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A Rooftop Agrivoltaic System: Pollinator Plant Establishment

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ABSTRACT

In a time of rapid habitat removal in favor of urbanization, green roofs have been recognized as a means to increase biodiversity while emulating native habitats in urban ecosystems. There is often competition over roof space for use as solar energy generation, or green roof space. Here we explore the inclusion of both green roof and photovoltaic (PV) energy generation systems stacked vertically in a rooftop system to better understand the impacts of PV arrays on six species of pollinator plants native to Colorado's Front Range and Great Plains Regions. We conducted randomized and replicated plant establishment and growth studies in a simulated rooftop system in full sun and under a fixed mounted PV array over the course of the initial growing season. Additionally, we measured the plant growing environment, including air temperature, substrate temperature, and substrate moisture to quantify the differences in the conditions in full sun compared to conditions under the PV arrays. Light conditions were modeled. We find plant establishment and overwinter survivability is greater under the PV array, while the seasonal plant growth index varies depending on the plant species. Substrate moisture was significantly higher under the PV while substrate temperature trended towards lower daytime temperatures and slightly raised nighttime temperatures under the PV. Based on this study, the microclimate under the PV array is amenable to plant growth, and differences in plant response to the shade may closely resemble ecotones found in nature. The combination of rooftop agrivoltaics and traditional full sun green roof plantings may lead to greater native plant establishment, and therefore greater diversity of habitat niches in the built environment.

Key words: rooftop agrivoltaics, pollinator plants, semi-arid, microclimate, green roof

INTRODUCTION

Currently, 4.4 billion individuals live in urban areas worldwide, and that number is expected to increase to account for 70% of all humans by 2050 (The World Bank 2023). Rapid urbanization experienced across the world has resulted in significant consequences for native ecological systems. This varies from habitat destruction to the introduction of non-native species, all leading to a decline in biodiversity and ecosystem services (Schwarz et al., 2017).

While urban areas are significantly altered due to the impacts of construction and infrastructure development, they still retain characteristics of the ecosystem surrounding them. Native plants are well adapted to thrive in their local environment with less maintenance and are suited to regional climate conditions. The reintroduction of native plants into urban hubs is a crucial step towards restoring the natural ecology in our human-centric urban environments. Therefore, urban landscapes, including rooftops, have the potential to imitate native ecosystem services by acting as localized ecological communities (Li and Yeung 2014).

This is especially important in areas of northern Colorado which are rapidly growing in population. Between 2010 and 2022, Colorado population increased by over 1% each year, resulting in 15.1% total increase over that time span (usafacts.org). This roughly equates to 764,530 additional people living in the state, largely concentrated in Denver, El Paso, Larimer, and Weld counties. Studies have shown that pollinator abundance and diversity decreases as urbanization increases. Wild bees are especially susceptible to anthropomorphic changes and significant declines have been reported in the populous areas of Denver, CO (Birdshire et al., 2020).

Green roofs offer a solution to increase green space in urban environments while maximizing the land use efficiency of the building footprint. Green roofs can host numerous benefits to humans, minimize urban energy consumption, while optimizing water, food, and nutrient flows in the context of urban metabolism (Kennedy et al., 2011), and play a key role in ecosystem services throughout the built environment (Oberndorfer et al., 2007; Francis and Jensen 2017). Native green roof habitat can encourage native pollinator fauna like birds, beetles, and bees into the urban environment (Oberndorfer et al., 2007). Increased urban pollinator habitat on green roofs has led to an increased documentation of pollinator fauna, and therefore higher pollinator visitation rates in an urban environment (Benvenuti 2014). This indicates that pollinator fauna may be able to work within the natural cycle of the urban ecosystem to pollinate plants and disperse seeds, potentially increasing biodiversity in the city.

The environmental conditions of green roofs are unique. The growing season tends to start earlier in the spring and last longer into the fall, expanding the overall growing season. It is essentially a separate ecotone, while providing a heterogenous landscape with a variety of niche habitats and microclimates (Dvorak 2021). These conditions serve to benefit pollinators, who are experiencing a variety of complications in relation to climate change, including emerging earlier from hibernation in the spring (Bartomeus et al., 2011, Guidi and Bousselot, 2024). The overall increase in global temperature is altering the phenology of invertebrates worldwide. Pollinator species are especially sensitive to this because their development and success is often tightly linked to their coevolved angiosperms (Johnson and Steiner 2000). Many flowering plants are exhibiting a mismatch in altered phenology to their corresponding pollinators. An increased growing season on green roofs can mitigate this impact and provide sanctuary for early emerging pollinators.

Urban Agrivoltaic Opportunity
As the global population trends higher every year, the need for resiliency and efficiency across the food, energy, and water nexus will become a top priority. Agrivoltaics (APV) enables multiple land uses on one piece of land by stacking solar photovoltaic (PV) energy and agricultural production at various scales on the same parcel of land, allowing plants and food crops to be grown under PV (Figure 1).

Figure 1. The scale of agrivoltaics, adapted from CSU extension fact sheet (Ballard et al., 2023).

Rooftop APV (RAPV) is a new frontier for research and implementation that combines PV energy production with specialized urban agriculture or horticulture operations into one synergistic rooftop system. RAPV research is a relatively new area of research, with early studies dating back only two decades (Köhler et al., 2002; Köhler et al., 2007) and several others in the past 10 years (Alshayeb and Chang 2018; Bousselot et al., 2017; Hendarti 2015; Lamnatou and Chemisana 2015; Nash et al., 2016).

Bringing APV and RTPV models to the urban landscape illuminates a new way to increase renewable energy production closest to where it is consumed. These systems provide specialized urban agricultural production and biodiversity where human populations are the greatest and therefore potential impact is the highest. Flat urban rooftops are often underutilized spaces but have vast potential to play host to energy production and plant growth.

Mutually Beneficial System
Vegetation paired with PV systems can offer plants protection from intense solar radiation and can increase productivity in rooftop settings that are exposed to intense direct solar radiation, or extreme high temperatures. This aspect of protection from extreme elements is especially important in hot and arid climates, like Northern CO. Water stressed plants can benefit from the shade of PV panels by providing a unique microclimate for plant growth in green roof systems, which are often exposed to extreme solar radiation (Bousselot et al., 2017). Ultraviolet (UV) radiation can cause damage to plants (Hollósy 2002).

APV systems, including RAPV systems, can dampen extreme solar radiation exposure to plants (Uchanski et al., 2023). In addition, PV installations can protect vegetation from extreme climate conditions, reduce drought stress, and increase substrate moisture with reduced irrigation requirements (Barron-Gafford et al., 2019; Elamri et al., 2018). Decreasing soil temperature and increasing soil moisture can benefit green roof plants in semi-arid and arid regions. A reduction in drought stress and an increase in soil moisture lessens the need for irrigation and water consumption. Prior research at Colorado State University (CSU) documented the effects of PV arrays on green roof plants and found higher average substrate moisture, better plant coverage, overall biomass, and resilience for plant species growing in the shade of PV panels (Bousselot et al. 2017).

Photovoltaics

PV installations can also benefit from this tandem integration. While PV panels generate electricity when the sun is shining, there is a threshold where they become too hot, resulting in decreased efficiency and overall power generation. The panel productivity can drop by a magnitude of 0.45% every degree C increase in temperature and it has been documented that panel inefficiencies can be avoided by introducing plants under the PV array (Makrides et al., 2009; Peck and van der Linde, 2010). The evaporation from the substrate and transpiration from the plants cool the underside of the panels which increases PV output, especially during the hottest times of the year (Hendarti 2013). RAPV research has found an increase in power output between 2% - 8.3% in panels with vegetation beneath when compared to a bare roof (Hendarti 2013; Hui 2009; Hui and Chan 2011; Kohler et al., 2007; Lamnatou and Chemisana 2015).

Considering the benefits of reintroducing biodiversity into urban environments in addition to the opportunity to increase renewable energy production on the same roof space, this research aims to analyze native pollinator plant response to the conditions within a RAPV system compared to standard green roof conditions. The objective of this study is to understand how PV arrays influence the green roof growing environment, and therefore the pollinator plant growth response under PV arrays in Colorado's semiarid climate. It was hypothesized that the shade from the PV modules would impact plant response through seasonal growth rate, establishment, and survivability.

MATERIALS AND METHODS

Site Description

CSU's Center for Next Generation Photovoltaics (NGPV) is situated on the eastern base of the foothills of Colorado's Front Range, which is the same RAPV site as in the Uchanski et al. (2023) study. The site is operated by the Mechanical Engineering Department at CSU's Foothills Campus in Fort Collins, Colorado (40° 35' 6.9288" N and 105° 5' 3.9084" W; Elevation 1,525 m). Fort Collins is in USDA hardiness zone 5b with a semi-arid steppe climate. The city experiences an average temperature of 10.2 °C, and an average precipitation of 40.9 cm annually. Fort Collins receives the most precipitation in spring (March - June) and the least amount in fall (September - December). Summers are hot with average high temperatures between 21-32 °C and winters are cold with average lows below freezing from November to March.

In the spring of 2021, the simulated RAPV research plot at the NGPV facility was installed. It includes a permanent 130 m^2 of growing area around 2 ground mounted PV arrays with various PV module types and transparencies (Figure 2). The arrays are mounted to an existing fixed racking system that was constructed at an angle of 35 degrees facing due south, to maximize annual solar radiation. They measure 17 m long and 1.2 m tall at the top edge of the modules and 36 cm above the substrate on the bottom edge.

Figure 2: Aerial plan view of CSU Foothills campus APV research site. The plant establishment trial is in the white dashed rectangle. Image courtesy of Matt Staver.

Opaque frameless cadmium telluride (O-CdTe) modules and full sun conditions were used as treatments for the pollinator species study. The simulated green roof system was built *in situ* around the PV arrays and on top of the existing landscape that has an approximate 18% grade downhill to the south. The simulated RAPV system was constructed with a root barrier and drainage layer (Extenduct by Green Roof Solutions, Glenview, Illinois, USA) to emulate a rooftop system.

The 15 cm deep growing substrate is composed of a custom green roof agricultural blend of 60% expanded shale aggregate, 20% compost, 10% vermiculite, and 10% peat moss, by volume. During establishment, irrigation was supplied 3 times a day for 15-minute intervals at 8:00, 12:00, and 16:00 by 1.5 lph (0.4 gph) Netafim drip emitters spaced at 15 cm (6 in) intervals and lines were spaced 30 cm (12 in) apart. After 3 weeks post planting, irrigation was reduced to twice per day, removing the 12:00 event.

Research Design

The study was designed to analyze plant establishment, growth rates, and growing conditions in open sun compared to the shade of O-CdTe PV modules. One treatment was in full sun and one treatment in the shade of the modules (Figure 3). We documented plant growth rates and survivability of 6 pollinator plant species that are native to the Great Plains and Colorado's Front Range. The plant species include: *Achillea millefolium* var. *lanulosa* (mountain yarrow), *Aquilegia caerulea* (Rocky Mountain columbine), *Echinacea purpurea* (purple coneflower), *Erigeron vetensis* (early blue-top fleabane), *Monarda fistulosa* (beebalm), *Penstemon strictus* (Rocky Mountain penstemon). *A. millefolium, E. purpurea*, and *M. fistulosa* were selected for their medicinal and pollinator value, and *A. caerulea*, *E. vetensis*, and *P. strictus* were selected for their value to pollinators. There were 10 randomized replications of each of the 6 species in each of the two treatments, totaling 120 plants (Figure 3).

The light conditions of the site were modeled (Figure 4) with Ladybug Tools (Sadeghipour Roudsari and Pak 2013) extensions of Grasshopper and Rhino3D Software to visualize and simulate the average ground level irradiance averaged over the data collection period (July-October). The Ladybug modeling plug-ins use validated simulation engines such as Radiance, EnergyPlus, and OpenStudio to conduct irradiance-based analyses in the

Rhinoceros 3D space. The PV array is modeled to scale in accordance with the ground mounted array at the CSU Foothills campus (Figure 2).

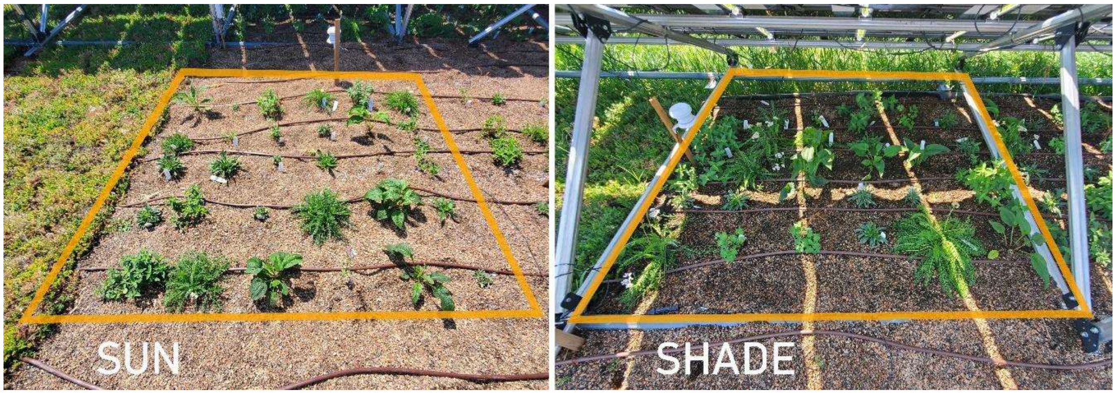

Figure 3. Native pollinator species are randomized and replicated in full sun and in the shade of solar panels.

The model used the Fort Collins-Loveland Municipal Airport TMY3 file. The output is mapped on a 0.25 m^2 substrate level grid. The irradiance modeling simulation outputs average irradiance W/m2), which is also converted to average photosynthetic photon flux density (PPFD) using a conversion factor of 2.02 described in Mavi and Tupper (2004). PPFD is the measurement of the number of photons (μmol photons m^{-2} $s^{-1)}$ in the photosynthetically active wavelengths, 400-700 nanometers, across unit space and time (Mõttus et al., 2012).

Monitoring Equipment and Variables Monitored
Growing conditions in full sun and under solar modules were continuously monitored using HOBO H21-USB micro station data loggers (Onset Computer Corporation, Bourne, MA, USA). Solar panel surface, air temperatures (measured at 30 cm [12 in] above the surface with solar shield), and substrate temperature were measured using HOBO 12-bit temperature smart sensors. ECH2O™ EC-5 Sensors (Onset Computer Corporation, Bourne, MA, USA; Decagon Devices, Pullman, WA) were used to measure the substrate moisture conditions. We documented the various temperatures and soil moisture every 15 minutes in each of the treatments.

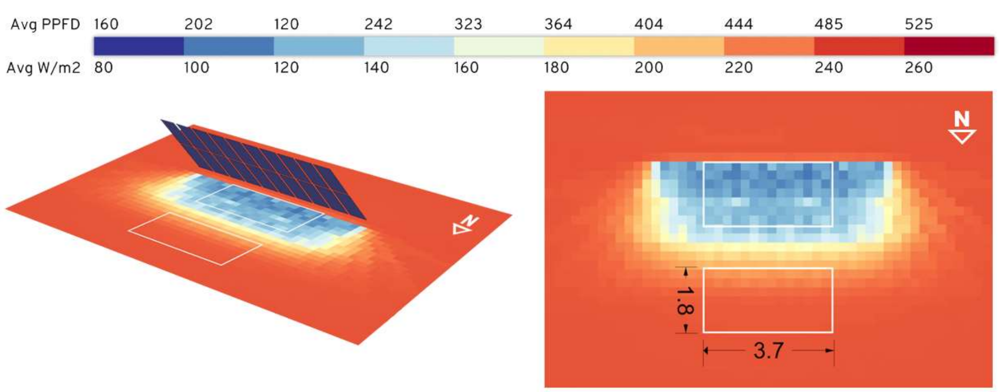

Figure 4. Analysis of average irradiance (perspective view, plan view, and legend) from July through October using Ladybug Tools plug-ins for Rhinoceros 3D software. Each white rectangle delineates the 3.7 m by 1.8 m full sun and shade treatment areas.

Plant height and width in perpendicular directions were collected twice a month from July 14, 2021, to October 14, 2021, to assess growth patterns over the growing season. The height and widths were then converted to plant growth index (PGI) using Equation 1 to compare overall volumetric growth rates between sun and shade environments.

Equation 1: PGI = (H + W1 + W2)/3

PGI results, calculated from Equation 1, are representative of the mean seasonal PGI of each species in each treatment. Mean seasonal PGI is defined by the mean PGI on week 1 of data collection subtracted from mean PGI on week 12 of data collection to show plant growth over the season (Equation 2).

Equation 2: Seasonal PGI = Mean PGI week 12 – Mean PGI week 1

Statistical analysis

Using R-Studio (2002, Boston, MA) a two-sample t-test was conducted to test for significance in the difference of means of PGI between the full sun and shade treatments. Data from the growing conditions were analyzed in Microsoft Excel (2022, Redmond, WA).

RESULTS AND DISCUSSION

Growing Environment

Air temperature

The ambient air temperature at 30 cm above the substrate surface showed no clear differences between the two treatments (Table 2, Figure 5). The tightly paired temperature data indicates that despite the shadow of the PV panels, air temperature remains consistent which is likely due to free-flowing air currents. Similar to results in Barron-Gafford et al. (2019) at grade and Uchanski et al. (2023), the air temperature is similar between treatments with only a slight reduction in the middle of the day.

Table 2. Maximum, mean, and minimum air temperature in C for each treatment by week from July 23, 2021-September 9, 2021. The air temperatures remain fairly constant between treatments, with maximum and minimum temperatures fluctuating between treatments over the 7 weeks.

Date	Full Sun Max Temp	O-CdTe Max Temp	Full Sun Mean Temp	O-CdTe Mean Temp	Full Sun Min Temp	O-CdTe Min Temp
Week 1	37.5	37.6	25.3	25.3	13.5	13.4
Week 2	34.4	34.9	21.6	21.6	11.2	11.0
Week 3	35.0	34.3	23.1	23.0	10.3	10.2
Week 4	36.4	35.7	22.0	21.8	9.0	8.9
Week 5	35.4	34.6	22.7	22.6	10.9	11.2
Week 6	35.0	34.4	21.0	20.9	6.6	7.5
Week 7	37.4	36.1	22.8	22.5	6.6	7.5

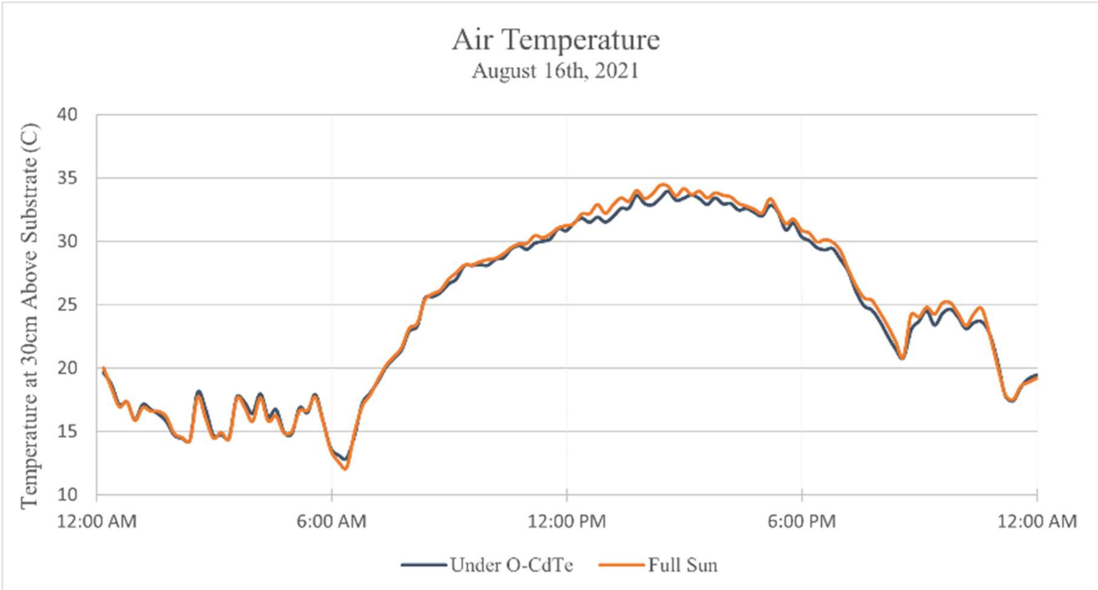

Figure 5. A comparison of air temperature at 30 cm above the substrate surface in both treatments over one day (August 16, 2021). This date was selected as an example to illustrate daily changes in air temperature.

Substrate Temperature

In this study the differences between treatments in maximum, mean, and minimum substrate temperatures were more pronounced than air temperature (Table 3). The substrate temperature under the O-CdTe PV panels was generally cooler during the day and slightly warmer at night compared to the full sun treatment. The substrate under the shade of the O-CdTe avoided extreme high and low temperatures resulting in a uniquely moderated environment near the surface of the root zone (Figure 6).

Table 3. Maximum, mean, and minimum substrate temperature in C for each treatment by week from July 23, 2021-September 9, 2021. The O-CdTE treatment experienced lower maximum temperatures and higher minimum temperatures each week.

Date	Full Sun Max Temp	O-CdTe Max Temp	Full Sun Mean Temp	O-CdTe Mean Temp	Full Sun Min Temp	O-CdTe Min Temp
Week 1	38.4	36.6	25.5	25.0	13.2	14.0
Week 2	34.8	34.2	21.6	21.5	11.2	11.6
Week 3	35.3	33.7	23.2	22.7	9.9	10.6
Week 4	36.5	34.5	22.7	22.0	9.1	9.4
Week 5	35.8	33.5	22.7	22.2	10.9	11.6
Week 6	35.3	34.2	21.0	20.7	6.9	7.7
Week 7	38.3	37.0	22.9	22.4	6.9	7.7

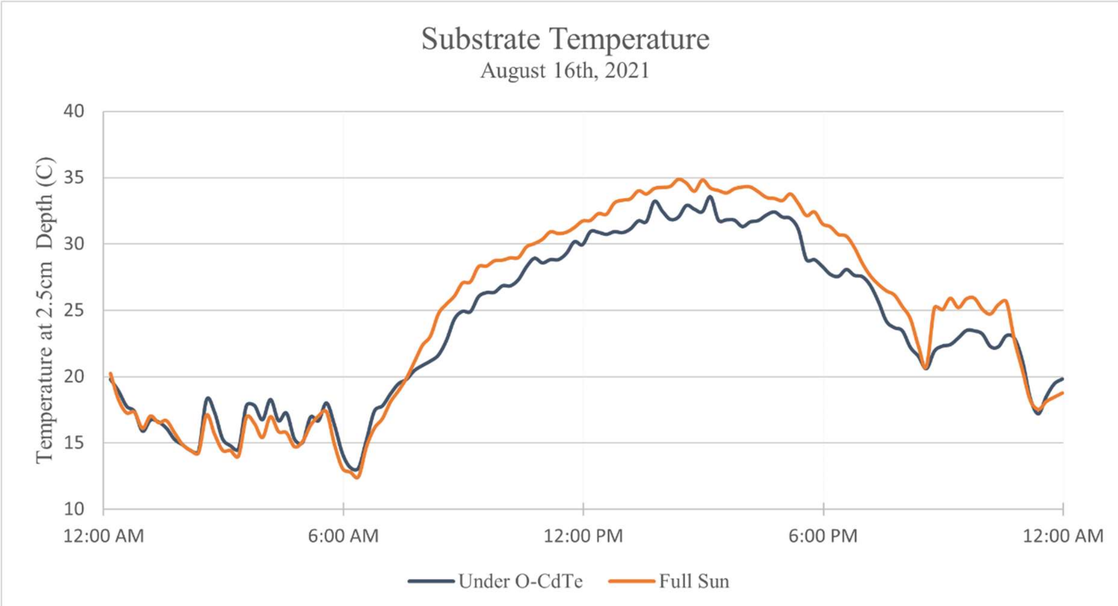

Figure 6. A comparison of substrate temperature at 2.5 cm beneath the substrate surface in both treatments over one day (August 16, 2021). This date was selected as an example to illustrate daily changes in substrate temperature.

The shade from the O-CdTe panels reduced the substrate temperature during the day and also minimized the heat loss during the night resulting in a moderated environment. These findings align with Bollman et al. (2021) in Corvallis, Oregon's dry Mediterranean climate where they found the green roof substrate had lower daytime temperatures coupled with higher nighttime temperatures under shade structures.

Substrate Moisture

Substrate moisture content was higher under the O-CdTe panels throughout the entire data collection period except immediately following rainfall events on July 30 and August 20 (Figure 7). The difference in moisture content between treatments is likely due to shading from the PV panels minimizing evapotranspiration rates and the slope of the landscape under the simulated RAPV system. In the O-CdTe treatment, the shadows from the panels move across the plot during the day as the sun moves east to west. Finding higher substrate moisture content in shade conditions aligns with the previous green roof study by Bousselot et al. (2017) in a similar Colorado climate and Getter et al. (2009) in Michigan's climate.

Because green roofs are water-limited systems, the increased water availability indicated by higher substrate moisture content in RAPV systems signals an opportunity to maximize irrigation efficiencies in green roofs (Hui and Chan 2011). Substrate moisture can be a key indicator for plant survivability in extensive green roof systems – particularly in semi-arid climates (Bousselot et al. 2011). The results from this study suggest that irrigation rates may be reduced in RAPV systems while maintaining adequate substrate moisture for native plant species. More research is needed to better understand the tradeoffs between any reduction in irrigation, light availability, PV energy generation, and plant growth in RAPV systems.

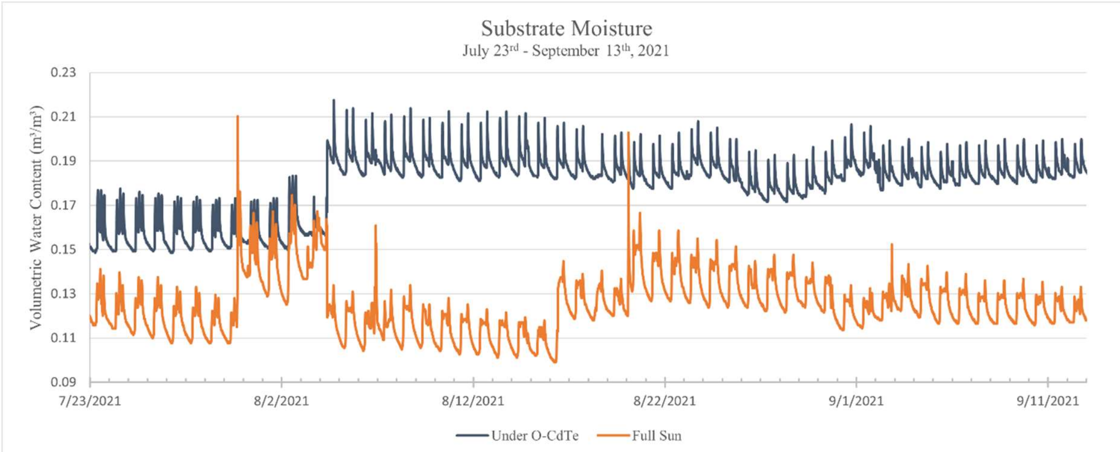

Figure 7. A comparison of volumetric water content at 2.5 cm beneath the substrate surface in each treatment from July 23-September 13. The daily peaks correlate with irrigation events. Substrate moisture remained higher in the O-CdTe treatment. There was a significant rainfall event on July 30-July 31 which is represented in the large spike in moisture in full sun plot but is not seen under the panels. The full sun sensor was partially exposed during the event and had to be recalibrated which corresponds to the shift in the graph on August 5.

Plant Growth Index

No significant differences were found between treatments within species. This result demonstrates that plants establish and grow in RAPV systems equally well in shade compared to full sun in Colorado. Overall, the trends showed that three species, including *E. pupurea, E. vetensis*, and *P. strictus* had greater seasonal PGI in the O-CdTe shade plot (Figure 8). *M. fistulosa* had equal seasonal PGI in both treatments with slightly more variation in the shade. *A. millefolium*, and *A. caerulea* had slightly greater seasonal PGI in the full sun treatment. *A. caerulea* was the only species to exhibit a reduction in plant size because it is a spring blooming species. Over the season the flower stalks senesce and overall PGI decreases; accordingly, this species did have a reduction in PGI uniformly across both treatments. This result is not uncommon later in the growing season when *A. caerulea* is grown at lower elevations on the Front Range, as it thrives in high elevation conditions in the Rocky Mountains with cool nighttime temperatures (Brunet and Eckert, 1998; USDA, 2024).

These results indicate that several native species may not require full sun to establish in green roof systems, and instead, can establish in the shade of RAPV systems. Irradiance measurements for this RAPV system were reported in Uchanski et al. (2023). It has been noted that shade can reduce the negative effects of high irradiance in high solar radiation environments, like Colorado (Bousselot et al., 2017), which may have influenced the success of the plants in the shade treatment.

As dual land-use for PV and pollinator habitat at-grade becomes the standard for utility scale PV facilities, the same framework to maximize land-use efficiency can be applied to urban rooftops. Research has found that the pollinator plants grown in partial shade gradients within PV facilities has resulted in delayed and prolonged seasonal blooms which can have a beneficial impact on pollinators in water-limited ecosystems (Graham et al., 2021).

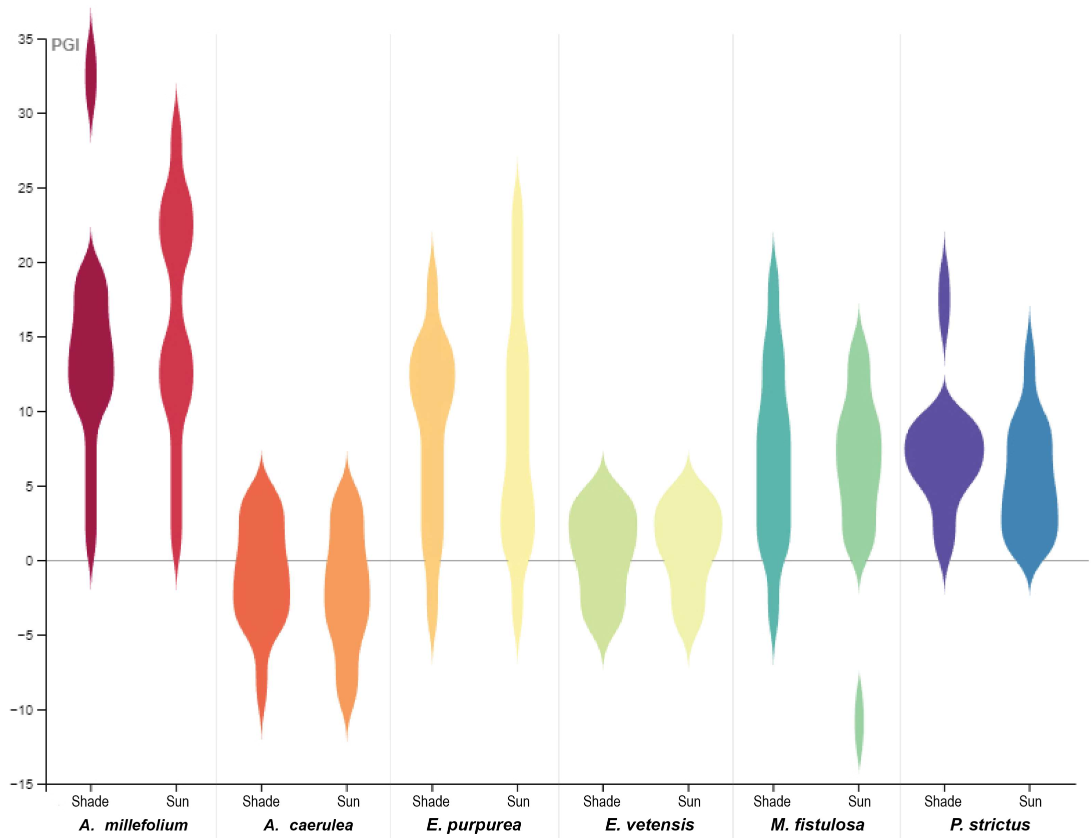

Figure 8. The violin plots show average seasonal PGI over the establishment period from July 28-October 14. The X-axis varies by species to show accurate comparisons between treatments. There were no significant differences in PGI between treatments in any of the species: *A. millefolium* p-value = 0.65, *A. caerulea* p-value = 0.64, *E. purpurea* p-value = 0.91, *E. vetensis* p-value = 0.55, *M. fistulosa* p-value = 0.40, *P. strictus* p-value = 0.44.

Taking these results in tandem with earlier flowering times on traditional full-sun green roofs (Ruszkowski and Bousselot 2024), there is great potential to increase bloom time and therefore widen the timeframe of pollinator resources in the urban built environment when pollinator plant palettes are grown in both traditional and RAPV systems. Furthermore, the variation in microclimates within these systems can increase plant species richness as certain species will fill the niches across the shade gradient that are best suited to them (Bousselot et al., 2017; Dewey et al., 2004). Greater species richness in the urban environment can lead to greater pollinator fauna resources, and therefore greater total urban biodiversity (Oberndorfer et al., 2007).

Overwintering Plant Survivability

During the initial growing season, only two individual plants in two species perished: one *A. caerulea* and one *E. vetensis*. Both plants were in the full sun treatment. All species had relatively high overwintering survivability rates and, when considering all species by treatment, plants had a greater overwintering rate in the shade treatment (97%), compared to the full sun treatment (85%; Table 4).

Specific overwintering rates varied by species. *M. fistulosa* and *P. strictus* had 100% overwinter survivability in both treatments and *E. vetensis* experienced 80% overwinter survivability in both treatments. In both *A. millefolium* and *A. caerulea* there was 100%

survivability under the solar panels and 80% survivability in the open sun treatment. The greatest difference was reported in *E. purpurea* with 100% survivability in the shade treatment and only 70% in the full sun treatment (Table 4).

Table 4. Pollinator plants overwinter survivability.

Scientific Name	Common Name	O-CdTe	Sun
Achillea millefolium	Mountain Yarrow	10 (100%)	8 (80%)
Aquilegia caerulea	Rocky Mountain Columbine	10 (100%)	8 (80%)
Echinacea purpurea	Purple Coneflower	10 (100%)	7 (70%)
Erigeron vetensis	Early Bluetop Fleabane	8 (80%)	8 (80%)
Monarda fistulosa	Wild Bergamot	10 (100%)	10 (100%)
Penstemon strictus	Rocky Mountain Penstemon	10 (100%)	10 (100%)
	Total	**58 (97%)**	**51 (85%)**

The ability of a plant species to survive and successfully reproduce under varying environmental conditions can directly influence its abundance in an ecosystem, and therefore contribute to species richness. In a similar study of shade impacts on green roofs, Getter et al. (2009) found no statistically significant differences in species richness between sun and shade treatments. While, this study analyzed survivability, we also found no statistically significant differences between treatments. Despite no statistical significance we found all species trending towards greater or equal survivability in the O-CdTe shade treatment. Previous research on native plant establishment and survivability in green roof systems shows varying results depending on regionality, irrigation, and light conditions (Dvorak and Volder 2010; Li and Yeung 2014). Our results indicate higher overwinter rates under the solar panels which may be attributed to a reduction in environmental stresses that has been noted in other studies on RAPV systems (Bousselot et al., 2017; Köhler et al., 2007).

We found that adding shade to green roof systems can alter the plant growing environment by increasing soil moisture and moderating substrate temperatures, while reducing the available light. This moderation of the growing environment under PV systems can create diverse microclimate pockets within one green roof system. The combination of shaded plots from solar panels with full sun areas can imitate natural ecotones and provide opportunities for greater species richness (Dvorak and Volder 2010). With a forecasted changing climate and associated increased prevalence of extreme weather events, the diversification of growing environments in urban areas, including green roofs, will be crucial to maximize species richness and total biodiversity in the built environment. RAPV systems are still relatively nascent, but show great promise to moderate light availability, temperature, and substrate moisture in green roof systems, enabling opportunities for greater plant species abundance in unique habitat niches while producing renewable energy close to the point of energy consumption.

Future studies in urban RAPV systems across various ecoregions are needed to better understand the nuanced relationships between specific native plant species and their response to various levels of shade in green roofs. The reported increase in substrate moisture under PV arrays could result in decreased demand for irrigation in green roof systems, while the long-term viability of native plant species in the same shade treatments must be tested. Comparative studies on pollinator insect visitation in sun and shade treatments will help determine the ecological impacts from RAPV systems. Additional studies on medicinal plants, including compounds and metabolites, and other edible plants, or crops paired with renewable energy production metrics will aid in a broader comprehension of RAPV systems roles in the overarching urban metabolism; considering how food, energy, and water flows in and out of urban areas.

Finding the ideal balance between shade from solar panels, light availability at the plant canopy level, reduction in irrigation, and solar energy generation will be the key for RAPV integration moving forward. While the shade provides protection from extreme elements, plants need adequate light for sustained growth. To maximize the benefits, RAPV systems should seek an optimal balance between energy production and light availability for long term plant growth.

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