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Photovoltaic array influences the growth of green roof plants

Jennifer Bousselot¹, Thomas Slabe², James Klett³, Ronda Koski⁴

¹*Affiliate Faculty and Instructor, Department of Horticulture and Landscape Architecture, Colorado State University jmbouss@colostate.edu*

²*Biologist, U.S. Environmental Protection Agency*

³*Professor, Department of Horticulture and Landscape Architecture, Colorado State University*

⁴*Research Associate, Department of Horticulture and Landscape Architecture, Colorado State University*

ABSTRACT

A multi-faceted research project was conducted on a modular green roof in semi-arid, high elevation Denver, Colorado U.S.A. A photovoltaic (PV) array ran along the southeastern edge of the research area and visibly influenced the plant growth, cover and biomass. Plants grown near the PV prospered compared to plants in the exposed area. Average summer temperatures in the modules under the PV array were cooler with less temperature variation compared to the modules located in the exposed areas of the green roof. Shading structures integrated on green roofs may produce effects that resemble natural ecotones tending towards greater plant coverage and biomass, and therefore greater green roof resilience.

Keywords: *solar panel, photovoltaic, plant survival, overwintering*

INTRODUCTION

Living architecture is increasingly popular in North America and across the world. Yet, green roofs can be viewed as competitors for space on rooftops with other environmentally-friendly building technology such as solar photovoltaics (PV). However, the integration of vegetative roofs and PV can be mutually beneficial.

Few studies have described the *in situ* performance of plants or PV when both technologies - share the same rooftop (Hui and Chan 2011, Köhler et al., 2007). It has been demonstrated that crystalline silicon PV arrays perform more efficiently when temperatures are cooler (Hui and Chan 2011), near the optimal operating temperature of 25°C, and decrease by half a percent in efficiency per temperature increase of one degree centigrade (Koka 2011). In one case, an increase of 6% efficiency of PV arrays above green roofs was realized (Köhler et al., 2007) and, similarly, a PV array generated 8.3% more electricity when installed on a green roof (Hui and Chan 2011).

Certain green roof plant communities appear to benefit from receiving partial shade (Dvorak and Volder 2010), which PV arrays and other shading structures can provide, especially those plants in high solar radiation environments. Shading lowers the impact of high irradiance and low substrate moisture (Hui and Chan 2011), so moisture is retained and less irrigation is required. In a study on PV and green roof interactions it was noted that green roof plant dry weight increased in the protection of PV arrays, likely due to reduced environmental stresses (Köhler et al., 2007). In another high solar irradiation location in the semi-arid western United States, Salt Lake City, Utah, researchers noted differences in species richness of plant communities based almost solely on solar exposure (Dewey et al., 2004). Others have noted that shading from upper-story floors can produce an effect on evapotranspiration rates of green roof plants (MacIvor and Lundholm 2011). Plant cover, evaluated on a green roof in full sun versus full shade did not change but relative species compositions did change (Getter et al., 2009). Increasing plant species richness on a green roof is ideal because as species fill niches to which they are more appropriately adapted the outcomes tend towards more uniform coverage.

Green roofs have been demonstrated to lower roof surface temperatures in semi-arid environments (Slabe et al., 2011). This is due to plants cooling their surrounding environment through evapotranspiration and the dissipation of energy as latent heat. Results from a modeling study indicate that a green roof combined with PV may reduce the overall summertime heat flux, compared to black membrane rooftops alone, by over 50% (Scherba et al., 2011).

Although the primary objectives of this study were to evaluate mixed stand plant species' performance and weather conditions on a green roof (see <https://www.epa.gov/sites/production/files/documents/BiologicalPerformanceQAPP.pdf>), a secondary objective emerged after it was observed in 2008 that partial shading from the PV array visibly influenced plant growth. *Ex post facto* examination of the results revealed observations

worthy of reporting, especially considering the growing interest in improving green roof performance and combining green roofs with PV electricity generation. Presented here is the vegetation and environmental data from the primary study as a post-hoc analysis.

MATERIALS AND METHODS

Research Site.

Plant species performance and weather data were collected in 2008-2010 on an existing mixed *Sedum* modular extensive green roof on the U.S. EPA Region 8 headquarters building in Denver, Colorado. Both the green roof and a proximate conventional gravel ballasted roof (control roof) were instrumented with Campbell Scientific weather stations. The methods for the plant species performance have been discussed in detail previously (Bousselot et al., 2012, Bousselot et al., 2010), and the methods for the weather data collection have been described in detail at: http://www2.epa.gov/sites/production/files/documents/QAPP_UHI.pdf.

Each PV array was elevated on metal support racks to a height of about 1.5 meters above the roof surface and ran along the southeastern edge of the research area (Figures 1 and 2). During the study period, the PV array created a microclimate where solar radiation was reduced during the morning hours casting shade on underlying plants; this area will be referred to as the ‘protected’ area. The protected area also collected notably more snow during the winter, had some protection from wind, increased thermal protection over the winter, as well as partial morning shade year-round. The remaining portion of the roof, which was exposed to direct

Figure 1. Overhead view of the USEPA Region 8 headquarters building green roof. The red outline is the green roof area (other roof areas are at higher levels); the yellow outline delineates the experimental area.

Figure 2. The sun near its zenith just before noon the PV array shades some plant modules.

sunlight and other environmental factors, will be referred to as the ‘exposed’ area. Plants growing in modules near the PV panels received shade cast by the panels during morning hours while the plants removed from the panels received greater sun exposure and no shade. Eight plant species (Table 1) were planted from plugs on 30 cm centers as mixed stands, one plant per species per module, and established in a greenhouse. Ten modules (61x122x10cm black plastic trays GreenGrid®, Weston Solutions Inc., Vernon Hills, IL, USA) and were filled with one of two substrate blends. The first substrate blend was proprietary and contained various percentages of heat expanded clay, peat, perlite, and vermiculite; the second substrate contained a blend of 50% by volume of the proprietary mixture and 50% zeolite (referred to as zeo below), an expanded calcium-potassium clinoptilolite product called ZeoPro™.

Table 1. The eight species planted as mixed stands in the green roof modules.

Scientific Name	Common Name
<i>Allium cernuum</i>	nodding onion
<i>Antennaria parvifolia</i>	small-leaf pussytoes
<i>Bouteloua gracilis</i>	blue grama
<i>Delosperma cooperi</i>	hardy ice plant
<i>Eriogonum umbellatum aureum</i>	Kannah Creek® buckwheat
<i>Opuntia fragilis</i>	brittle prickly pear
<i>Sedum lanceolatum</i>	lanceleaf stonecrop
<i>Sempervivum</i> ‘Royal Ruby’	hens and chicks, houseleek

Data collected were plant cover (cm²), soil volumetric moisture content, and plant dry weight (g). Plant cover data were derived from images analyzed using digital image analysis software SigmaScan Pro 5.0 as described in Bousselot et al. (2010). Plant dry weight was collected by harvesting all aboveground plant parts on 15 October 2009 and drying in a 70°C oven for 48 hours. Volumetric moisture content of the substrate was determined on a volume/volume basis

using a 5cm ThetaProbe ML2X in seven random locations per sampling date in each of the ten experimental modules.

Five of ten modules were assigned locations adjacent to the PV array and thus were within the shadow of the panels (Figures 1 and 2) and five were removed some distance from the panels. Two replications of the 0% zeo treatment and three replications of the 50% zeo were in the exposed area of the roof and three replications of the 0% zeo treatment and two of the 50% zeo treatment were in the protected area.

RESULTS AND DISCUSSION

Plant cover

Since plant cover is desirable on a green roof, overall plant cover is reported instead of individual plant species results (Table 2). Exposure type appears to have influenced plant coverage, in part due to the overwintering success of each species. In the 0% zeo treatment, plant cover was one third greater in the protected compared to the exposed location. For the 50% zeo treatment, little difference appeared in coverage coming out of winter, regardless of exposure, which is consistent with results from Bousselot et al. (2012).

Table 2. Results of spring (13 May 2009) and fall plant cover (collected 30 September 2009) averaged per module by exposure and substrate type.

Season	Exposed (E)	Protected (P)	0% zeo	50% zeo		
	0% zeo ¹	50% zeo ²	0% zeo ²	50% zeo ¹	P-E/P*100	P-E/P*100
	<i>Plant Cover (cm²)</i>				%	
Spring (S)	2440.59	1719.17	3307.14	1690.60	26.2%	-1.7%
Fall (F)	3675.60	2490.15	4098.36	4459.43	10.3%	44.2%
(F-S)/F	33.6%	31.0%	19%	62.1%		

¹n=2; ²n=3

Possibly even more telling of the effect of shading from the PV array is the change in plant cover from spring to fall (Table 2). However, it should be noted that due to the overwintering loss of plants in modules in the exposed location, fewer plants competed for the same resources in each one of those modules, (i.e., 4-6 plants verses 7-8 individuals per module in exposed and protected areas, respectively). Within the 0% zeo treatment, plant cover increased proportionally more in the exposed area than in the protected area, likely due to less competition, but coverage was still lower by the end of the growing season in the exposed area. While plant cover was near equal between exposure types within the 50% zeo treatment coming out of overwintering, a two times greater increase occurred in the protected area by the end of the season compared to the exposed area.

Dry weight

Higher dry weights were found in the 50% zeo than the 0% zeo, regardless of exposure type (Table 3). There was less of a difference in dry weight between substrate treatments in the exposed area; even though plant coverage was less in the fall in the exposed 50% treatment, dry weight was higher than in the 0% zeo treatment. This could be due to the higher nutrient content of the zeolite influenced dry weight accumulation but that it did not translate into horizontal plant coverage, but rather the vertical growth of plants like *B. gracilis* and *O. fragilis* that do not spread much.

Table 3. Results of dry weights, fresh weights and the difference (water) at harvest (collected 15 October 2009) averaged within modules.

Harvest	Exposed		Protected	
	0% zeo ¹	50% zeo ²	0% zeo ²	50% zeo ¹
	Weight (g)			
Dry weight	418.10	514.53	303.93	547.90
Fresh weight	2113.5	2849.06	1618.33	2545.10
Difference (water)	1695.40	2334.53	1314.40	1997.20

¹n=2; ²n=3

A relative lower dry weight in the 0% zeo protected area compared to the exposed area was seen even though plant coverage showed the opposite effect. These data agree with the assertion that as species richness increased the dominant species declined in dry weight due to resource competition (Nagase and Dunnett 2010). Having good plant coverage but relatively lower dry weight could be beneficial since smaller plants require fewer resources and lead to greater species diversity even if dry weight does not increase.

As an additional demonstration of resource competition as a factor of these results, fresh weight of plants at harvest is reported (Table 3). Even though the dry weight accumulation was lower in the exposed 50% zeo treatment than the protected 50% zeo treatment, overall water weight was higher. Therefore, it can be concluded that with the lower number of surviving plants in modules in the exposed area, those plants had relatively more water available for uptake within the finite confines of the rootzone in these modules.

Substrate volumetric moisture content

Substrate moisture content (Table 4) varied by exposure more in 2008 when drip irrigation was still being used and while all plants in all modules were still alive, except for one species, *A. cernuum*. Note that in 2008, the exposed areas had lower substrate moisture content (except 50% zeo in the protected area where the drip emitters had plugging issues) but in 2009, there was less difference in substrate moisture content. The small increase in moisture content in the exposed area (except exposed 0% zeo) demonstrates that the fewer plants probably used less total water in those modules. When looking at substrate type, the 0% zeo almost always had higher moisture content. However, in 2009 plant cover and dry weight data demonstrate that the larger plants in the 50% zeo treatment would likely use more water.

Table 4. Substrate volumetric moisture content by exposure and substrate type on four sampling dates.

Dates		Exposed		Protected	
		0% zeo ¹	50% zeo ²	0% zeo ¹	50% zeo ²
		Substrate volumetric moisture content (%)			
2008	22-Aug	6.51	6.77	15.55	8.61
	30-Sep	8.74	5.12	12.41	3.45
2009	19-Aug	7.57	9.00	8.27	8.24
	30-Sep	10.42	7.77	8.24	7.61

¹n=2; ²n=3

Solar Irradiance

Solar irradiance is presented as kilowatts per square meter (kW/m²). The maximum solar irradiance is quite high in the region, exceeding 1.100 kW/m² at least once per month for ten months out of the 24-month study. The maximum irradiance recorded over the two-year study was 1.260 kW/m², (maximum solar irradiance at earth's outer atmosphere is 1.361 kW/m².)

For the growing season solar irradiance during afternoon hours relative to morning hours is more attenuated (Figure 3), presumably due to atmospheric interferences such as cloud formation and perhaps air pollution. During the growing season, cloud formation appears to be more frequent during afternoon hours than during morning hours and these data support that observation.

Figure 3. July ave = average 5-minute solar irradiance for July 2009 and 2010; July AM values = average 5-minute irradiance values from before midday (1:00 PM) plotted in reverse, from 1:00 PM until sunset, to create symmetrical, bell-shape curve; Jul AM – PM = the difference between July AM values and July ave (for the AM hours the difference is 0 W/m²).

Temperatures

Temperature data were recorded over a five month period using thermocouples (tc), temperature data loggers (dl; see Figure 4), and temperature/humidity probes at 9 positions, including (1) Exposed location on the control roof gravel surface (cr tc gravel), (2) Green roof substrate surface in an exposed location (gr tc SS), (3) 10 cm above the green roof substrate surface in an exposed location with the data logger (gr dl SS); (4) Buried beneath the green roof substrate surface in an exposed location (gr dl BSS); (5) At the green roof substrate surface beneath the photovoltaic panels (gr dl SS PV), (6) Between the plant module and green roof membrane in an otherwise exposed location (gr tc BSS mem), and (7) Buried beneath the green roof substrate surface and beneath photovoltaic panels (gr dl BSS PV).

Two thermocouples (cr tc gravel and gr tc SS) and one data logger (gr dl SS) – positioned in the three most highly exposed locations on the control and green roof display highest average temperatures. For gr dl SS (position 3) the data were nearly identical to ambient temperature data collected with Temperature/humidity probes (positions 8 and 9) in exposed locations. By contrast, average temperatures recorded in two protected areas, between the plant module and green roof membrane surface (gr tc BSS mem) and beneath photovoltaic panels and buried beneath the green roof substrate surface (gr dl BSS PV,) displayed the lowest average temperatures. The greatest temperature variation occurred in highly exposed locations on the control and green roof surfaces with decreasing variation in more protected locations.

Figure 4. Thermocouple and data logger 3-hour average temperature values for June - October, 2009, for exposed and protected positions on the control and green roof: “average”, “standard deviation” of average, “average daily maximum”, and “average daily minimum” temperatures: cr = control roof, gr =

green roof, tc = thermocouple, dl = temperature data logger, SS = substrate surface, BSS = beneath substrate surface, PV = beneath photovoltaic panels.

Plants protected from temperature extremes and morning sun have better overwintering survival and coverage. Green roof modules that were not a part of the “formal” plant performance study beneath and adjacent to the PV array remained fully vegetated while coverage in more exposed location was patchy. The modules in the area of transition between most shaded and most exposed contained thick stands of *Sedum spurium*, (Figure 5). Beyond the extent of the protection, plant growth becomes patchier, a typical condition in moisture stressed plant communities that are regularly exposed to high levels of direct solar irradiance (Werner et al., 1999).

Figure 5. (a) Effects of protection from the PV array on the green roof where vegetation appears to have greater coverage (b) in areas shaded from direct sunlight for a portion of each day.

CONCLUSION

Protection from the array showed an increase in plant cover by fall, likely due to the reduced temperature fluctuations, solar irradiance, and therefore photoinhibition, but that success did not necessarily translate to increased dry weight in each module. It has been theorized that the dry weight of plants may be increased in shade (Getter et al., 2009) and an increase in dry weight has been specifically observed in the shade of a PV array (Köhler et al., 2007). However, our results indicate a reduction in dry weight, which might be explained by greater species survival in the protected modules and the subsequent increase in competition for the same amount of finite resources.

Substrate moisture content, in general, especially when plant competition was comparable, increased in the protected area, like results in a green roof shading study done in Michigan (Getter et al., 2009) and observances noted in moisture content of the substrate in experimental blocks where shading became a factor (MacIvor and Lundholm 2011).

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