ("Central City 2035 – Ecoroof Standard"). Chemisana states that "The modules protect the plants from high irradiances." (p.256) (Chemisana et al. 2014). Lamnatou in the 2015 article states that "PVs protect plants from direct

exposure to sunlight and in this way plant growth and plant species variety are enhanced.” (p.270) (Lamnatou et al. 2015b). Note that Lamnatou references the Chemisana article, *Photovoltaic-Green Roofs: An Experimental Evaluation of System Performance* when citing this claim, but that article does not have any citations or research for their claim. Witmer’s 2011 article mentions, “PVs benefit from the thermal properties of the green roof while the green roof simultaneously benefits by reduced scorching from the partial shading of the array.” (p.3) (Witmer et al. 2011). The main research article that does not wholly agree is Jahanfar’s, who theorized the reason for the better plant growth with the taller panels is because there was better solar radiation and rain exposure (Jahanfar et al. 2018). Jahanfar did not use sedum and did not quantitatively conduct additional research to prove this theory. Sedum Album, which was used in this research, prefers full sun but can tolerate light shade (“Sedum Album Care.”).

8.0 Results

These results came from data analyzed and collected between October 18th, 2018, to September 10th, 2019. First, the moisture data results will be analyzed, followed by the shading effect analysis of the panels using the Google Sketchup model.

8.1 Moisture Data Results:

The refined data took the averages of each day to correspond to the National Oceanic and Atmosphere Association’s (NOAA) and the National Centers for Environmental Information (NCEI) Portland Airport precipitation data, which was daily (“National Centers for Environmental Information”). Outlier data was removed when it was outside twice the standard deviation. Only two data points were removed. To analyze the effects of moisture of the soil in regard to the PV Cells, the front moisture level of each pan was averaged, and the back moisture

level of each pan was averaged (See Graph 1). Three distinct patterns emerged from the overall graph where were categorized by three different seasons. A rainy season from October 18th, 2018 to April 18th, 2019, where there was constant rainfall, and the front and back moisture levels followed similarly (See Graph 2). The transitional season was from April 19th, 2019 to June 18th, 2019 (See Graph 3). It was during the transitional season that the graph started to diverge, with the emergence of dry periods, but the pans were also not irrigated at this time. Finally, a dry season occurred from June 19th, 2019 to September 10th, 2019, which was mainly in the summer and occurred when the pans were being irrigated regularly.

Irrigation needed to be identified in the data set. The pans were irrigated, but the exact dates of irrigation were not part of the original data set. Irrigation was found by identifying when there was a jump in moisture but not precipitation, which occurred starting on June 19th, 2019. The irrigation following the Jun 19th date was found out to be weekly, approximately until August 8th, 2019, when it seemed that irrigation was stopped.

Graph 1. All Pans Averaged: Moisture Level vs. Date

331 During the rainy season, displayed in the above figure, the front of the pan has a slightly higher
 332 moisture level than the back of the pan (See graph 2). In Graph 2, the two lines of data of the
 333 front and back moisture levels are consistent with each other. The majority of the standard error
 334 bars for the moisture level overlap, suggesting that the difference in moisture levels from the
 335 front of the pans to the back is nearly insignificant. When comparing Graph 6 through Graphs 8,
 336 it can be seen that graphs 5 and 7 show a higher moisture level in front of the pans, while Graphs
 337 6 and 8 show high moisture levels in the back of the pans. Generally, the data shows moisture
 338 levels increasing with rainfall events and decreasing during dry periods.

339 Graph 2. Rainy Season: Moisture Level vs. Date
 340 In Graph 3, there are very few of the standard error bars which overlap during the transition
 341 period. Note that in Graph 3, the back sensors had a higher moisture percentage. The one point
 342

where there was a switch back to the front sensors having a higher moisture level was after a major rainfall event starting on May 24th, 2019, with the back sensors regaining the higher moisture level on June 6th, 2019.

Graph 3. Transition Season: Moisture Level vs. Date

Finally, the dry season data shown by Graph 4 displays the summer and early fall months where it was the driest and when the pans were irrigated. Moisture level jumps in Graph 4, where no precipitation is present, are most likely due to spray irrigation that happened approximately once a week. When looking at Graphs 6 and 7 in the same time period, there were more sporadic jumps in the front sensors compared to the back. From June 19th, 2019 to August 28th, 2019, the front sensors displayed a significantly higher moisture percentage. After the 28th, the sensors at the back of the panels display a higher moisture percentage again. When looking at the moisture

percentages trend of having the percent rise when there is no rainfall event stops on August 12th, 2019, indicating that this was most likely when irrigation stopped as well.

Graph 4. Dry Season: Moisture level vs. Date

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364 Graph 5. Pan 1: Moisture level vs. Date

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366 Graph 6. Pan 2: Moisture level vs. Date

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368 Graph 7. Pan 3: Moisture level vs. Date

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371 Graph 8. Pan 4: Moisture level vs. Date

8.2 Shading Effect Modeling Results:

The dates chosen for the sunshade modeling were taken in the middle of the rainy, transition, and dry season. Three pictures were created as results from the eighty percent transparency overlapping. Figure 10 is from January 16th, Figure 11 is from May 19th, 2019, from 6:00 a.m. to 8:00 p.m., and Figure 12 is from July 30th, 2019, from 6:00 a.m. to 8:00 p.m. The sedum section of the testbed was colored white to display the shadows more clearly. The overall area the shadows appeared on the pan are highlighted by a red box. January's figure had fewer sunlight hours overall and was darker in general (See Figure 10). The section of the box covered with a shadow is at the very back of the pan, with the section under the front of the solar panel receiving a decent amount of sunlight.

Figure 10. Shading Effects Rainy Season 1/16/2019 9 a.m. to 6 p.m.

The rainy season was the longest period observed in this study. Figures 11 and 12 look very different from Figure 10 with there being a 124-day difference between Figures 10 and 11, but

Figures 11 and 12 had a 73-day difference. That being said, Figures 11 and 12 look similar to each other and will be discussed together. In both figures, the shadow area is moved forward to be closer to the front of the PV Cells with the back of the pan, receiving more sunlight. The overall width of the shadow is slightly more in the spring and summer months. In Figures 10 through 12, there are complex lighter and darker areas of the overall shadow, meaning that different areas underneath the panel do not receive the same amount of sunlight throughout the day or year because of the changing position of the sun and the width of the panel slits.

Figure 11. Shading Effects Transitional Season 5/19/2019 6 a.m. to 8 p.m.

Figure 12. Shading Effects Dry Season 7/30/2019 6 a.m. to 8 p.m.

An elementary rain shadow was created in Googled Sketchup and can be seen in Figure 13. The grey section of the model underneath the PV Cells is the approximate area that would be affected by a rain shadow. The grey area would potentially receive less rainfall and thus soil moisture because the PV Cells would be covering the ground. The light blue area in the model displays what areas would receive an average amount of rainfall. The dark turquoise section of the model displays a rough estimate of the section of the pan that would receive extra water because the rain that falls on the solar panels would, in theory, run down the panels, which created a small pooling effect at the base. Because this is just a physical model and not a water simulation, the areas are not exact.

Figure 13. Potential Rain Shadow

9.0 Discussion

The overall effects of the PV-ecorooftop green system and substrate moisture levels, errors that could have come throughout the experiment, the potential rain and shade shadow for the rainy, transitional, and dry seasons, and future research is described in this section.

Shading through the model did not display large areas that received more shade or light behind the panels. The transitional and dry season showed more defined lines of lighter and darker sun shadows, but overall, there was a general shading behind the panels with the sun light reaching the back throughout the day. The latitudinal and longitudinal location and the south-west facing position were factors and allowed for light to hit the plants behind the panels, but still, receive more shade throughout the day than the plants in the front. Taking into account that shading differences in the front versus the back of the PV cells could potentially help with understanding how to install a more diverse plant selection, because some eco-rooftop plants may want less direct

exposure of sunlight throughout the day (Lamnatou et al. 2015b). The Ecoroof standard for the City of Portland suggested having panels to allow for water and sunlight to reach plants, having a slit in between the panel placement did allow for water and sunlight to come through, but not evenly (“Central City 2035 – Ecoroof Standard”).

The moisture levels changed throughout the seasons, with a rain shadow being the likely culprit. The potential rain shadow area in Figure 13 displays where dry spots may occur because the panel blocks the rainwater. Higher moisture levels in the front of the testbed in Figure 2 could be attributed to this lack of a shadow, but this was when water was most available, and there was at most a 3% difference from the front and back moisture sensors. Schroll theorized that plant selection would primarily affect the retention of water events (Schroll et al. 2011). The choosing of plants for combined system PV-ecoroofs could be enhanced by understanding this subtle change in moisture levels in front and behind the PV-cells. The moisture level behind the panels seemed to stay moist longer after large rainfall events in the transitional and dry periods when dismissing irrigation. This experiment’s spray irrigation system did not seem to each of the sensors, as well as rainfall did. The reason for the back-panel soil keeping moisture longer is potentially because there was less direct exposure to the sun. Ecoroofs are generally designed to require less maintenance and little to no irrigation compared to green roofs, so having soil stay moist for longer periods of time after a rainfall event in Portland, OR, is helpful when designing new installations. Overall having a better understanding of the rain shadow and sunshade is valuable when deciding on plant heterogeneity.

There were several potential sources of error that occurred during the experiment. When observing Graphs, 3 to 8 negative moisture percentages were displayed. The moisture sensors were calibrated using previous measurements of soil moisture. The initial calibration of moisture

444 was too low, resulting in negative moisture percentages in drier weather. Negative 6% is most
445 likely closer to 0% moisture, due to it being the lowest percentage observed. Note that even
446 though absolute values for moisture content may be off, the relative differences between the
447 sensors at different locations should still be valid. When observing Graph 3, on 6/6/2019, there
448 was a large rainfall event without an equally high jump in moisture level after the event. The
449 reason for a large precipitation record without a proportional jump in soil moisture could have
450 been because the precipitation data were collected at the weather station at the Portland Airport,
451 which is seven miles away from the project site. Although the rainfall mainly corresponds to the
452 jumps in moisture in the graphs, there is potential for considerable weather changes in that seven
453 miles. The airport could have received much more rain that day than at Portland State's Campus.
454 The other reason for the discrepancy is the Hysteresis effect in soil. Hysteresis is defined as the
455 difference in the relationship between the water content of the soil and the corresponding water
456 potential obtained under the wetting and drying process. The soil was dry for an extended period
457 and thus hardened, which in turn could have reduced its ability to absorb water from the rainfall
458 event. Lastly, when observing the individual pan's graphs (Graph 5 to 8), Pans 1 and 3 (Graphs 5
459 and 7) display large jumps in the front line for the dry season. The jumps in the front panel
460 moisture level start soon after irrigation begins. A reason for the erratic jumps could be because
461 of poor sensor placement, so those four sensors receive more water during the spray irrigation.

462 Looking at moisture levels in front and behind PV Cells should continue to be looked at, but with
463 the following recommended alterations. The experiment should be redone using different slit
464 measurements. Modifying such measurements could help observe any substantial changes. A
465 larger pan should be used with PV Cells behind the front panels as well to determine if the
466 sedum is negatively impacted by the shadows the extended out of the box in this experiment. At

least twice as many moisture sensors are needed in each pan to increase accuracy. Having a drip irrigation system instead of a spray one would be more compliant with the City of Portland's standards and potentially reduce the error experienced in the summer with Graphs 5 and 7. A water model would give a more in-depth understanding of how the water moves, pools, and where the rain shadow is in regard to PV Cells and eco-roofs. The precipitation data should be collected at the site of the panels for more accuracy, or at least in closer proximity than the seven miles in this experiment. Finally, this experiment set up should be reproduced in multiple locations. The microclimate created on top of the PSU STRC means these results thus far only apply to this specific location. For these findings to be generalized more research in the different locations must be done. There are numerous improvements that can be made and different variables to test in this subtopic of combined systems, and the previous recommendations are a start.

Combined system green roofs and PV cells have the greatest influence on moisture heterogeneity in the transition and dry period for the irrigated roof. It is likely that unirrigated roofs would see the greatest PV influence on substrate moisture variation in the summer months in Portland. More work is needed to determine how this increase in moisture behind PV cells can be utilized to maximize green roof ecosystem services. Future work also should address this question at multiple locations with different irrigation systems and plants to determine if these findings are applicable on a larger scale.

10.0 Conclusion

The climate of Portland is characterized by long periods of rain, short summers, and scarce snow that has an overall natural effect. When there are periods of rain, the soil in the front of the panels displays higher moisture levels. While in the dry periods, the soil behind the panels has a higher moisture level, most likely due to the shadow effects delaying evaporation. The difference between the soil moisture levels in the front and back of the PV Cells are similar. Although not a focus in this study, through surface-level observation, the sedum in the front was at the same density as the back of the panel with similar growth. Overall, the PV Cells did not have a noticeable negative effect of the sedum of the eco-roof, and aside from minor changes with the season and the major irrigation change, the solar panel worked well in the combined system.

The benefits of long-term PV-green roof systems are worth the initial investment if feasible. More cities include incentives and building codes to support green roofs, such as Portland. Further research should be done on how to optimize the combined system best. The research around moisture levels at different sections of the green roof is just one possible research topic to better understand and explore. If PV Cells have no negative effect on eco-roofs in a combined system, and in fact, the eco-roof positively benefits the solar panel energy output, then why should the city of Portland standard only allow 40% of solar on green roofs?

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