THESIS

PLANT GROWTH UNDER PHOTOVOLTAIC ARRAYS OF VARYING TRANSPARENCIES – A STUDY OF PLANT RESPONSE TO LIGHT AND SHADOW IN AGRIVOLTAIC SYSTEMS

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ABSTRACT

PLANT GROWTH UNDER PHOTOVOLTAIC ARRAYS OF VARYING TRANSPARENCIES – A STUDY OF PLANT RESPONSE TO LIGHT AND SHADOW IN AGRIVOLTAIC SYSTEMS

Amidst the rising global pressures put on the interdependent systems in the food, energy, and water nexus, this document highlights the potential for systems-based solutions at the intersection of food cultivation, ecosystem services, and energy production in urban and rural environments. Agrivoltaics (APV) is a land-use model that enables simultaneous cultivation of food crops and electricity generation on the same plot of land. Agrivoltaic systems integrate solar photovoltaic (PV) energy generation with agricultural operations, maximizing the utilization of solar energy. This approach has gained significant research interest in the United States with scalable implementation is on the horizon.

Research efforts at Colorado State University (CSU) aim to advance the understanding of plant responses to various shade conditions under PV arrays, benefiting stakeholders in agriculture, solar energy industries, policymakers, and governmental agencies. In particular, agrivoltaic research conducted at CSU's Horticulture and Landscape Architecture (HLA) department has focused on open field specialty crops and native pollinator plant species while documenting the overarching light and temperature growing environment. A replicated 2-year crop trial was conducted at the open field test site, comparing crop yield and growing conditions under three different PV module types with varying transparencies to traditional full sun production. Statistical analysis revealed a reduction in squash yield directly under the PV panels while no significant differences in yield for bell peppers, jalapeno peppers, lettuce and tomatoes growing north and south of the arrays. In a separate study, a simulated green roof structure was constructed around an existing PV array at CSU's Foothills Campus to explore the feasibility of rooftop agrivoltaics. A one-year study of six native pollinator plant species was conducted to assess differences in establishment, survivability, growth index, and growing conditions between full sun and PV shade environments. Overall, there were no statistically significant differences in mean Plant Growth Index (PGI) throughout the establishment season, however, notable variations in overwinter survivability were observed.

In both studies the PV modules moderated the environment, resulting in lower maximum daytime ambient temperatures and even greater reduction in soil temperature throughout the growing season. Light levels are reduced under all PV module types with the least reduction under semi-transparent modules. Variations in growing conditions in these APV systems indicate the need for further research to optimize PV systems in order to maximize energy production and plant vitality.

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Chapter 2

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CHAPTER 1: Part 1 - AGRIVOLTAIC OPPORTUNITY

Introduction

Facilitated by improved technology, decreasing costs and a societal desire to reduce fossil fuel emissions, the global demand for solar photovoltaic (PV) energy is on the rise. While PV can provide renewable energy at scale, it requires large areas of land close to urban hubs to achieve this goal. At the same time, global food demand is projected to increase significantly along with the global population over the next several decades. The need to keep agricultural land in production while increasing renewable PV energy on a scale has led to competition for land. (Dinesh and Pearce, 2014; Dupraz et al., 2011; Wesselek et al., 2019)

Agrivoltaics (APV) is a land use model initially introduced in Germany in 1982 (Goetzberger, & Zastrow, 1982) with the means to provide society with the clean energy it wants while keeping agricultural soils active and productive. While initial uptake was slow, adoption is on the rise as the dual use of land for agriculture and photovoltaic power generation has the potential to counteract the scarcity of usable land and contribute to the sustainable development of rural areas (Fraunhofer, 2020; DOE, 2021). While agrivoltaic implementation is still nascent in the United States, innovations have been seen around the world in Japan, China, Germany, France and beyond. As the potential of APV is now realized in the US - from Alaska to Vermont and Arizona to Georgia – research, development, and demonstration will be key to informed and responsible adoption at scale (NREL, 2021).

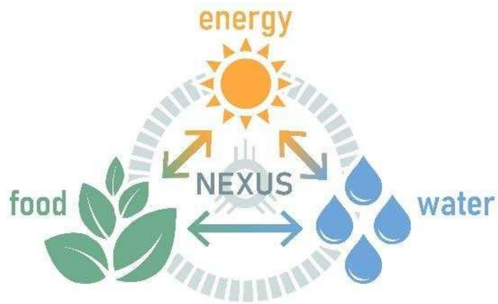

Figure 1: Food Energy Water (FEW) Nexus

As the global population trends higher every year, the need for resilient and efficient food, energy, and water systems will become a top priority. The United Nations Food and Agriculture Organization has projected that global energy consumption will grow by up to 50% by 2035, while food production must rise 60% in order to feed the world population in 2050 (FAO, 2014). Agrivoltaic land use addresses both concerns as a means to produce food and generate renewable energy on the same plot of land.

Land Use

With the prospect of land use competition and decreasing prices of solar energy development, agrivoltaic research has been of significant interest in the past 10 years (Dinesh and Pearce, 2014). In 2011 researchers in France published an article that was amongst the first to encourage the maximization of land use efficiency by combining food crops and solar panels on the same plot of land (Dupraz et. al., 2011). While the concept had been introduced decades prior in Germany, and adoption happening concurrently in Japan, to a large extent Dupraz et al.'s article re-introduced the concept of APV to the scientific community (Trommsdorf et al., 2022; Tajima and Iida, 2021). They acknowledge the impending competition for agricultural land and impending hardships of climate change to suggest that we can maximize land use through the APV model (Dupraz et al., 2011).

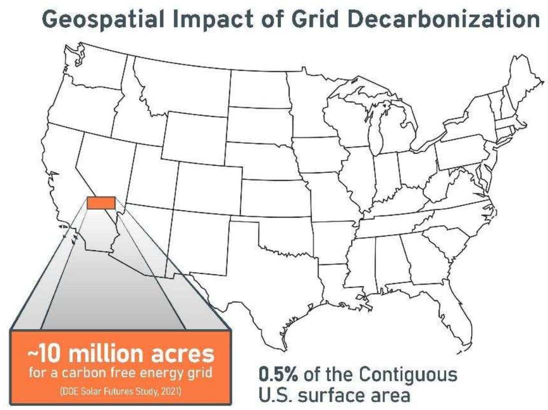

Figure 2: Geospatial Impact of Grid Decarbonization in the US. Illustration created from information provided in the US DOE Solar Futures Study (2021).

Inspired by the opportunity for dual-land use along with 10+ years of research, the Fraunhofer Report: *Agrivoltaics: Opportunities for Agriculture and the Energy Transition* goes far beyond land efficiencies to offer an overview of the current state of technology, highlight successful application examples and presents practical advice for the major stakeholders in this field such as agriculture businesses, municipalities and companies (Fraunhofer, 2020).

In the US, the Department of Energy's Solar Future Study predicted that we are moving towards grid decarbonization scenarios that will require 0.5% of the land surface area, or ~10 million acres of land, in the contiguous US to be developed to PV energy generation (Figure 2) (DOE, 2021). Land use in the United States varies from most other countries across the developed world as the US has large tracts of land across the interior West and Midwest that have not yet been urbanized. Currently, 43% of the contiguous US land surface, equivalent to nearly 900 million acres, is used for agricultural production. Agricultural land is often prime for solar development because it is already open to the sun - free from major plant or building obstructions, it is generally a low-slope landscape, and it is close to energy transmission infrastructure. Considering the impending demand for renewable energy generation paired with the considerable amount of agricultural land we have in the US, it has been predicted that at current efficiencies, installing dual use APV systems on just 1% of agricultural land will enable us to reach a decarbonized grid (Adeh, et al., 2019).

Water Use

In addition to land use efficiency, APV systems are being researched for their ability to improve agricultural water use efficiency through increased soil moisture and decreased evaporation rates. Previous research highlighting APV systems in the arid western region of the US both found water use efficiency to be a key outcome. Barron-Gafford et al. found a decrease in plant drought stress indicators and reduced PV panel heat stress while producing equal or greater amounts of food in the shade at their research plot in Tucson, Arizona (2019). In a similar study taking place at Oregon State University in Corvallis, Oregon researchers found that land under PV maintained higher soil moisture throughout the season, a 90% increase in biomass under PV and a 328% water efficiency rating under the PV (Hassanpour et al., 2018).

Figure 3: The agrivoltaic cycle in semi-arid climates can be mutually beneficial.

These results are very significant, proving the water use benefits APV can provide for arid and semi-arid regions. In addition to ground level benefits from the shade of PV, research has found that PV panels can also benefit in this system from the cooling effect from evapotranspiration form the plants and soil under the array enabling them to operate at a higher energy conversion efficiency rate (Described in Figure 3) (Barron-Gafford et al., 2019)

Horticultural Crops

As described above, food production, and specifically horticultural crop production has been at the core of APV research for the past decade. As the APV concept has taken hold, groups across the world have studied the impacts of PV array configurations on horticultural crop growth metrics in distinct climates, from Italy to Japan, and Germany to the United States (Trommsdorf et al., 2022). In the US, dual use research is being conducted across several states at a variety of scales through NREL's InSPIRE project in addition to federal funding through the USDA and DOE (Macknick et al., 2022). States with horticultural APV research include Arizona, Colorado, Illinois and Massachusetts with more on the way.

In a brief review of literature on horticultural crops in APV systems with an international scope, Touil et al. (2021) found inhibitory effects on crop growth were observed generally with shade coverage ratio of 50% to 100%, except for select crops (strawberries and spinach). Additionally, they found increased water use efficiency for some crops species in dry land agriculture and arid climates. In summary, it was suggested to limit APV shading ratios to lower than 25% in APV systems with a priority on maintaining agricultural productivity. While this recommendation serves as a general baseline for prioritizing crop success, research shows optimal shading ratios can vary significantly depending on the system's climate and the crop type.

Political, Social, and Economic Considerations

Current and recent research is proving the viability of APV from an objective standpoint, but it is becoming clear that further research is needed to understand the web of political, economic, and societal barriers before we see successful adoption. Due to the complex nature of food, energy and water systems that are present with APV development, the various stakeholder values are diverse and dynamic (Barron-Gafford et al., 2021). To better understand the opportunities and barriers to dual land-use systems Pascaris et al. conducted a series of interviews with industry stakeholders to identify barriers that can be used to refine the technology to increase adoption among farmers' (2020). They found agricultural stakeholders expressed a need to better understand the long-term productivity, market value, and compensation metrics, while farmers and solar industry stakeholders both expressed interest in the development of flexibility within the system to accommodate dynamic farming practices and operations at various scales (Pascaris et al., 2020). Further research that aims to better understand the socio-economic and political barriers and opportunities will be essential for mutually beneficial widespread APV adoption.

Rooftop Agrivoltaics

Current research is leading to a robust understanding of how these systems can function at-grade, but APV on underutilized urban rooftops provides a new opportunity to produce food and energy where the demand is highest - urban hubs. Rooftop APV is a new frontier for research and implementation in the US. Many urban rooftops are underutilized as they remain barren, while others play home to PV energy production or rooftop agricultural operations. Rooftop APV combines PV energy production and agricultural operations into one synergistic rooftop system. While there is little current research on rooftop APV systems, there is tangential research highlighting the effect of PV arrays on green roof plants. Bousselot et al. found that green roof plant species growing under the shade of PV panels greater coverage and resilience in green roof systems (2017). These findings can be used as a baseline to inform future studies on rooftop APV systems. Based on this research plus the outcomes of at-grade research, there could be great potential for improved crop growth and water efficiency in rooftop settings with PV situated above plants, particularly in semi-arid regions of the US.

RAPV systems can address key indicators of material and energy flows within the framework of urban metabolism that was introduced in Kennedy et al. (2007). RAPV systems can have a positive impact on urban metabolism as they maximize land use efficiency by hosting renewable energy generation and food production or ecological habitat on the same building footprint. Generating energy and food close to the point of consumption and reintroducing ecosystem services in metropolitan hubs allows a city the ability to sustain itself over time. More research and analysis are needed to accurately quantify the impacts that green roofs, RAPV and urban agriculture can have in the greater lens of urban metabolism.

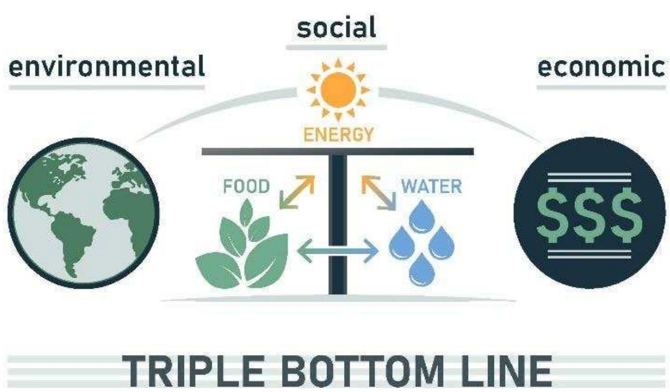

Figure 4: The agrivoltaic land use model can impact all three pillars of the triple bottom line – environmental, social. economic

Overview

Agrivoltaics has vast potential to positively impact society on many fronts. Considering the FEW Nexus, APV can increase land and water use efficiency by producing renewable energy and food on the same plot of land while simultaneously increasing soil moisture. APV research is allowing us to understand the technical benefits these systems can provide regarding our food, energy and water systems. Despite the clear technical benefits, more research in the social, economic, and political spheres must be conducted to evaluate the attributes of APV systems that lead to the success or failure. Understanding the triple bottom line - environmental, economic and social aspects will be a crucial step to increase the adoption rate across the country (Barron-Gafford et al, 2019, Pascaris et al., 2020).

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CHAPTER 1, PART 2 – AGRIVOLTAICS IN COLORADO

Reformatted from the CSU Colorado Agrivoltaic Fact Sheet

By T. Ballard, J. Bousselot, S. Conrad, B. Gornick, C. Hayes, **T. Hickey**, R. Meyer, and M. Uchanski* (3/23)

Figure 5: There is an ever-persistent demand for solar energy (photovoltaics or PV) installations concurring with increasing global populations demanding more energy and related issues surrounding climate change.

Agrivoltaics is the practice of producing both electricity (using solar panels) and food (agriculture) on the same land. This fact sheet provides a background on agrivoltaics, what we know from research, and some important considerations if you are considering agrivoltaics on your farm or property. Another CSU Extension resource, Photovoltaic System Feasibility Calculator can be used as a decision making tool. Agrivoltaic installation options not only include areas of active crop production, but also livestock grazing land, pollinator habitat, commodity and fiber crops, urban rooftop farms (Figure 10), and “floatovoltaics” in aquaponic systems (Mow 2018; Pringle 2017). While not directly integrating both systems, low impact PV installations can be located adjacent to center pivot irrigated fields in dryland corners, or on land that is not being utilized for other purposes (Mow 2018).

PV systems accounted for approximately 55% of renewable energy installations worldwide in 2019 (Agostini et al., 2021). As of 2021, small-scale solar PV energy generation in Colorado was at 95 gigawatt hours (GWh) or 95 million kilowatt hours (kWh), which contributes 2.5% of all small-scale PV generation in the US. In comparison, total PV generation in the US was at 88 terawatt hours (TWh) or 88 billion kWh, which equates to about 2.2% of the energy demand in the US (USEIA, 2021).

Figure 6: Crops Growing under semi-transparent PV modules at CSU Foothills Campus

Agrivoltaic systems provide an option for reducing land competition between agriculture and renewable energy generation to meet current and future electricity demands (Adeh et al., 2019). Food, fuel, fiber, and energy markets typically compete for land use while agrivoltaics combines food and energy production systems at the same physical location (Barron-Gafford et al., 2019).

In some countries where cropland is limited (particularly in some US counties and states), there is a large potential for agricultural production and electric power generation to co-exist (Dupraz et al., 2011). Further utilizing land for agrivoltaics systems has the potential to increase farm productivity by 35-73% (Dupraz et al., 2011), although the best photovoltaic systems that will efficiently accommodate agricultural operations at various scales are still being investigated by researchers.

Overall Benefits of Agrivoltaics

Bringing PV systems to agricultural land can provide improved land efficiencies in both PV systems and agroecosystems relative to conventional PV systems. Research has found that plants experienced less drought stress and heat stress when shaded by PV systems in arid climates (Barron-Gafford et al., 2019). Evapotranspiration from soil and plants under the array creates a cooler microclimate that benefits PV energy output because reduced air temperatures around PV panels increases their overall power output efficiencies, especially in warmer months (Adeh et al., 2019).

In addition, research currently being done in Arizona by Barron-Gafford, et. al found higher nighttime and lower daytime air temperatures under PV panels when compared to traditional crop fields. In these systems, tomatoes showed improved photosynthesis and transpiration efficiencies in PV shade (Barron-Gafford et al., 2019). Shading may improve plant carbon dioxide uptake resulting in increased vegetative plant growth as plants grow larger to capture light (Barron-Gafford et al., 2019). In addition to crops, growing native plants below solar arrays can also benefit plant pollinator species (insects, and animals) resulting in cross benefits for the farm (Dunbar 2019).

The co-location of agriculture and energy production also has the potential to bring more reliable electricity to rural communities and directly offset on-farm energy consumption. Looking ahead, increased PV energy generation on farms and greenhouse operations will enable new opportunities for rural and agricultural communities. On-site PV can power rural microgrids, energize electric farm equipment, aid in on-site nitrate (fertilizer) production, and integrate into greenhouse glazing to offset energy inputs for controlled environment agriculture.

The combined land use in agrivoltaic systems can greatly increase land use efficiencies while decreasing land use competition. The US Department of Energy's 2021 Solar Future Study projects that we will install ground-based solar on ~10 million acres, or, 0.5% of Contiguous US land area by the year 2050 (DOE, 2021). To reach these metrics it is likely much of the added ground-based solar capacity will be installed on currently zoned agricultural lands. Agrivoltaics provides a solution to mitigate land-use conflicts by keeping lands agriculturally productive while producing renewable energy simultaneously on the same plot of land.

Figure 7: Squash growing under semi-transparent PV modules at CSU ARDEC South

Crops and Agrivoltaics

Crops planted beneath solar panels receive protection from harsh weather such as hail or intense sunlight, helping crops to reach their production potential and saving some farms from unexpected crop loss (Trommsdorff et al., 2021).

Research has found that some crops are generally productive and have better overall health as a result from the unique microclimate present under PV systems (Touil et al., 2021). While some crops experienced reduced yield, other crops experienced no negative effect on productivity, and then some crops showed significantly improved performance from the shading effect of the PV system. Reported yield results from various garden plants are mixed under PV systems, but in one study tomato plants increased yield by 50% with higher shading (Barron-Gafford et al., 2019). The gain in yield is attributed in part to lower canopy temperatures, and higher soil moisture from the shade under the solar panels (Touil et al., 2021).

Overall, crop growth in agrivoltaic systems depends on many factors like regional climate (irradiance, precipitation, length of growing season, temperature) and PV array configuration (ex: height, row spacing, panel transparency, etc.), amongst others like soil type and growth habit. More research-validated crop modeling is needed to understand how crops and grasslands (Sturchio et al., 2022) respond to specific regions, irrigation, and PV configurations.

Figure 8: Plants growing at CSU Foothills Campus agrivoltaic research site.

Water and Agrivoltaics

The shade produced by solar panels can also help reduce irrigation requirements (Al-agele et al., 2021). Drought stress is mitigated by shading under the solar panels as plants lose less water from evapotranspiration (Barron-Gafford et al., 2019; Elamri et al., 2018). Lettuce plants, for example, grown under solar panels were found to be productive, although lower in yield, with a 20% reduction in irrigation (Elamri et al., 2018). Water savings is particularly important in arid climates like Colorado with limited quantities of water available for irrigation.

The Economics of Agrivoltaics

Research has suggested that the economic benefits to landowners adopting agrivoltaics are compelling. Overall, the economic factors such as electricity generation, water savings, crop production, and land value will be a determining factor in PV adaptability and compatibility with both agriculture and energy production systems being located together (Riaz et al., 2021; Touil et al., 2021). Some early research indicates that agrivoltaics systems provide increased revenue per acre in added income from electricity generation. When land area is limited for solar array installations, as in Europe, agrivoltaics systems make the utilized space more economically viable (Agostini et al., 2021). Studies have found that farms containing agrivoltaic systems increase the lands' sale value by over 30% (Majumdar and Pasqualetti, 2018; Ouzts 2017). Further economic benefits to agrivoltaics systems may exist, such as the use of grazing animals to harvest residue to reduce the costs (i.e., pesticides and labor) needed to maintain vegetation in those areas while also financially benefiting from the animals (Andrew et al., 2021). These potential benefits and trade-offs are currently under investigation in Colorado locations with high altitude and intense solar radiation.

Climate Benefits of Agrivoltaics

Implementing PV systems reduces non-renewable energy demands. Agrivoltaics has the potential to increase renewable energy generation, thereby decreasing carbon emissions and the impact of extreme weather events because of climate change (Adeh et al., 2019; Barron-Gafford et al., 2019). Worldwide, the production and use of energy accounts for 80% of carbon emissions. Coal power plants emit 756-1310 grams of CO2/kWh while PV power plants produce only 13-731 CO2/kWh (Shahsavari and Akbari, 2018). Extreme weather events also appear to be increasing in number and any decrease in non-renewable energy consumption could improve these conditions. When considering the vast agricultural footprint, if just 1% of cropland is converted to agrivoltaics systems, this could significantly offset global use of carbon-based energy sources (Adeh et al., 2019).

Agrivoltaic systems can also provide ecosystem services that are not realized with traditional PV systems. These systems maintain functionality of stormwater management, soil erosion prevention, and pollinator habitat (Ouzts 2017). Native pollinators benefit from established native flowering plants below solar panels, which can help reverse declining pollinator populations, especially in urban areas (Dunbar 2019).

Figure 9: Crops growing at CSU Foothills Campus

Future Challenges

Co-optimization challenges still exist between agricultural production and energy generation (Figure 10). Leading challenges include adjusting farming techniques to align with maximizing solar array orientation, incorporation of semi-transparent panels, and determining optimal coverage density (Majumdar and Pasqualetti, 2018; Riaz et al., 2021). Other challenges include planting and harvesting activities, along with crop choice, beneath solar panels.

Locating a solar farm can also be challenging as potential sites are positioned in rural spaces and may not be close enough to existing substation and transmission infrastructure to be viable. Previous geospatial research at CSU indicates that having a substation within 1 mile of these systems greatly affects PV installation feasibility.

Researchers in Colorado and a few other states are currently investigating agricultural cropping strategies to manage these issues along with additional concerns related to agrivoltaics. One aspect currently being investigated includes avoiding and managing soil compaction resulting from PV installations. In addition, research is investigating how to best manage cropping strategies that involve equipment for both planting and harvesting operations. This challenge may include solar panels that are located higher above the crop canopy or solar panels that can rotate out of equipment's paths during field operations.

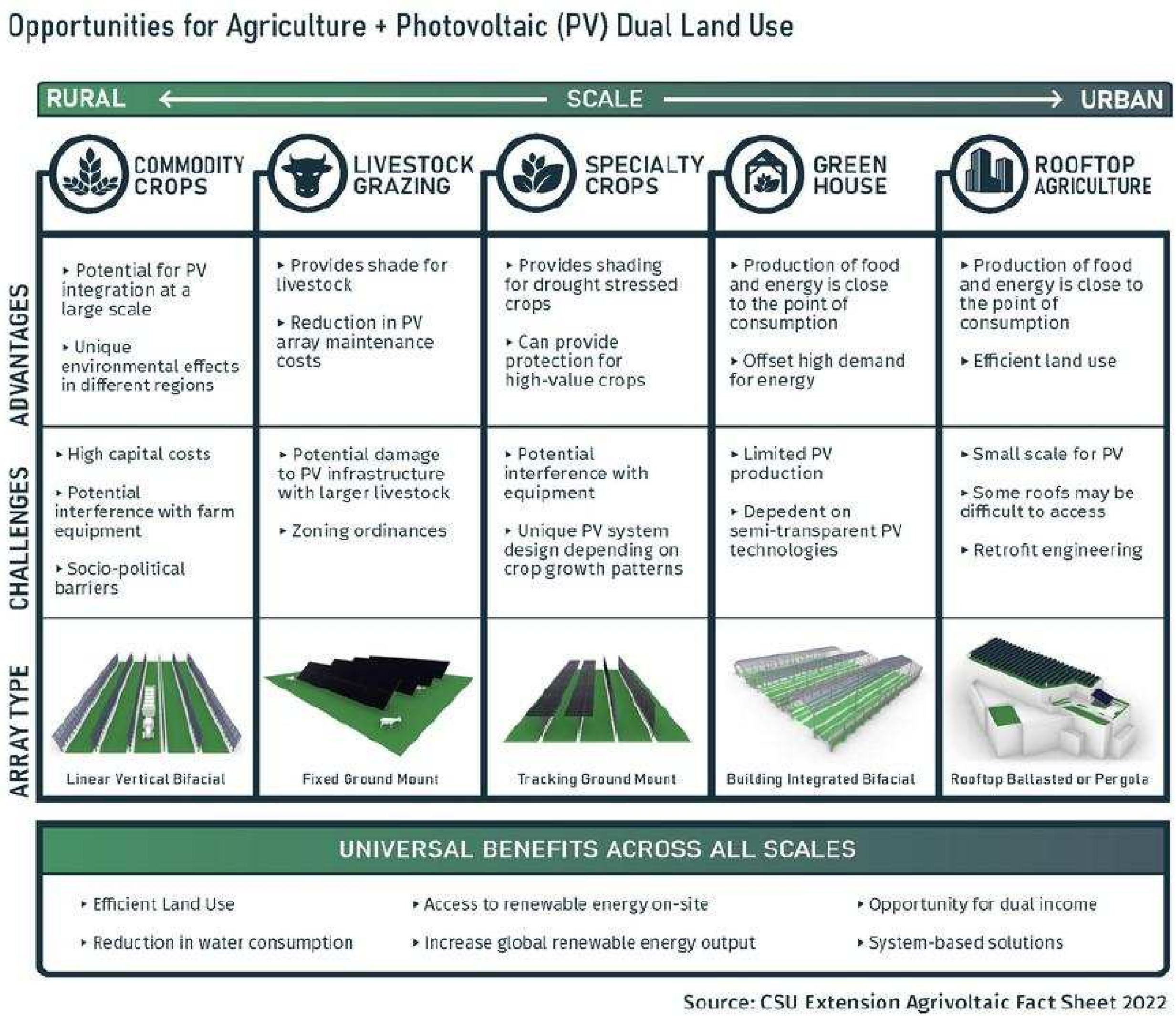

Figure 10: Agrivoltaic applications at multiple scales.

Other crop strategies are simpler to manage such as grazing below the panels with sheep, cattle, or goats. Rooftop agriculture offers different challenges such as installation and maintenance of both the PV system and agricultural production on tops of buildings. However, rooftop agrivoltaics does not have the agricultural equipment issue as planting, maintaining, and harvesting is accomplished by hand labor. As with any green energy plan, upfront costs are high but corresponding returns from both energy production and food production can be positive over time. This return is dependent on the value received for both electricity generated and crop produced.

Broad adoption of solar development on agricultural lands will depend on local acceptance of new technology and positive economics, which relies on community level support, crop yields, and supportive local regulations (Pascaris et al., 2020), along with equipment and installation costs for PV systems. To better understand agrivoltaic feasibility in your area, check with your appropriate local county advisory board, land commission and utility power company. Community engagement and outreach will be an essential component in achieving widespread implementation of this technology (Irie et al., 2019).

A multitude of diverse solutions will be needed to meet the renewable energy goals of the coming decades while protecting agricultural productivity and farm income. Agrivoltaics may provide environmentally and economically sustainable options for producers and landowners as we plan for a sustainable future.

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CHAPTER 2

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Characterization of Agrivoltaic Crop Environment Conditions Using Opaque and Thin-Film Semi-Transparent Modules

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Abstract: Agrivoltaics (APV), the co-location of agriculture and photovoltaics (PV), addresses an inherent competition for land usage. Taking the same dual-use concept to the urban landscape, rooftop APV can provide locally grown food in areas of need while providing distributed energy generation. In this multi-year investigation, different APV plots in northern Colorado, USA, were studied for crop metrics, light transmission, air temperature, soil/substrate temperature and moisture. Crops were grown under different solar panel types including opaque silicon and opaque and semi-transparent (ST) thin-film CdTe technologies. Growth conditions were characterized showing generally improved conditions and moderated temperatures under the panels. The ST-CdTe panels had increased photosynthetically active radiation (PAR) compared to both opaque panel types without a significant corresponding increase in temperature.

Keywords: agrivoltaics; solar; agriculture; CdTe; thin-film; green roofs; semi-transparent PV; photosynthetically active radiation (PAR)

1. Introduction

1.1. Solar Photovoltaics (PV)

Climate change is the most urgent problem facing humanity. Estimates from the Natural Resources Defense Council (NRDC) [1] indicate that, unaddressed, climate change could cost the US economy USD 615 B per year by 2050. This represents 1.47% of the US GDP. Many countries, including the United States, are committed to net-zero carbon emissions by 2050. The European Green Deal is the European Union's long-term framework to achieve climate neutrality by 2050. It relies on solar PV to help achieve economic development, future prosperity, and resilience [2]. Based on economic modeling, achieving 100% with more than 60% solar power is the most cost-effective approach to reach climate neutrality by 2050 [3].

According to the US Energy Information Administration (EIA) [4], solar PV electricity accounted for 2.8% of the electricity generated in the US in 2021. To achieve 60% capacity, approximately 500 gigawatts (GW) of new residential solar installations and 1500 GW of new utility scale solar will need to be constructed by 2050 in the US alone. Economics drives the increase in PV deployment—the lower the cost, the greater the uptake. Solar PV costs have dropped dramatically over the last five years and now cost less than other power-generation technologies. In the US, subsidy-free power is now produced at the utility scale below USD 30/megawatt Hour (MWh) [5], well below the cost of coal generation. Even with today's significant growth rate for PV deployment, it will take several decades to achieve carbon-free energy for most of the world. The significant increase in demand for PV electricity will require different approaches to deployment and integration.

1.2. Agrivoltaics

The term agrivoltaics (APV) is a contraction of the two words agriculture and photovoltaics. As demand for renewable solar energy surges in the US and across the world, so will the demand for food. The United Nations Food and Agriculture Organization (FAO) has projected that while global energy consumption will grow by up to 50% by 2035, food production must rise 60% in order to feed the world population by 2050 [6]. The energy consumption from agriculture is a significant contributor to overall energy use [7]. The APV model provides a framework to address these challenges within the food–energy–water nexus.

APV is a land-use model with the means to provide decarbonized energy while keeping agricultural land productive. APV's multi-land-use strategy maximizes the use of the sun's energy by capturing some of it for PV energy production while allowing the rest to be utilized for agricultural food production. The APV model has existed across the globe for several decades, but scalable adoption has been sporadic [8]. Agrivoltaics have been shown to provide overall economic benefits [9,10].

As the costs of PV technology drop, and the demands increase to convert agricultural lands to solar farms, the potential for APV is on the rise. The improved understanding of the crop growth environment is beneficial to increasing implementation and designing optimized farms [11]. Specifically, there is a need to understand the crop growth environment created in an agrivoltaics system in a particular geographic area, and its potential impacts on crops that are important to that region (e.g., vegetables). Studies have shown favorable results for APV systems [12], particularly when deployed in warmer regions [13,14].

In APVs, the shadow effect from the high coverage of opaque panels has been shown to have negative impacts on plants [15]. Semi-transparent solar panels are beginning to be investigated for APV [16–18]. Silicon ST panels use gaps between the opaque cells for light to pass. Thin-film ST panels are a newer technology with potential benefits for APV. The ST thin-film APVs are uniformly transparent [18] and use relatively less semiconductor absorber films than the opaque counterparts. The amount of light passing through the panel (and subsequently available for crop growth) can be tailored during manufacturing. Cadmium telluride (CdTe) solar is the most successful thin-film technology and has demonstrated very low energy costs for utility scale applications [19]. ST CdTe panels are being investigated for building integration for windows [20,21]; however, little research has been reported for semi-transparent CdTe used for APV [16].

1.3. Rooftop Agrivoltaics (RAPV)

APV can be deployed in an open field space or integrated onto rooftop settings forming rooftop agrivoltaics (RAPV). Rooftops are a primary frontier in the search for urban food security [22]. Urban areas have limited space available for traditional food production to occur. Paradoxically, there is often a significant amount of unused space on the rooftops of buildings. RAPV could provide a fully integrated solution on underused space beneath the panels and address issues at the food–water–energy nexus.

Studies demonstrate the feasibility of growing food on low-slope rooftops in urban areas. As of the publication of the paper by [23], there were about 17.5 hectares of rooftop farms in the world, with the majority (about 15 hectares) in North America. There is an opportunity to combine rooftop farms with PV energy production. In these synergistic RAPV installations, plants evaporatively cool solar panels, and solar panels partially shade plants in the high temperature, water-limiting space on green roofs. The protection from solar panels slows the water-use rate of the plants below them, reducing the drought stress of food crops.

1.4. Agrivoltaic Deployment

APV deployment addresses a key concern for PV land-use allocation by opening agricultural areas to PV deployment [13]. Most APV installations involve installing standard PV systems, perhaps on modified or elevated racking, in standard agricultural environments. This would allow agricultural laborers and machinery access to the crops under the panels. Although this simple co-location can be beneficial, there are tradeoffs between agricultural and PV production. For example, panel rows are typically spaced farther apart than in non-agricultural PV installations. This is to enable sufficient sunlight to reach the crops. This approach has demonstrated benefits including reduced plant drought stress, greater food production for regionally important vegetable crops, and reduced PV panel heat stress [13].

There is an active tradeoff between energy production (high PV panel density with significant crop shading) and high photosynthetically active radiation (PAR) or low panel density with minimal shading. To achieve 80% of the open sky photosynthetically active radiation (PAR), only ~50% of panel coverage can be implemented in traditional APV deployments [24]. The use of newly developed semi-transparent PV could potentially mitigate these issues and is studied here. These tradeoffs require increased system design costs and an understanding of crop PAR requirements to balance the capital expense costs, power production, and crop yield to maintain the overall economics.

In this work, we investigate the crop growth environment under four types of APV installations in two separate sites. Semi-transparent thin-film CdTe panels are compared with similar opaque CdTe and crystalline silicon. Spectroradiometer readings, air temperature above the crops, and soil temperature data are reported for each panel type.

2. APV Experiments

These experiments investigate APV growing environments under experimental PV arrays using different panel types, installation configurations, and orientations. Three different PV panel types deployed at two separate APV sites were studied. Both sites are located on land owned by Colorado State University (CSU), approximately 14 km from each other. The first, ARDEC South, which will be referred to as “ARDEC,” has nine pole-mounted PV arrays (Figures 11 and 12). The second, Foothills Campus, which will be referred to as “Foothills,” has a simulated RAPV growing system under a ground-mounted PV array (Figure 13). Three types of panels were investigated: opaque polycrystalline silicon (O-Si), opaque thin-film cadmium telluride (O-CdTe), and thin-film semi-transparent cadmium telluride (ST-CdTe) with 40% transparency (Figure 11).

Figure 11. Experimental APV system with semi-transparent CdTe panels. Panels have 40% transparency.

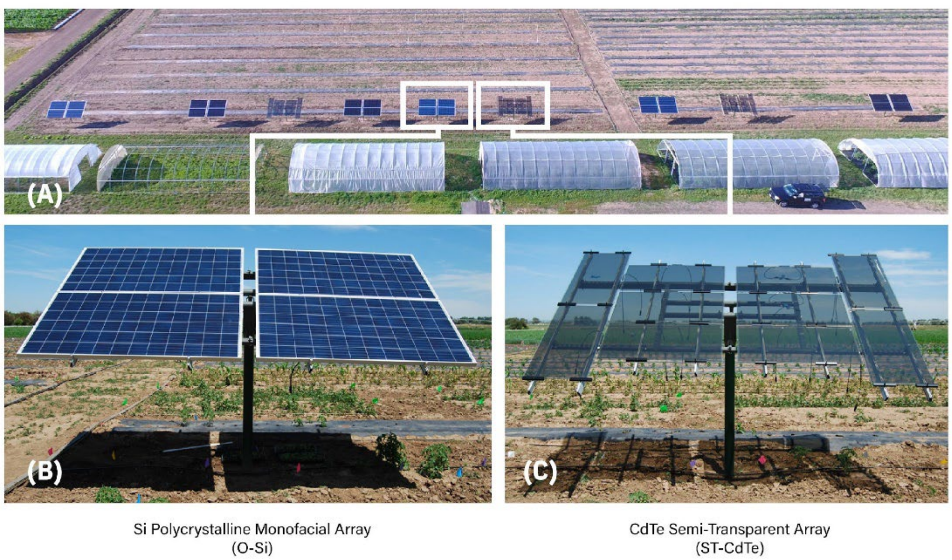

Figure 12. ARDEC site overview (**A**) Replicated AV test plots at CSU's ARDEC South location. (**B**) Opaque silicon (O-Si). (**C**) Semi-transparent CdTe (ST-CdTe).

Figure 13. Foothills Campus site overview. (**A**) Construction emulates a RAPV installation. (**B**) Growing environment under the O-CdTe panels at Foothills. (**C**) Growing environment under the 40% ST-CdTe solar panels at Foothills.

2.1. ARDEC South (ARDEC)

This study was conducted on a permanent experimental installation of pole-mounted PV arrays on certified organic land at the CSU Agricultural Research, Development, and Education Center, South (ARDEC) (40.610012, −104.993979; altitude: 1523 m), in 2020 and 2021. CSU in Fort Collins, CO, has 3.4 ha of certified organic field space dedicated to vegetable cropping systems research and demonstrations. The soil at ARDEC is classified as a Nunn clay loam [25]. Soil samples were collected to a depth of 20–30 cm each year before planting and were tested at the CSU Soil, Water, and Plant Testing Laboratory. Soil was analyzed for pH, electrical conductivity, lime, texture, organic matter, and nutrient content to determine recommended fertilizer rates during the growing season.

The PV plots were installed as a randomized complete block design (RCBD) with three panel transparency types and one full sun control in three replications in an open field environment

(Figure 12A). Two types of panels at ARDEC were included in this study. The first type was the thin-film telluride CdTe (ST-CdTe) with 40% transparency (Figure 12C), manufactured by Advanced Solar Power in Hangzhou, China. These are smaller than most commercially available panels designed for utility scale installations and have a rated output of 57 W. Their dimensions were 1200 mm long × 600 mm wide × 7 mm thick. The second type was polycrystalline silicon (Opaque Si), model JKM325PP-72, with 0% transparency (Figure 12B), manufactured by Jinko Solar in Shanghai, China. These have a rated output of 325 W; their dimensions were 1956 mm long × 992 mm wide × 41 mm thick.

The O-Si panel type is commercially available; however, the ST-CdTe panels are not yet UL-listed for grid connection in the US, and therefore, are being researched on an experimental basis. Similar opaque panels are listed and are routinely installed in grid-connected sites. The ST-CdTe panels consist of small, alternating regions of fully opaque solar cells and fully transparent areas (no solar cell material). The panels are fabricated as fully opaque, and laser ablation is used to selectively remove the solar absorber materials [26]. After ablation, the panels are laminated on the back with glass. According to the manufacturer, the PV transparency can be tuned at the factory between 0% and 90% light transmission. The spacing is narrow, and from a meter away the panel appears as uniform diffused light (Figure 12C). The ability to control this type of transmission by selective ablation is a specific attribute to the thin-film technology.

Each of the six PV arrays was mounted on the Montana Solar Top-4 racking system (Figure 12). The ST-CdTe arrays had six landscape-oriented and four portrait-oriented panels (Figure 12C). This provides a similar surface area to the silicon arrays. The racking system of each array was attached to a 152.5 mm diameter steel pole that was installed into a 600 mm-wide × 1830 mm-deep concrete pad. The angle of the arrays could be adjusted manually from vertical (0 degrees) to near horizontal (~90 degrees), parallel with the soil. Throughout the growing season, the arrays were set to 35 degrees to the south. When the panels were angled at 35 degrees, the bottom edge of the panel was 1220 mm above the ground and the back edge of the panels was 2360 mm above the ground. Each of the 12 subplots (both PV and control) was 4.3 m wide, and the subplots were spaced 4.3 m apart. The arrays were designed to simulate replicated field conditions for open field APV operations.

Drip irrigation was installed across all plots. The crop species tested in 2020 and 2021 included peppers (cultivars: Ace F1 bell, Jalapeño Early), summer squash (cultivar: Early Prolific Straightneck), and lettuce (cultivar: Butterhead). The tomato cultivars tested in 2021 included Red Racer and Tasmanian Chocolate. These vegetable crop species are important to small- and medium-sized growers who represent some early agrivoltaics adopters in northern Colorado.

2.2. Foothills Campus (Foothills)

A simulated RAPV study was conducted under existing solar panel arrays at the CSU Foothills campus west of Fort Collins, Colorado (40.586318–105.147377). During the 2020 growing season, a pilot study was initiated in 600 mm long × 1200 mm wide × 100 mm deep modular green roof trays, the same ones used in [27]. The green roof substrate was the Rooflite^{TM} intensive agricultural blend (Landenberg, PA, USA). In the study, treatments were in full sun, in the shade of the ST-CdTe panels, and in the shade of O-CdTe panels. Selected crops included lettuce, bush beans, and cilantro. The solar panels were an O-CdTe type with 1200 mm × 600 mm dimension and mounted in a configuration with approximately a 20–30 mm gap between the panels. The configuration is shown on the left side of Figure 13. Table 1 shows the locations, array configurations and panel types at both sites.

Table 1: Location, array configuration, and panel types for both sites.

LOCATION	**ARDEC**		**FOOTHILLS**	
ARRAY CONFIGURATION	9 Pole Mounted Arrays		Ground Mounted System	
PANEL TYPES	ST-CdTe	O-Si	ST-CdTe	O-CdTe

During the 2021 growing season, the site was expanded to include a 17 m × 8.7 m × 15 cm deep green roof system underneath and between two existing solar panel arrays. In the green roof system, the 20 mm root barrier and Extenduct drainage/water retention layer were supplied by Green Roof Solutions (Glenview, IL, USA). The growing substrate was a custom green roof agricultural blend of 60% expanded shale aggregate, 20% compost, 10% vermiculite, and 10% peat moss by volume. One treatment was in full sun, one treatment in deep shade under O-CdTe, and one in the shade of 40% ST-CdTe frameless solar panels (Figure 13). These panels were the same as the ST-CdTe panels used in the ARDEC site. The panels were mounted to a standard ground-mounted racking system angled at approximately 35 degrees to the south. The front edge of the panels was 350 mm above the substrate and the back edge was 1220 mm above the substrate. Irrigation was supplied by 1.5 lph Netafim drip emitters spaced at 150 mm intervals and lines were spaced 300 mm apart. Two pepper (Ace, jalapeño) and two tomato (Red Racer, Tasmanian Chocolate) cultivars were grown in addition to lettuce and yellow summer squash.

2.3. Data Collected

Growing conditions at ARDEC and Foothills in both full sun and under solar panels were continuously monitored using HOBO H21-USB micro station data loggers (Onset Computer Corporation; Bourne, MA, USA). An Apogee Spectroradiometer (Model SS-110, 340–820 nm; Logan, UT, USA) was used to quantify the light conditions in terms of Photon Flux Density (PFD) and Photosynthetic Photon Flux Density (PPFD). PFD is the measure of micromoles of light that land in one square meter in one second ($\mu mol \cdot m^{-2} \cdot s^{-1}$). PPFD is a similar metric but only accounts for photons of light within the PAR range (400-700nm), that land in one square meter in one second. At each site, three spectroradiometer readings were taken at 5 min intervals and then averaged. Data parameters collected at both research sites included PPFD, air temperatures at 30 cm above the soil/substrate, and soil/substrate temperatures at 2.5 cm deep. Data collection varied over the years at both sites. The variation is attributed to different construction dates.

3. Results and Discussion

To demonstrate the differences in the growing conditions under the PV arrays compared to full sun, we show data from one example date (14 August) for each 2020–2021 growing season at the ARDEC site and the 2020–2021 growing season at the Foothills site. We selected this date as representative of peak vegetable harvest where the plant canopy is established, thus optimally providing evapotranspiration benefits for the PV panels. The spectroradiometer readings are from 2022 at ARDEC and Foothills. We collected and analyzed light and temperature data as they are both key indicators of crop success in a specific growing environment.

3.1. Spectroradiometer

The spectroradiometer was used to analyze the differences in quantity and quality of light through measures of PPFD (PAR $\mu mol \cdot m^{-2} \cdot s^{-1)}$ under each of the PV panel types compared to full sun conditions. The measures of PPFD are commonly used by agriculturalists to define light conditions and requirements for various crops in controlled agricultural environments.

3.2. Spectroradiometer Results

Solar photon flux varies depending on the time of year, the time of day, and cloud cover or atmospheric moisture content. We show PPFD in full sun, under ST-CdTe, and under O-Si panels at each location to compare the impact on light conditions in each individual PV array configuration (Figure 14). The orange line symbolizes the wavelengths of the full sun, the gray line symbolizes the wavelengths reaching the canopy level under ST-CdTe panels, and the blue line symbolizes the wavelengths reaching the canopy level under O-Si or O-CdTe panels, respectively.

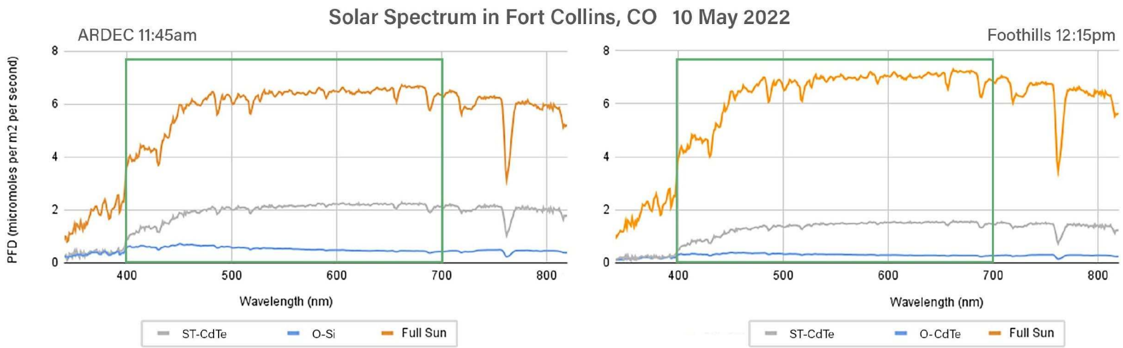

Figure 14. Spectroradiometer readings (ARDEC, 2022/Foothills, 2022).

In Figure 14, the green rectangle delineates light in the PAR range (PPFD) from other wavelengths of light. The spectroradiometer readings from ARDEC and Foothills show similar patterns of PPFD between the full sun and under-PV panel types. Both types of PV panels allowed all light wavelengths through, but with varying intensity. At ARDEC at 11:45 pm on 10 May 2022, the average PPFD in full sun was 1816, while it was 601 under ST-CdTe and 163 under O-Si. At Foothills at 12:15 on 10 May 2022, the average PPFD in full sun was 1970, while it was 405 under ST-CdTe and 92 under O-CdTe. Ultraviolet (UV) light in the 10–400 nm wavelengths was also notably absorbed by the PV panels.

At both locations, the opaque panels had the greatest impact on the amount of light reaching the plant canopy. The ST-CdTe panels allowed significantly less light than full sun, but more than three times the amount of light under the opaque panels at each respective site. The PV panels influenced the quantity of light at the soil/substrate surface but did not disproportionately impact any specific wavelength or quality of light. The reduction in the quantity of PPFD under the panels has the potential to impact plant physiology, stress, and yield in various ways depending on the climate and other crop system factors.

In regions with a short growing season or low light intensity, the sustained reduction in PPFD may impact plant growth negatively, while controlled light reduction in regions with a long growing season or high light intensity is likely to benefit plant growth.

The mitigation of UV radiation in the plant-growing environment is important to note because UV radiation is known to damage physiological and reproductive plant processes [28]. The negative impacts of UV exposure can be exacerbated in regions of high elevation and greater solar radiation, like Colorado. In these settings, plants are often overexposed to sunlight and, as a result, cannot utilize all the sunlight that reaches their canopies. Light beyond the needs of photosynthesis becomes a stressor and is managed as excess heat to be dissipated via transpiration and other mechanisms. When water is limited, plants close their pore-like openings, called stomata, which effectively stops transpiration. Temperatures inside the plant increase and trigger photoinhibition, resulting in inefficient carbon use and additional plant stress. Providing shade and air temperature moderation when the sun is at its zenith can alleviate the damage caused by these plant stressors. In fact, many specialty crop growers in high solar radiation locations use shade cloths in their operation to prevent plant stress and sun scalding [29]. Our results show moderated light conditions designed to shade plants and improve growing conditions for crops under the shade or partial shade from PV panels.

The ST-CdTe panels were specifically included in this investigation to evaluate the relative impact of light transmission for crops because the mitigation of light reduction is amongst the top priorities in agrivoltaic research [16,30]. The relatively higher light transmission under ST-CdTe panels compared to that of opaque PV panels can enable a higher panel density compared to other APV configurations. An increased and uniform panel density provides economic benefit through decreased PV installation costs. Because uniform panel density is the standard in the PV industry, this type of array allows for the same economic models, installation techniques, and operations and maintenance protocols that are already used. Increasing the uniform panel density without compromising light transmission increases economic viability for PV installation and an opportunity for plant growth.

3.3. Air Temperatures

Ambient air temperatures at both ARDEC and Foothills recorded at the plant canopy level (30 cm above the soil) indicate that the shade from the PV arrays resulted in cooler ambient air temperature by an average of 1.3 °C during the hottest hours of the day (Figure 15). Most notably, the air temperature under the ST-CdTe did not differ from the air temperature below O-Si or O-CdTe. This is consistent with data provided by others [13,27], which showed similar differences between the substrate surface temperature in full sun compared to under opaque PV panels. Considering the higher light level under the ST-CdTe compared to either opaque panel type, without a corresponding higher air temperature, we suggest that the growing conditions under semi-transparent panels are more suitable for plant growth.

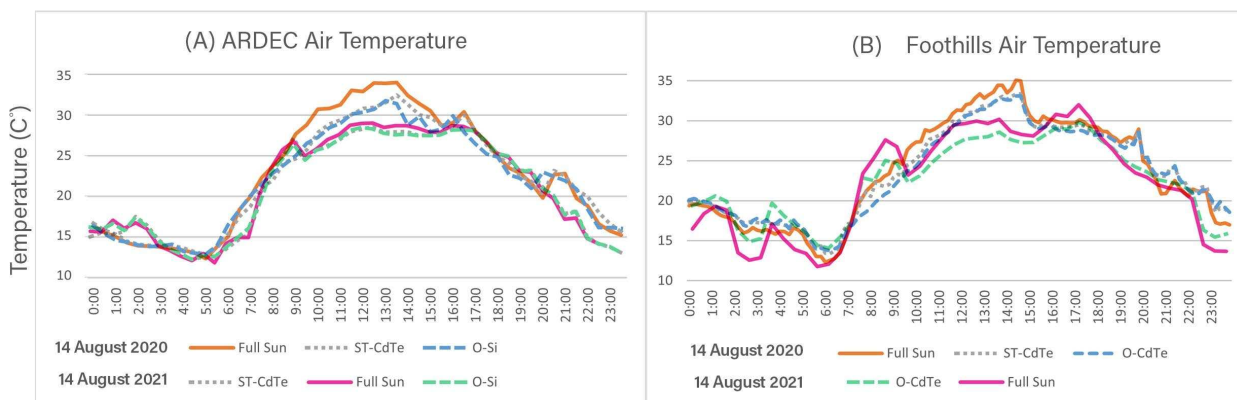

Figure 15. Air temperatures across both sites at 30 cm high. (**A**) ARDEC 2020 and 2021 and (**B**) Foothills 2020 and 2021.

3.4. Soil Temperature

It has been documented that soil temperature is closely associated with plant growth, plant stress (particularly at the initial root zone), and soil microbial diversity [32]. When soil temperatures rise above the optimum threshold, it can impede physiological processes such as plant water and nutrient uptake, plant growth regulator (PGR) signaling, and metabolite production, causing damage to plants. Extreme high temperatures can significantly impact crop growth and cause damage to plants [32]. Maintaining moderated soil temperatures through additional shade provided by APV systems can benefit temperate crops.

3.4.1. ARDEC South Soil Temperature

Soil temperatures at ARDEC show a much-attenuated temperature fluctuation in comparison to the air temperature results (Figure 16A). Shading from the PV panels, especially the ST-CdTe, generated lower temperatures midday. More specifically, in 2020, the soil temperature was 3 °C cooler under ST-CdTe panels in the afternoon. Overall, the solar panels provide moderated soil temperatures resulting in cooler daytime temperatures and lower nighttime temperatures, especially in the shade of PV panels.

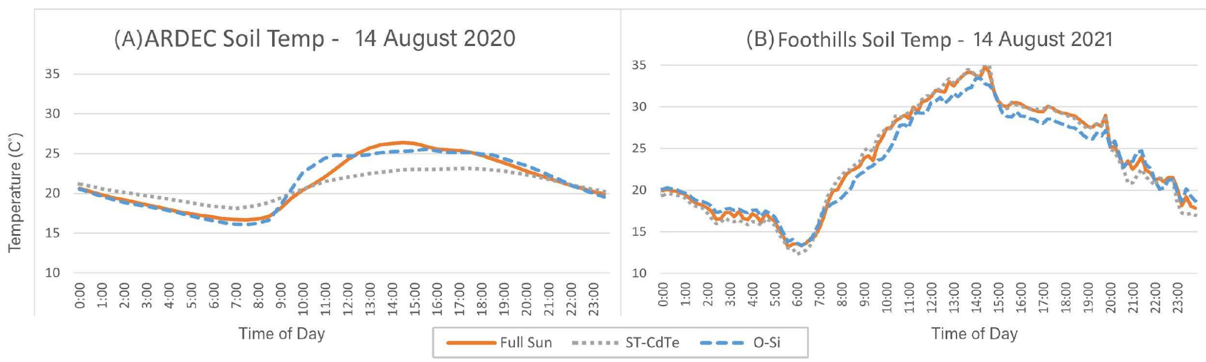

Figure 16. Soil Temperature at 2.5 cm depth (ARDEC, 2020, and Foothills, 2021).

3.4.2. Foothills Soil Temperature

The green roof substrate temperature among both panel types aligned closely with air temperatures (Figure 16B). This is likely due to the green roof substrate water-holding capacity, which is much lower than field soils, especially the clay-rich soils at ARDEC. Green roof substrate's lower water-holding capacity results in less soil moisture and subsequently higher substrate temperatures when compared to growing conditions at-grade.

4. Conclusions

In this study, we compared the effects of three types of PV panels on light and temperature compared to an open field agricultural growing environment and a green roof environment. Overall, our findings demonstrate that the agrivoltaic concept holds promise for plant growth in conjunction with PV land-use across various scales. The benefits of partial shade [23] from PV arrays produces a growing environment that could allow for the expansion of PV integration in combination with agriculturally productive rural and urban regions across the globe [13,27].

Compared to the opaque panels, the semi-transparent panels allowed for greater light intensity to the plants while not increasing the soil/substrate or air temperatures, which can be beneficial to plants [32]. This finding warrants further exploration of semi-transparent panels for RAPV and building integrated photovoltaics (BIPV) with indoor climate-controlled crop operations. While the microclimate in small scale agrivoltaic systems with semi-transparent panels should not be considered a controlled environment [12], it can be considered a semi-controlled growing environment for crop systems due to the moderated temperature and light conditions, not unlike the shade cloth described earlier.

Semi-transparent PV panels offer a solution that caters to specific agricultural applications depending on the crop type and climate. The integration of PV with agricultural operations enables the expansion of renewable energy development while maintaining productive agricultural operations [12,13]. Future studies are needed to analyze soil moisture, crop yield impact across diverse climates [22], and panel temperatures with relative efficiencies for responsible agrivoltaic deployment at scale.

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CHAPTER 3

A Rooftop Agrivoltaic System: Pollinator Plant Establishment

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Introduction

Pollinator Plants, Urban Environments & Green Roofs

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). The reintroduction of native plants into urban hubs is a crucial step towards restoring the natural ecology in our human-centric urban environments. Native plants are well adapted to thrive in their local environment with less maintenance and are suited to regional climate conditions. Therefore, urban landscapes, including rooftops, have the potential to replicate native ecosystem services by acting as localized ecological communities (Li and Yeung 2014).

Green roofs offer a solution to increase green space in urban environments while maximizing the land use efficiency of the building footprint. Green roofs host numerous benefits to humans, urban metabolism flows (Kennedy et al., 2007), and can play a key role in urban ecosystem services (Oberndorfer et al., 2007). 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 pollination 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.

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 solar panels (Figure 17).

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, 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).

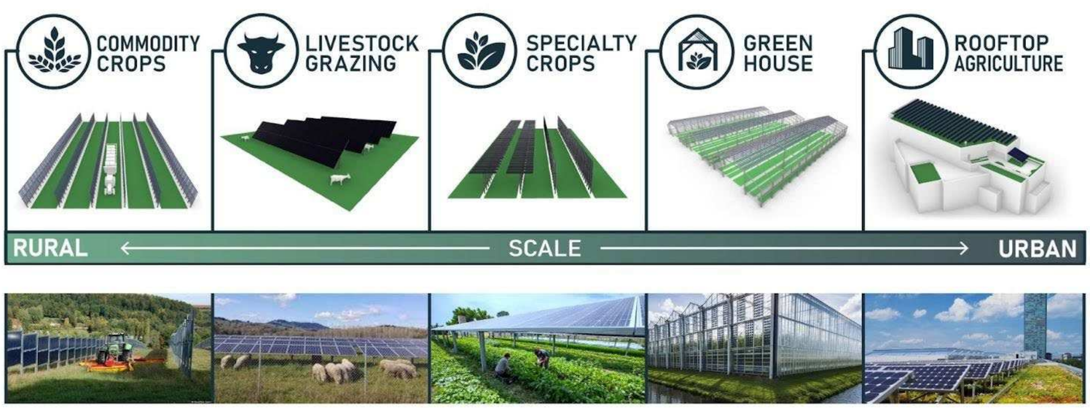

Figure 17: The Scale of Agrivoltaics – Adapted from CSU Extension Fact Sheet.

Currently, 4.4 billion individuals live in urban areas, and that number is expected to increase to account for 70% of all humans by 2050(The World Bank, 2023). Bringing APV and RTPV models to the urban landscape illuminates a new way to increase renewable energy production, specialized urban agricultural production, and biodiversity where human populations are the greatest. Flat urban rooftops are often underutilized spaces but have vast potential to play host to energy production and plant growth.

Mutually Beneficial System

Plants

Planting systems paired with PV systems have the ability to offer plants protection from intense solar radiation and can increase productivity in rooftops settings. The shade of the PV panels provides 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 in particular can cause damage to plants (Hollósy, 2002).

APV 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 (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 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 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 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 Celsius 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 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; Lamnatou and Chemisana 2015).

MATERIALS & 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 expanded to include a permanent 130 m^2 growing area around 2 ground mounted PV arrays with various PV module types and transparencies (Figure 18). The arrays are fixed due south at a tilted latitude of 35 degrees, which is the ideal at this latitude. 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. 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,

Figure 18: Aerial plan view of CSU Foothills campus RAPV research site. The plant establishment trial is in the white dashed rectangle.

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. At 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 19). 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. lanulosa, 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, totalling 120 plants (Figure 19).

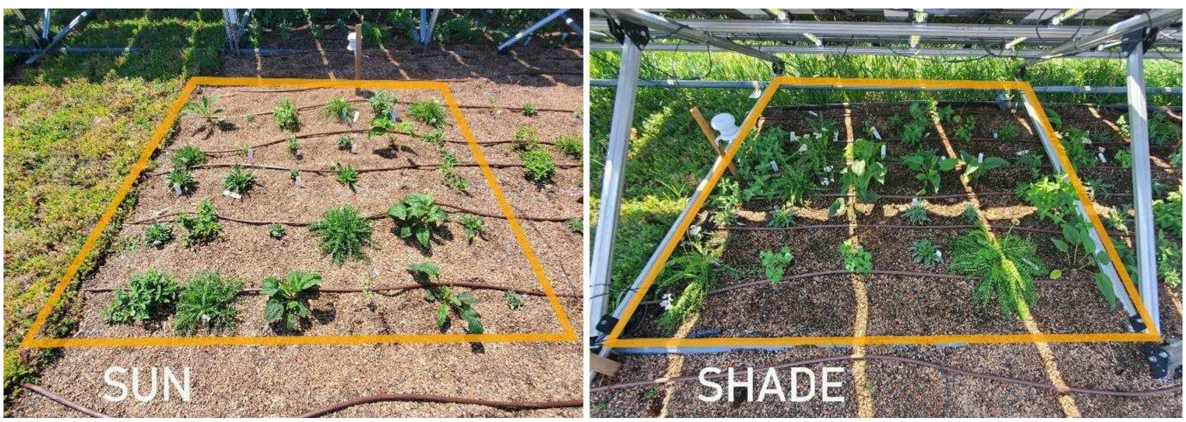

Figure 19: Native pollinator species are randomized and replicated in full sun and in the shade of solar panels.

The light conditions of the site were modeled using the SPADE Agrivoltaic Design Tool (Figure 20), a software program that models irradiance in agrivoltaic systems based on climate and PV configuration. The software is powered by Ladybug Tools (Sadeghipour Roudsari and Pak, 2013) extension of Grasshopper and Rhino3D Software to analyze the average ground level irradiance over the data collection period (July-October). The PV array is modeled to scale in accordance with the ground mounted array at the CSU Foothills campus.

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 SPADE Agrivoltaic Design Tool converts the average irradiance to average photosynthetic photon flux density (PPFD). 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).

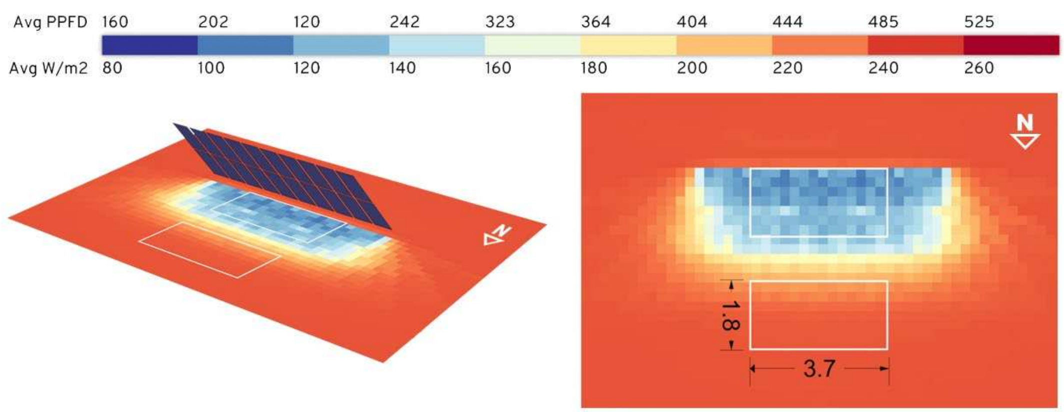

Figure 20: Analysis of average irradiance (perspective view, plan view, and legend) from July through October using SPADE Agrivoltaic Design Tool. Each white rectangle delineates the 3.7 m by 1.8 m full sun and shade treatment areas.

Monitoring equipment & 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. EC-5 volumetric moisture sensors (Onset Computer Corporation, Bourne, MA, USA) were used to measure the substrate moisture conditions. We documented the various temperatures and soil moisture every 15 minutes in each of the treatments.

Plant height and width in perpendicular directions were collected twice a month from July 14th, 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) with Equation 1 to compare overall volumetric growth rates between sun and shade environments.

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

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

Table 2: Maximum, mean, and minimum air temperature in each treatment by week from 7/23/2021-9/9/2021. The table also includes the difference between treatments in Celsius by week.

AIR TEMP **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 (7/23-7/29)	37.5	37.6	25.3	25.3	13.5	13.4
Week 2 (7/30-8/5)	34.4	34.9	21.6	21.6	11.2	11.0
Week 3 (8/6-8/12)	35.0	34.3	23.1	23.0	10.3	10.2
Week 4 (8/13-8/19)	36.4	35.7	22.0	21.8	9.0	8.9
Week 5 (8/20-8/26)	35.4	34.6	22.7	22.6	10.9	11.2
Week 6 (8/27-9/2)	35.0	34.4	21.0	20.9	6.6	7.5
Week 7(9/3-9/9)	37.4	36.1	22.8	22.5	6.6	7.5

Air temperature

The ambient air temperature at 30 cm above the substrate surface showed no significant differences between the two treatments (Figure 21a). The tightly paired temperature indicates that despite the shadow of the PV panels, air temperature remains consistent which is likely due to free-flowing air currents. Like 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.

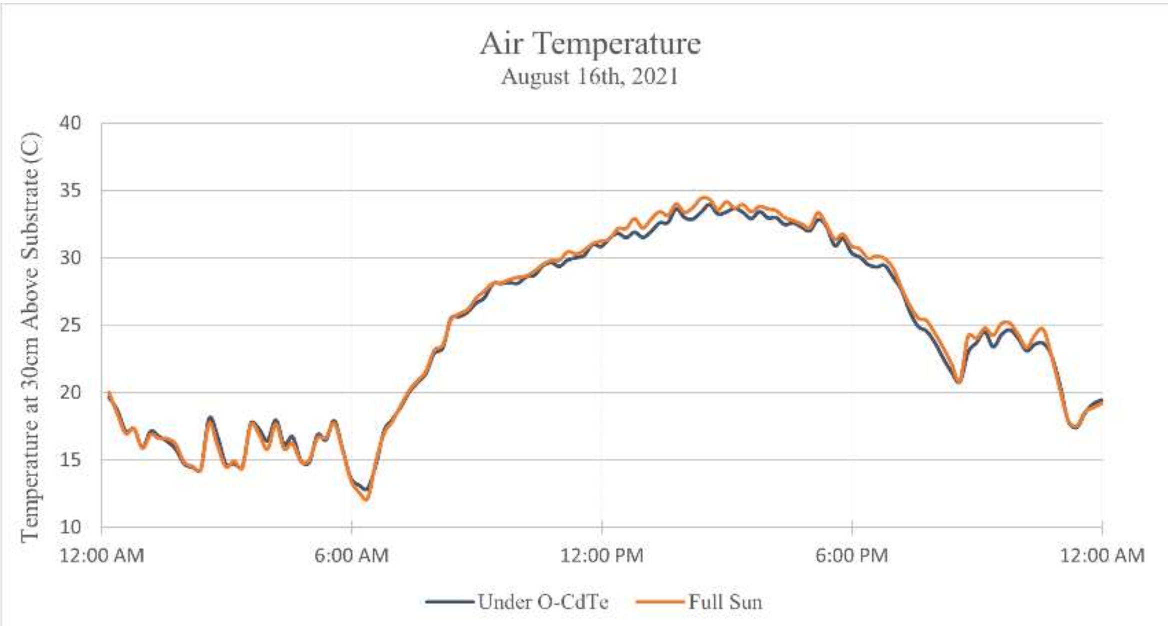

Figure 21a: A comparison of air temperature at 30 cm above the substrate surface in both treatments over one day (8/16/2021). 8/16 was selected as an example to illustrate daily changes in air temperature.

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 21b).

Table 3: Maximum, mean, and minimum substrate temperature in each treatment by week from 7/23/2021-9/9/2021. The table also includes the difference between treatments in Celsius by 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 (7/23-7/29)	38.4	36.6	25.5	25.0	13.2	14.0
Week 2 (7/30-8/5)	34.8	34.2	21.6	21.5	11.2	11.6
Week 3 (8/6-8/12)	35.3	33.7	23.2	22.7	9.9	10.6
Week 4 (8/13-8/19)	36.5	34.5	22.7	22.0	9.1	9.4
Week 5 (8/20-8/26)	35.8	33.5	22.7	22.2	10.9	11.6
Week 6 (8/27-9/2)	35.3	34.2	21.0	20.7	6.9	7.7
Week 7 (9/3-9/9)	38.3	37.0	22.9	22.4	6.9	7.7

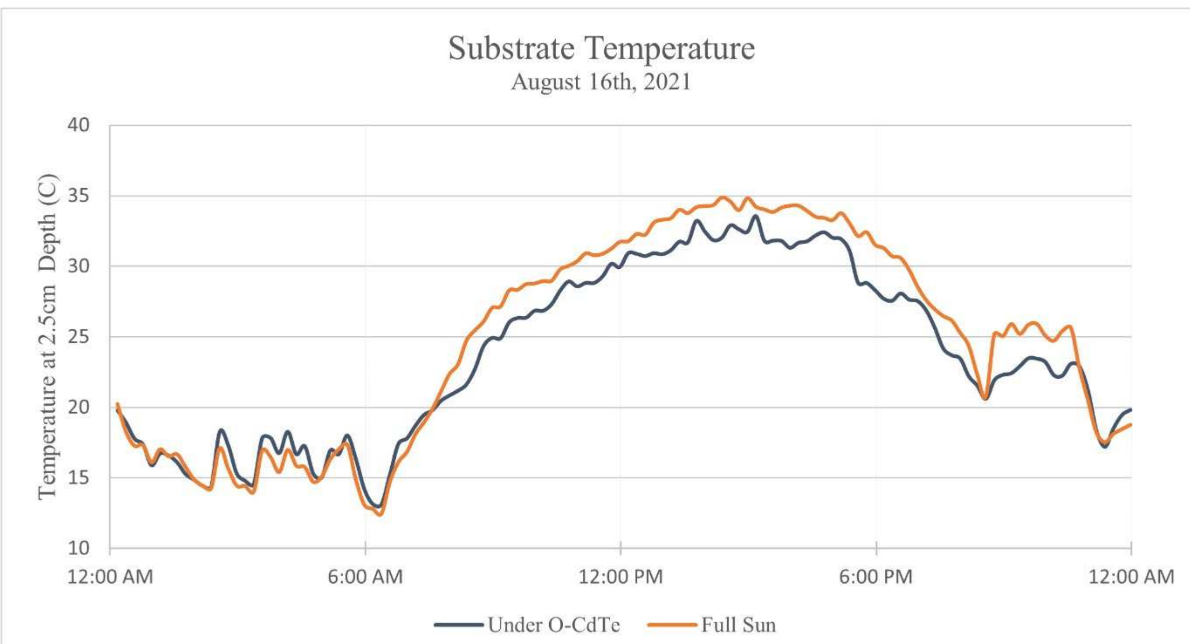

Figure 21b: A comparison of substrate temperature at 2.5 cm beneath the substrate surface in both treatments over one day (8/16/2021). 8/16 was selected as an example to illustrate daily changes in substrate temperature.

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.'s study in Corvallis Oregon's dry Mediterranean climate where they found the green roof media 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 7/30 and 8/20 (Figure 22). 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 previous green roof study by Bousselot et al. (2017) in a similar Colorado climate and Getter et al. (2009), in Michigan's climate.

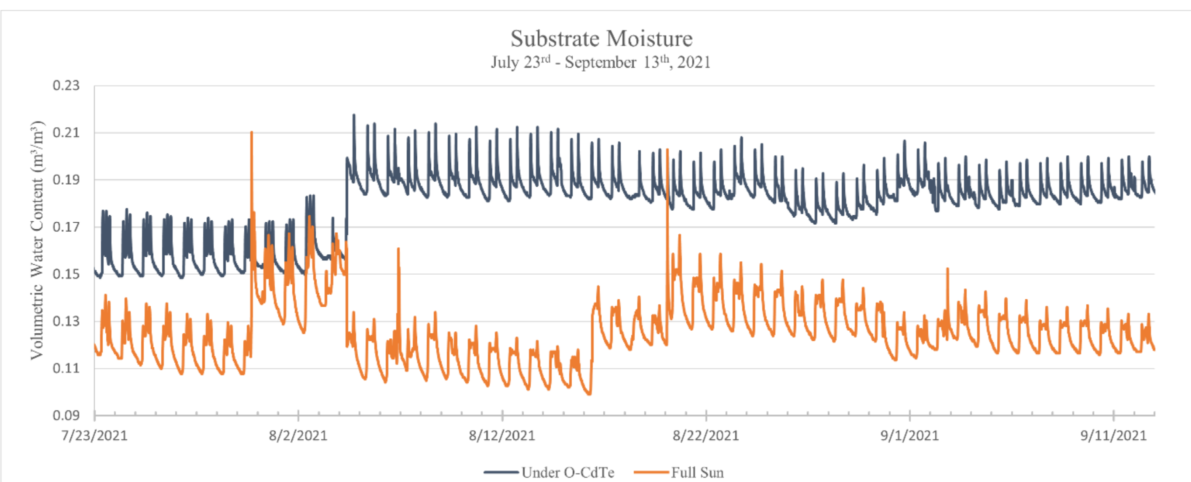

Figure 22: A comparison of volumetric water content at 2.5 cm beneath the substrate surface in each treatment from 7/23-9/13. The daily peaks correlate with irrigation events. Substrate moisture remained higher in the O-CdTe treatment.

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.

Plant Growth Index

PGI measurements were collected and evaluated using Equation 1 over the course of the study. The results are representative of the mean seasonal PGI of each species in each treatment (Figure 23). 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: $$\text{Seasonal PGI} = \text{Mean PGI}_{\text{week 12}} - \text{Mean PGI}_{\text{week 1}}$$

No significant differences were found between treatments within species. This result means 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. vitensis*, and *P. strictus* had greater seasonal PGI in the O-CdTe shade plot (Figure 23). *M. fistulosa* had equal seasonal PGI in both treatments with slightly more variation in the shade. *A. lanulosa*, and *A. caerulea* had slightly greater seasonal PGI in the full sun treatment. *A. caerulea* was the only species to exhibit negative growth over the season, and it did so uniformly across both treatments. The 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, sub-alpine regions of the Rocky Mountains with cool nighttime temperatures.

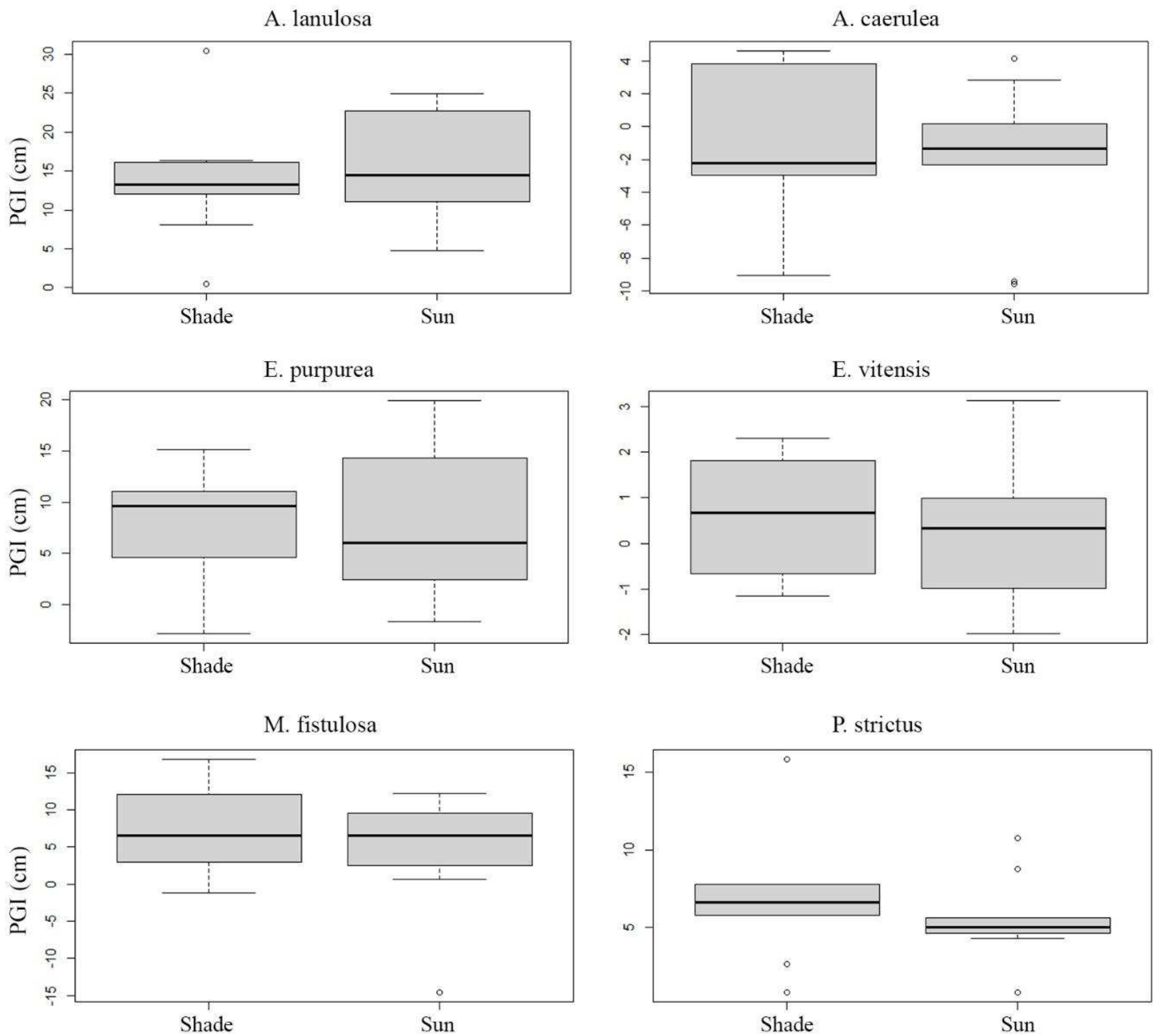

Figure 23: The boxplots show average seasonal PGI over the establishment period from 7/28-10/14. The Y-axis varies by species to show accurate comparisons between treatments.

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 as well. 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).
Taking these results in tandem with earlier flowering times on traditional full-sun green roofs (Ruszkowski 2023), 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 green roof 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).

Overwinter Plant Survivability

During the initial growing season only two individual plants in two species perished: one *A. caerulea* and one *E. vetensi*s. Both plants were in 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%).

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. lanulosa* 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 Plant Overwinter Survivability

Scientific Name	**Common Name**	**O-CdTe**	**Sun**
Achillea millefolium var. *lanulosa*	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%)**

Similar to findings from another shade study on green roofs, (Getter et al. 2009) there were no statistically significant differences in species richness between sun and shade treatments. However, 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 (Li and Yeung 2014, Dvorak and Volder 2010). 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 find 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. The combination of shaded plots from solar panels in combination with full sun areas can imitate natural ecoregions leading to greater species richness (Dvorak and Volder, 2010).

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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CHAPTER 4

Vegetable Crop Growth Under Photovoltaic (PV) Modules of Varying Transparencies

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Introduction: Agrivoltaic Opportunity

The drivers of agrivoltaic development are multifaceted, encompassing energy transition objectives, land-use efficiency, crop performance, economic benefits, and climate resilience. In the US alone it is predicted that 10 million acres of land-based PV will be installed as we move towards a decarbonized grid by the year 2050 (DOE, 2021). Land scarcity and competition for agricultural land have motivated researchers and practitioners to explore ways to maximize land-use efficiency (Dinesh & Pearce, 2016, Trommsdorf et al., 2022). Agrivoltaics allow for the productive use of land by harnessing solar energy without compromising agricultural activities (Dupraz et al., 2011). Researchers have identified key barriers to adoption from the agricultural sector that can be used to guide research objectives to optimize mutual benefits (Pascaris et al., 2020). A recent report from NREL highlights the 5 C's for agrivoltaic success bringing technical and social considerations to the forefront of APV development - Climate, Configuration, Crop, Compatibility and Collaboration are essential components of a larger framework for successful agrivoltaic integration. By sharing the same land, there is opportunity for farmers to generate additional income from solar power while preserving the primary agricultural function within the framework of the larger Food Energy Water Nexus (FEW Nexus) (Macknick et al., 2022).

Shading from solar panels in agrivoltaic systems reduces evaporation rates, preserving soil moisture and enhancing water-use efficiency. By mitigating water loss through evaporation, agrivoltaics help alleviate the strain on water resources, especially in arid and semi-arid regions

(Barron-Gafford et al., 2019). Many studies have found increased soil moisture and reduced soil temperature within APV systems (Marrou et al., 2013a; Uchanski et al.; 2023, Williams et al, 2023). Other studies have indicated that the reduced evaporation in agrivoltaic systems contributes to improved water-use efficiency, allowing crops to grow with reduced irrigation requirements (Adeh et al., 2018; Barron-Gafford et al., 2019). The integration of solar panels within agricultural landscapes creates a microclimate that shields crops from extreme weather events such as hail, wind and excessive UV radiation. This protective microclimate can mitigate crop damage, ensures more stable growing conditions. While some studies report profound microclimatic effects from PV canopy in their climate, it is important to account for specific climatic conditions when interpreting data (Marrou et al., 2013a).

Agrivoltaic systems implemented globally predominantly utilize conventional opaque PV modules, which can significantly alter the microclimate beneath the panels, particularly under high shading ratios (Gorjian et al., 2022). Semi-transparent PV (STPV) module technology has emerged as a potential solution to mitigate the negative effects of dense shade in cropping systems while maintaining a high panel density. While STPV modules have not been studied at the same rate as opaque it the technologies, they offer several opportunities to provide optimal plant growth conditions in APV systems through tunable transparencies, spectrum splitting technologies, and building integrated solutions (Gorjian et al., 2022). With further research specific STPV technologies will emerge as optimal solutions for distinct crop types and climates across the globe. Here we report findings from several module types, including thin film STPV panels that are not currently found in the literature.

Crop Yield

The impact of varying shade conditions from PV modules on crop yield has been studied for more than 10 years with results across the board depending on crop type, APV system configuration, and the climate (Barron-Gafford et al., 2019, Marrou et al., 2013, Amaducci et al., 2018, Trommsdorf et al., 2021, Tajma & Iida, 2022, Gorjian et al., 2022, Laub et al., 2022). Several different crop types and cultivars have been studied in APV systems over the past 2 decades including vegetative crops and fruiting crops. Field trials and experimental studies have demonstrated that different plant species exhibit varying responses to alterations in light conditions associated with different regional climates and APV configurations (Touil et al., 2021) (Aroca-Delgado et el. 2018). In an APV system with elevated panels in Arizona, researchers found yield increase in specific pepper cultivars (Barron-Gafford et al., 2019), while other studies have found yield reduction with greater shading density (Touil et al., 2021). Solar panels in agrivoltaic systems provide shading, mitigating the negative impacts of excessive heat on crops. Reduced heat stress can translate into improved crop yields, as higher temperatures often hinder physiological processes and limit photosynthetic activity (Barron-Gafford et al., 2019).

We report on the findings of a 2-year study of vegetable crops growing under fixed-tilt solar arrays with three panel types - monofacial, bifacial, and thin-film semitransparent (STPV). This research aims to investigate and analyze the application of semi-transparent technologies in agrivoltaic systems, focusing on the crop yield response and microclimate changes when comparing conventional opaque PV modules, semi-transparent modules and full sun treatments.

2. Materials & Methods

Site Description

This study was carried out during the growing seasons of 2020 and 2021 at the CSU Agricultural Research, Development, and Education Center, South (ARDEC), which is located at coordinates 40.610012, −104.993979, with an altitude of 1523 m above sea level. The ARDEC site in Fort Collins, CO, encompasses 3.4 hectares of certified organic land specifically designated for research and demonstrations related to vegetable cropping systems. The soil at ARDEC is classified as Nunn clay loam (NRCS USDA, 2018). Prior to planting each year, soil samples were collected from a depth of 20-30 cm and analyzed at the CSU Soil, Water, and Plant Testing Laboratory to measure pH, electrical conductivity, lime, texture, organic matter, and nutrient content to determine the appropriate fertilizer rates for the growing season. The study utilized a permanent experimental installation of 9 pole-mounted PV arrays on the certified organic land at ARDEC as described in the field study in Uchanski et al. (2023).

PV description

The PV plots were arranged in a randomized complete block design (RCBD) with three different panel transparency types and one full sun control, replicated three times in an open field setting (Figure 24). This study incorporated three panel types at the ARDEC site. The first is a thin-film cadmium telluride CdTe (ST-CdTe), which had a transparency of 40% (Figure 24). These panels were manufactured by Advanced Solar Power in Hangzhou, China, and were smaller than the typical panels used for large-scale installations, with a rated output of 57 W. Their dimensions measured 1200 mm in length, 600 mm in width, and 7 mm in thickness. The second panel type is an opaque polycrystalline silicon (O-Si), model JKM325PP-72 by Jinko Solar (Shanghai, China), which had 0% transparency (Figure 24). These panels had a rated output of 325 W, with dimensions of 1956 mm in length, 992 mm in width, and 41 mm in thickness. The third panel type is a bifacial monocrystalline (BF-Si), model LR6-72BP-360M by Longi, which had a transparency of approximately 5% and a rated output of 360W.

Each of the nine PV arrays were mounted on the Montana Solar Top-4 racking system, as shown in Figure 24. The ST-CdTe arrays consisted of a combination of six landscape-oriented and four portrait-oriented panels, providing a comparable surface area to the silicon arrays (Figure 24). The racking system for each array was fixed to a single pole mount with a diameter of 152.5 mm, which was installed into a concrete pad measuring 600 mm in width and 1830 mm in depth. The arrays' tilt angle could be manually adjusted, ranging from a vertical position (~0 degrees) (Figure 25) to a nearly horizontal position (90 degrees), parallel to the soil surface. The adjustable tilt allows for farm equipment to pass close to the array for field preparation, and then can be angled flat to maximize crop protection or maximize shade for farmer welfare during

Figure 24: Monofacial polycrystalline module (0% transparent), Bifacial monocrystalline module (~5% transparent), Cadmium telluride (CdTe) thin-film module (40% transparent)

Figure 25: Array adjustability for field preparation.

harvest season. Throughout the growing season, the arrays were set at an angle of 35 degrees facing south. At this angle, the bottom edge of the panels was positioned 1220 mm above the ground, while the back edge reached a height of 2360 mm above the ground. Each of the 12 subplots, including both PV arrays and control plots, spanned a width of 4.3 m, with a 4.3 m spacing between adjacent subplots. Due to the single pole mount configuration the shadow cast from the modules moves throughout the day. With this, the crops received direct sun early and late in the day, with maximum shade during the peak hours of the day. The design of the arrays aimed to replicate field conditions encountered in open field agrivoltaic operations (Uchanski et al., 2023).

Agriculture Materials

The crop species tested in 2020 included pepper cultivars *Capsicum annuum* 'Ace F1' and *Capsicum annuum* 'Early Jalapeño', summer squash cultivar *Cucurbita pepo* 'Early Prolific Straightneck', and lettuce cultivar *Lactuca sativa* 'Capitata'. In 2021 the peppers, lettuce, and squash cultivars remained the same to complete a 2-year study, while we introduced tomato cultivars *Solanum lycopersicum* ‘Tasmanian Chocolate’ and *Solanum lycopersicum* ‘Red Racer’.

Planting Plan

In the years 2020 and 2021 we studied twelve plots in total, using a randomized complete block design (RCBD) with three replications and drip irrigation across all plots. Each replication had three photovoltaic panel (module) types (i.e., transparency levels) and full sun control with no solar modules. Three plots were in an open field and served as the control plots, three plots were underneath traditional opaque solar modules, three plots were underneath bifacial solar modules, and three plots were underneath semi-transparent thin-film CdTe solar modules.

There were 3 planted rows across the entire site - north, middle and south as shown in Figure 26. Lettuce, peppers, and tomatoes were planted in two offset sub-rows in 0.9 m beds covered with black plastic mulch in the north and south rows. Squash was exclusively planted in the middle row both years with 1.2m spacing on center. The north and south rows each had one line of drip irrigation buried under the plastic, while the middle row was supplied with two lines of exposed drip irrigation. Irrigation was supplied at 15 Lpm/30.5m for 3-hour intervals 3 days a week across all plots.

Figure 26: ARDEC South agrivoltaic research site planted with open bed in the middle row, and plastic mulch in the north and south rows.

Data Collection Materials

Yield weight/plant

Parameters measured included total yield in weight per harvest per plant, individual fruit count per squash plant, spectroradiometer readings, air temperature at 30 cm above the soil surface modules, and soil temperature 2.5 cm under soil surface (Figure 27). Soil and air temperatures were measured at 30-minute intervals over the course of the entire growing season using HOBO H21-USB micro station data loggers (Onset Computer Corporation; Bourne, MA, USA). Crop yield was routinely evaluated as crops reached harvestability, which is dependent on the crop type and growing habits. Squash yield was collected once a week consistently for 5 weeks after the initial harvest. Lettuce yield was measured only once per year by destructively harvesting the crops 6 weeks after planting. Pepper yield was collected on a rolling basis every two weeks after the initial harvest until the end of the growing season. Tomatoes were harvested every two weeks after the initial harvest. Crop yield is reported in weight (g) per plant as a plant count and weight were taken at each yield collection event. The average weight per plant accounts for plant mortality throughout the growing season. Individual fruit count was collected for squash, but not for peppers or tomatoes.

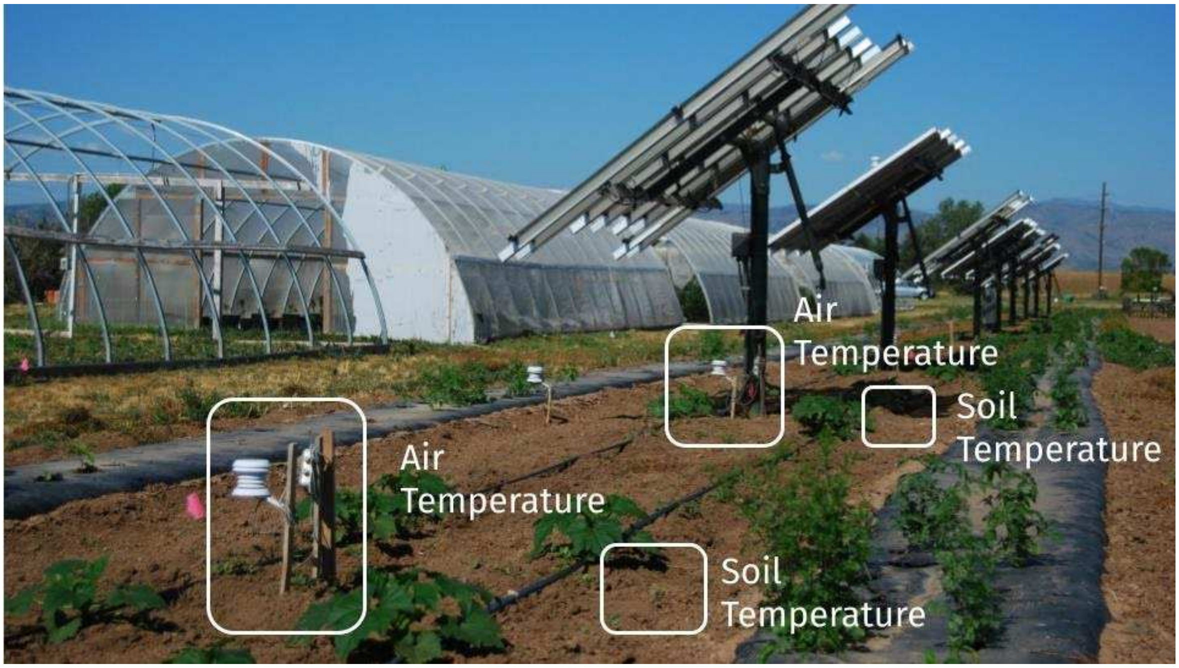

Figure 27: Air and soil temperature data collection points.

Data Analysis

R-studio (2002, Boston, MA) was used to analyze the results of our data collection using two separate linear mixed models - one for squash, and one for all other crops in the north and south rows to test for significance among treatments. Pairwise comparisons of mean yield/plant using the Kenward-Roger method and Tukey adjustment were used to compare a family of four estimates for significance at a 95% confidence interval.

3. Results & Discussion

Light

Sunlight is fundamental to both agricultural and photovoltaic systems and can be the primary factor of plant success in agrivoltaic systems. The positioning and arrangement of solar panels within these systems can significantly influence the availability and distribution of sunlight reaching the underlying crops. Several studies across the world have quantified the impacts of shade from PV on crop systems (Trommsdorf et al., 2021, Tajma & Iida, 2022, Gorjian et al., 2022, Laub et al., 2022).

The spectroradiometer readings from this site presented in Uchanski et al. (2023) showed that the quantity of light within the photosynthetically active radiation (PAR) range was reduced under all panel types, while no specific wavelengths within the PAR spectrum were absorbed at a greater rate. The greatest reduction in PAR was experienced in the shadow under the O-Si panels (91%) and least reduction (65%) under the ST-CdTe during the peak sun hours. Overall, only the quantity of PAR light was affected while the quality (wavelength) of light passing through did not change across the spectrum.

In APV systems, the reduction in the available light caused by the PV modules prompts variations in plant responses, emphasizing the need to explore and comprehend the implications of altered light conditions on crop growth and productivity in novel agrivoltaic configurations. In these systems, light, or solar radiation, is often the primary independent variable, leading to altered temperature temperatures and soil moisture.

Seasonal light conditions were modeled using SPADE Beta software (Figure 28) to analyze the differences in total average solar radiation that reaches the crop canopy, or ground level under each array type. Figure 28a and 28b show the average irradiance over the course of the growing season – May - October – for the climate in Fort Collins, CO. Figure 28c shows a comparison of irradiance under the O-Si arrays during three months that align with the summer solstice, fall equinox, and winter solstice to highlight how the shadow moves throughout the solar year.

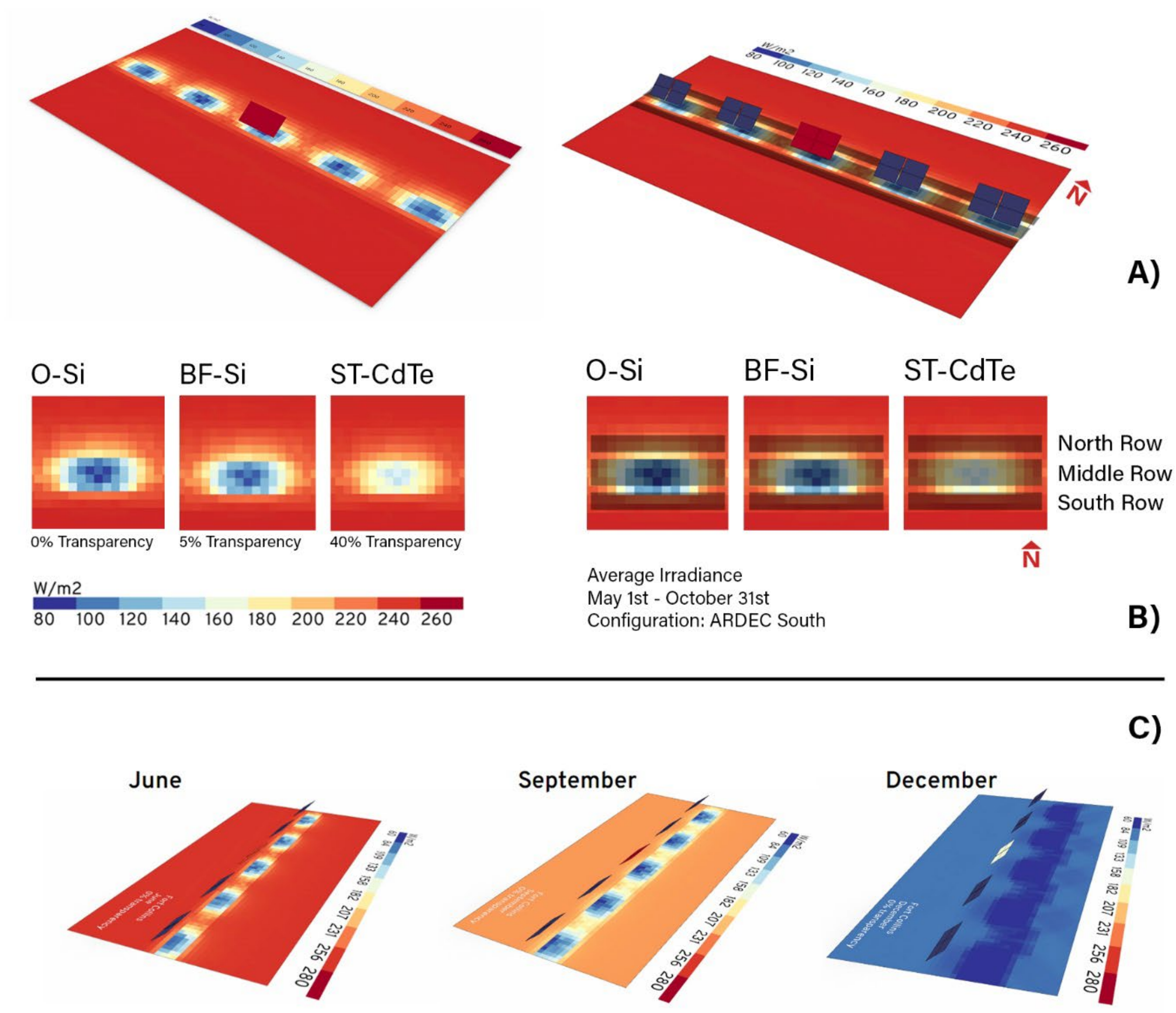

Figure 28: Seasonal Light Analysis using SPADE Beta.

A) Aerial Perspective of the 3D model space with row outlines for reference on the right side.
B) Plan view output visualizing differences in ground level irradiance between the 3 module types. The right side includes row planting outlines for spatial reference.
C) A comparison of ground level irradiance under the O-Si array in June, September, and December.

Temperature

Air Temperature

In Fort Collins Colorado July is the hottest month on average. The maximum, minimum and average air temperature (Table 5), and soil temperature (Table 6) for the month of July 2021 are shown here. On average, during the month of July, the air temperature at 30cm was .4 °C cooler under the ST-CdTe treatment compared to the full sun treatment, and .6°C and .5 °C cooler under O-Si and BF-Si respectively (Figure 29).

Table5: Air Temperature under APV arrays in July

July Air Temperature	Full Sun Temp, °C	ST-CdTe Temp, °C	O-Si Temp, °C	BF-Si Temp, °C
July Max	40.7	39.0	38.1	38.4
July Min	10.2	10.2	10.3	10.5
July Mean	23.2	22.8	22.6	22.7

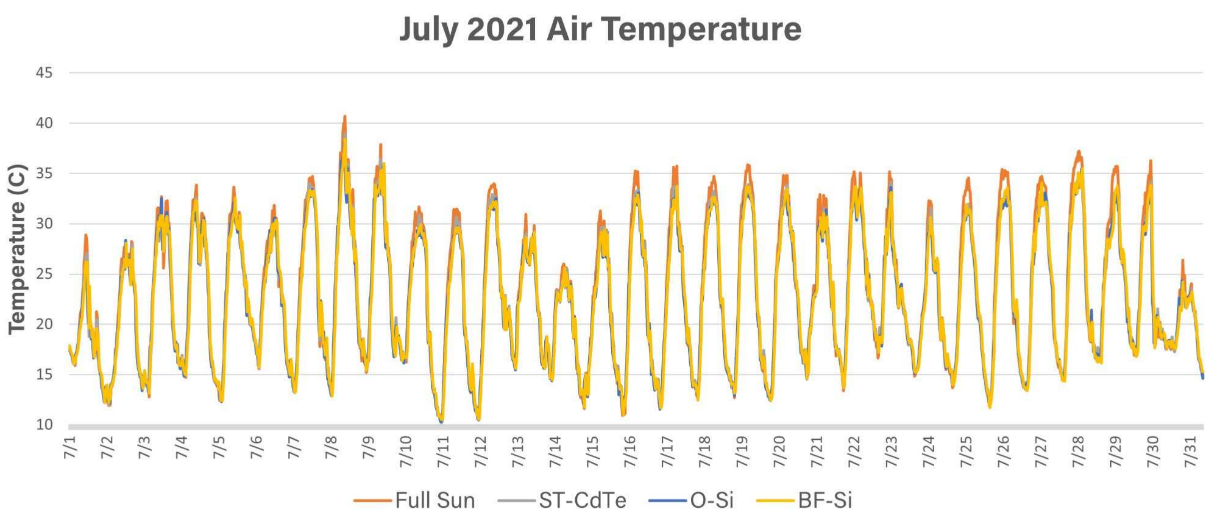

Figure 29: Air Temperature under APV arrays in July

Soil Temperature

The average soil temperature at 2.5cm deep was 3.3 °C cooler under the ST-CdTe treatment compared to the full sun treatment, and 4.3°C and 2.3°C cooler under O-Si and BF-Si respectively (Figure 30). Overall, we find that shade from PV can reduce the maximum, mean, and minimum soil temperatures and maximum daily air temperatures, while minimum air temperatures remain fairly constant in all treatments.

Table 6: Soil temperature under APV arrays in July

July Soil Temperature	Full Sun Temp, °C	ST-CdTe Temp, °C	O-Si Temp, °C	BF-Si Temp, °C
July Max	40.7	31.7	26.3	34.9
July Min	16.7	15.8	15.7	15.0
July Mean	25.4	22.1	21.1	23.1

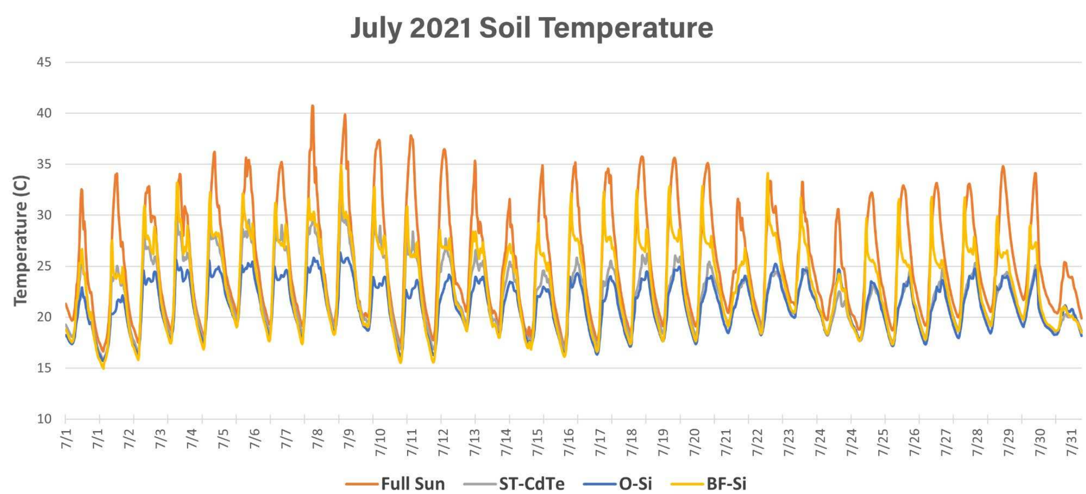

Figure 30: Soil temperature under APV arrays in July

Our findings are comparable to Marrou et al., where they found soil temperature was lower, specifically -0.5 °C to -2.3 °C, in shaded areas when compared to non-shaded soil portions in the APV system, but no significant differences in air temperature were reported (2013b). In the same study in France, Marrou et al. found more profound differences between shade and non-shaded soil temperature compared to air temperatures.

The results we present here also align with a study in Italy where Amaducci et al. found an average decrease of 1 °C under APV systems (2018). They relate the reduction in solar radiation to the decrease in mean soil temperature in addition to evapotranspiration and water balance (2018).

Others have suggested that variation in air temperature in APV systems may be dependent on the shading pattern from the system configuration (Weselek et. al., 2019). APV system configuration including inter-row spacing, tracking or fixed, elevation above the ground, module transparency, etc. can all impact the shading density and pattern throughout the day which can impact other microclimatic conditions like temperature and soil moisture (Adeh et al., 2018). Research conducted in Arizona's arid climate found that crops sustained less heat and drought stress under the shade of their elevated APV structure. Taking their results to greater context of the FEW nexus, Barron-Gafford et al. (2019), have indicated that the microclimatic effects from these systems can play a significant role in the reduction of evapotranspiration, increase plant efficiency, and therefore reduced irrigation needs in arid and semi-arid regions.

Crop Yield

We report the crop yield from summer squash, lettuce, jalapeno peppers and bell peppers as a replicated two-year study, while two tomato cultivars are reported as a one-year study. All yield findings are presented as the result of the four replicated treatments - Full Sun (control), O-Si, BF-Si, and ST-CdTe. We note that throughout this study the south row of crops never received shade from the PV (Figure 26, Figure 28b). We analyze crops grown in the north and south row as a combined analysis, as this is how crops would be planted in a ground mounted fixed south array configuration. We also note that all treatments experienced edge effect due to the nature of the single pole mounted structures. All treatments received light in the morning and the evening but remained shaded during the hours surrounding solar noon every day. While the array configurations are fixed south, the diurnal light pattern closely resembles that of a single axis tracking system.

The effective yield of most crops increased as the transparency of solar panels increased. Peppers, tomatoes, and lettuce all produced more yield in the ST-CdTe treatments than the full sun control plots. However, the summer squash performed best in the full sun control plots.

There were statistically significant differences between the yield of squash grown in the shade of various modules when compared to full sun. There was a general trend towards a slight yield increase in the panel treatments in both pepper varieties, lettuce and tomatoes. However, the yields for these crops grown in the north and south rows showed no significant differences between any treatments when compared to full sun.

Squash

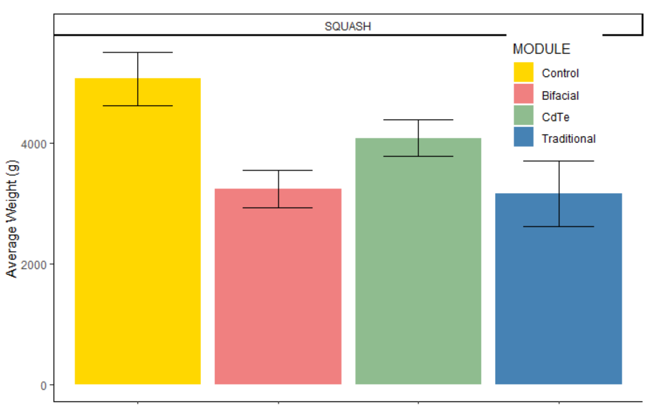

Figure 31: Average squash yield (g) per plant

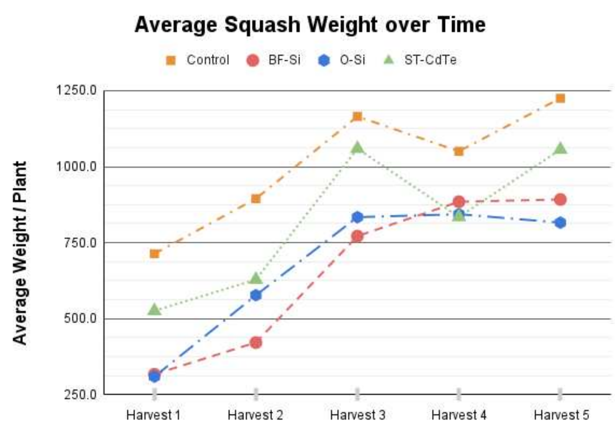

Figure 32: Average squash yield per plant for each harvest

Squash was grown in the center bed, directly under the panels, in 2020 and 2021 (Figure 26, Figure 28b). During the 2020 growing season, squash yielded an average of 4.5 kg per plant in full sun control treatment, 2.8 kg in the BF-Si treatment, 2.5 kg in the O-Si treatment, and 3.3 kg in the ST- CdTe treatment (not shown). In 2021 season, the squash yielded an average of 5.6

kg per plant in full sun control treatment, 3.6 kg in the BF-Si treatment, 3.8 kg in the O-Si treatment, and 4.7 kg in the ST- CdTe treatment (not shown).

The combined analysis of the 2020 and 2021 growing season, the squash yielded 5.06 kg per plant in full sun control treatment, 3.23 kg in the BF-Si treatment, 3.15 kg in the O-Si treatment, and 4.08 kg in the ST- CdTe treatment (Figure 31). When considering squash yield over time, Figure 9 details the average weight under each treatment by harvest. The full sun treatment had the highest yield at harvest 1 and maintained greater production throughout subsequent harvests. All modules' treatments show a delay in harvestable yield and never reach the quantity of the full sun in any of the harvests (Figure 32).

There have not yet been any published studies reporting squash yield in agrivoltaic systems, however, Rogers completed a consumer study on several crops that were grown in an agrivoltaic system, including winter squash (2022). In this study Rogers found that squash samples grown in shade were preferred by consumers, along with shade-grown basil and potatoes, while beans grown in full sun were preferred by taste-testers.

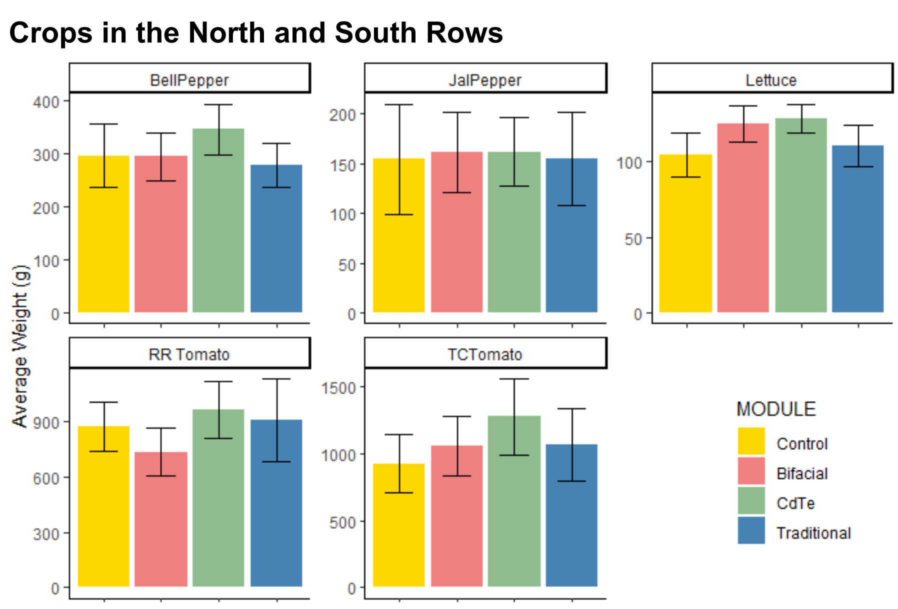

Figure 33: Average yield of crops grown in the north and south rows.

Bell Pepper & Jalapeño Pepper

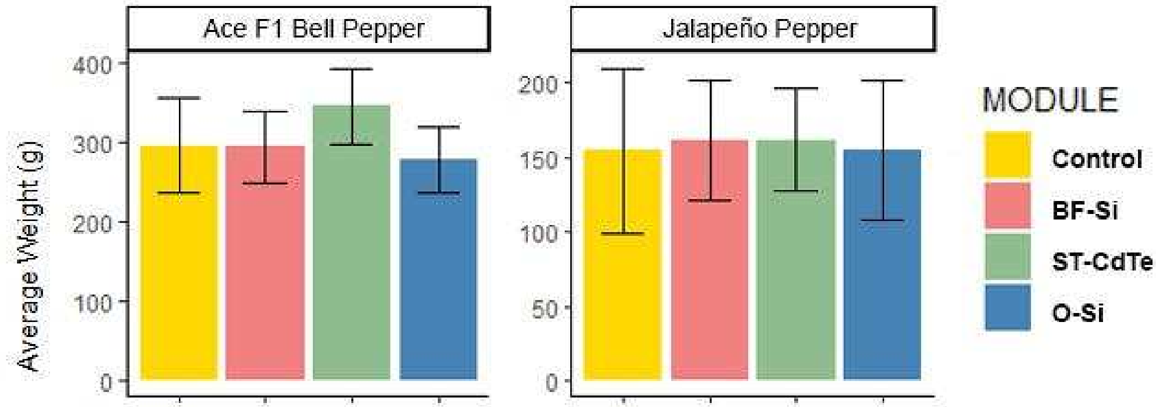

Figure 34: Average pepper yield

We find numerically higher average yield in both pepper varieties in the ST-CdTe treatments while no significant differences between treatments are reported. The combined analysis of the 2020 and 2021 growing season, the Jalapeno pepper variety yielded 155 g per plant in full sun control treatment, 161g in the BF-Si treatment, 155 g in the O-Si treatment, and 162 g in the ST-CdTe treatment (Figure 34). The combined analysis of the 2020 and 2021 growing season, the Bell pepper variety yielded 295 g per plant in full sun control treatment, 294 g in the BF-Si treatment, 278 g in the O-Si treatment, and 346 g in the ST- CdTe treatment (Figure 34).

Barron-Gafford et al. (2019) reported chiltepin pepper fruit count production was three times greater under dense shade of their APV system, while jalapeno fruit count production was slightly greater in full sun control, but not significantly. In the semi-arid climate of the Negev Desert, sweet peppers cultivated under moderate shade conditions (12-26% reduction of full sunlight) exhibited enhanced yields and increased plant heights (Rylski and Spigelman, 1986).

The study revealed a decrease in sunscald occurrence when plants were grown under shaded conditions compared to full-sun exposure. This finding highlights the significant role of shading in providing protection against excessive solar radiation and high temperatures in the examined region. It is common for producers to use light reduction structures such as shade cloth in high elevation regions such as Colorado, New Mexico and Utah to protect high value fruiting crops like peppers from sun scalding. Growing high value specialty crops that are prone to sun scalding, like peppers, in partial shade of APV systems offer an alternate solution for mitigation of intense light while introducing energy production on-site.

Lettuce

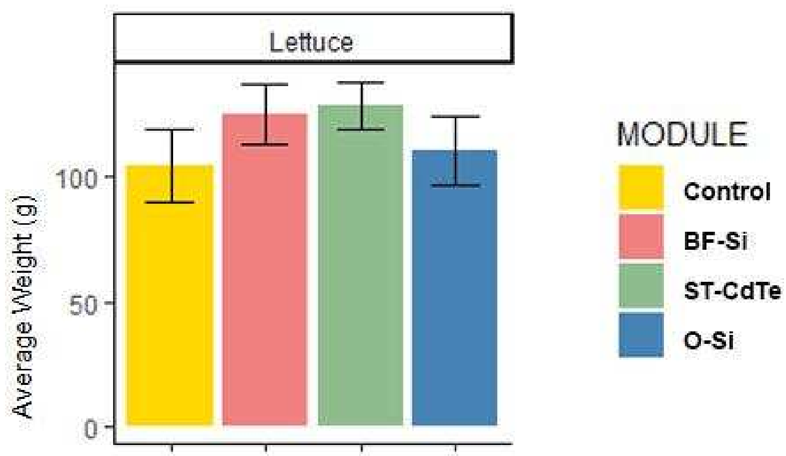

Figure 35: Average lettuce yield

Both years we conducted a single destructive harvest of the lettuce crop at plant maturity, four weeks after planting. We found that lettuce yield did not differ significantly between any of the treatments and full sun control during the summer growing season. The combined analysis of the 2020 and 2021 growing season, the lettuce biomass equaled 105 g per head in full sun control treatment, 126 g in the BF-Si treatment, 111 g in the O-Si treatment, and 129 g in the ST- CdTe treatment (Figure 35).

In one of the first studies on lettuce growth in APV systems Marrou et al. (2013c) reported mixed results depending on the season of planting and the density of PV modules overhead the lettuce. They found a significant reduction in lettuce yield one season in full density shade but that was not the case in the spring season. Elamri et al. (2018) found cultivated lettuces under solar panels decrease plant water consumption by 20% and shading can cause a delay of plant maturity up to one week. While a delay in crop harvest may seem negative, pairing the reduction of water consumption and maintained yield with the harvest delay may provide opportunity for growers to prolong seasonality of lettuce marketability, particularly in arid and semi-arid regions.

Tomato Red Racer & Tasmanian Chocolate

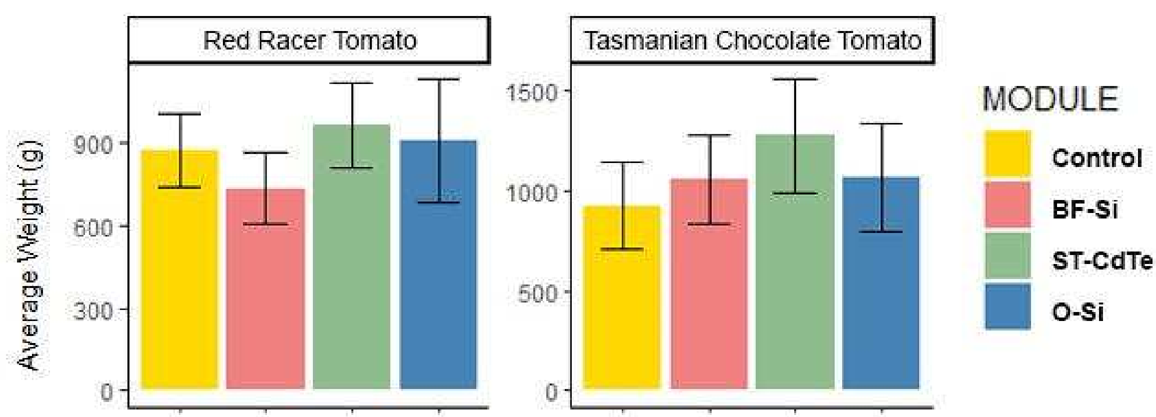

Figure 36: Average tomato yield

In the one-year study of tomato growth in an APV system we find no significant differences between treatments, however, we find highest average yield in the St-CdTe treatments, similar to the other crops grown in the north and south rows in the 2-year study. In 2021 season, the 'Tasmanian Chocolate' yielded an average of 926 g per plant in full sun control treatment, 1060 g in the BF-Si treatment, 1069 g in the O-Si treatment, and 1278 g in the ST- CdTe treatment

(Figure 36). During the same season, the ‘Red Racer’ yielded an average of 867 g per plant in full sun control treatment, 733 g in the BF-Si treatment, 903 g in the O-Si treatment, and 962 g in the ST- CdTe treatment (Figure 36).

While we report fruit yield in weight (biomass), Barron-Gafford et al., reported a doubling of cherry tomato fruit count in the shade treatment of their experiment in Arizona (2019). These profound results demonstrate the opportunity that APV systems can provide in arid regions of the world when the crop type and the PV configuration are paired with the climate in mind. Al-Agele et al. studied tomatoes growing in three different locations within a fixed south APV system in the state of Oregon. They found crop yield decreased as shade increased and note in fixed south systems have a large amount of heterogeneity in yield, which is likely due to the distinct light patterns in these systems (AL-Agele et al., 2021). Several other studies involving tomatoes in APV systems have been conducted in controlled environments (Touil et al., 2021, Waller et al., 2021) with mixed results depending on percentage of light reduction.

There have been other studies on tomato yield under partial shade conditions in semi-arid climates, however, these studies use shade netting instead of PV panels as the source of the shade. The results from these studies have shown that fruit yield exhibits an increase under moderate shading conditions (35% reduction of full sunlight) in semi-arid regions characterized by high light intensities (Kittas et al., 2012, Nangare et al., 2015, Masabni et al., 2016).

4. Conclusions

In this study we report temperature and crop yield response under three types of PV arrays in comparison to full sun. During the hottest month of the year maximum air temperatures were reduced under all PV types, and even greater reduction in soil temperatures in the shade. The alteration of the growing environment through reduction of light and extreme temperature encourages further investigation into plant response to the unique microclimate in APV systems. The yield results varied depending on the crop type, and location within the APV system, which can be attributed to the varying light conditions under the different treatments and row placement. The shade had the greatest impact on the squash yield as it was planted in the middle row directly under the APV arrays, while all other crops grown in the north and south rows did not experience as much impact from shade and therefore, we did not find any reduction in yield.

The results of this study demonstrate the potential to optimize solar racking and semi-transparent module technologies to match a specific specialty crop operation. The optimization of the agrivoltaic array with semi-transparent PV modules could increase agricultural production while providing other benefits of agrivoltaic systems. Further research will explore modeling, different module transparencies and the effect on crop yield, soil moisture and evapotranspiration rates. Further research, technological advancements, and supportive policies are essential to unlock the full potential of agrivoltaics and facilitate its widespread adoption across diverse agricultural systems globally.

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APPENDIX

A Photo Journal of Agrivoltaic System Configurations Across the World

Photography Credit: Thomas Hickey + Location specified on each page.

Figure 37: Agrivoltaics in Japan - Chiba Prefecture

Figure 38: Agrivoltaics in Japan - Fukushima Prefecture

Figure 39: Agrivoltaics in Italy - Piacenza

Figure 40: Agrivoltaics in Italy - Piacenza

Figure 41: Rooftop Agrivoltaics in USA - University of Arizona ENR2 Building, Main Campus

Figure 42: Rooftop Agrivoltaics in USA - University of Arizona, Biosphere 2

Figure 43: Agrivoltaics in USA - National Renewable Energy Lab (NREL) South Table Mountain Campus

Figure 44: Agrivoltaics in USA - Jacks Solar Garden, Longmont, CO

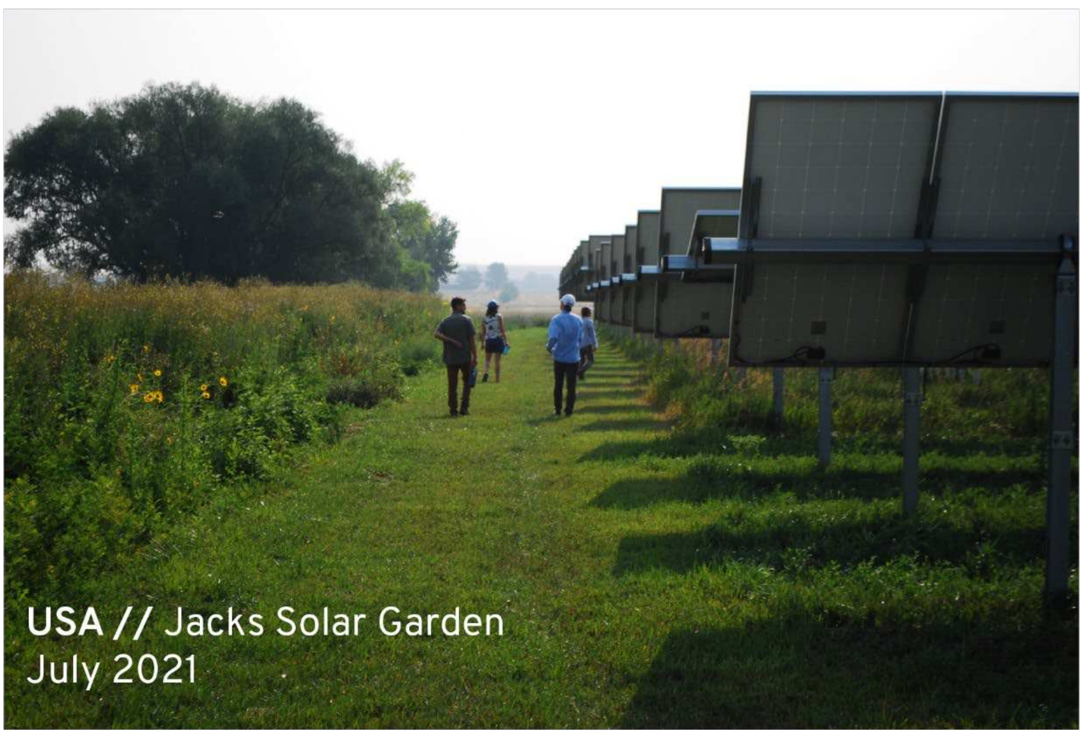

Figure 45: Agrivoltaics in USA - Jacks Solar Garden, Longmont, CO

Figure 46: Agrivoltaics in USA - CSU ARDEC South, Fort Collins, CO

Figure 47: Rooftop Agrivoltaics in USA - CSU Foothills Campus, Fort Collins, CO

Figure 48: Rooftop Agrivoltaics in USA - CSU Spur Campus, Denver, CO