Crop Production in Partial Shade of Solar Photovoltaic Panels on Trackers

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Abstract. Kale, chard, broccoli, peppers, tomatoes, and spinach were grown at various positions within partial shade of a solar photovoltaic array during the growing seasons from late March through August 2017 and 2018. The rows of panels were oriented north-south and tracked east to west during the daylight hours, creating three levels of shade for the plants: 7% of full sun, 55-65% of full sun, and 85% of full sun, as well as a full sun control outside the array. Average daily air temperature at canopy height was within ± 0.5°C across the shade conditions. Over two field seasons, biomass accumulated in correlation with the quantity of photosynthetically active radiation (PAR). Kale produced the same amount of harvestable biomass in all PAR levels between 55% and 85% of full sun. Chard yield was similar in PAR levels 85% and greater. Tomatoes produced the same amount of harvestable biomass in all PAR levels greater than 55% of full sun. Broccoli produced significantly more harvestable head biomass at 85% than at full sun irradiance but required at least 85% of full PAR to produce appreciable harvestable material. Peppers generated harvestable fruit biomass at PAR of 55% of full sun or less, but yielded best at 85% of full sun or more. Spinach was sensitive to shade, yielding poorly under low PAR, but increased in biomass production as PAR increased. Microclimate variations under PV arrays influence plant yields depending on location within a solar array. Adequate PAR and moderated temperature extremes can couple to produce crop yields in reduced PAR environments similar to and in some cases better than those in full sun. Results from our study showed that careful attention must be made when developing PV arrays over the crops and when choosing which crops to plant among the arrays.

INTRODUCTION

Alternative sources of energy are required to meet increasing demand in a manner that is sustainable and less environmentally damaging. Solar photovoltaic (PV) electricity production is a widely adopted, renewable energy source with significant research and commercial investment that can address this issue. The cost to install solar systems has decreased substantially in recent years[1], and through 2020, utility-based solar power generated 1.7% of total U.S. electricity[2]. Given the high levels of solar energy reaching the ground in parts of the USA, there is significant potential for PV energy expansion. One potential opportunity is on land dedicated to agricultural production ("agrivoltaics"). With agrivoltaics, there is competition for light between electricity production and crop production, potentially leading to a shift of land to electricity which will result in reductions in food. In addition, the impacts of solar power installations on their surrounding environments have not been comprehensively addressed. These impacts include water availability, water use by the vegetation, soil temperature, and energy balance along the soil-plant-atmosphere continuum (SPAC), among others[3]. Many municipalities have reacted by protecting farmland to assure that there will always be adequate agricultural land for growing food[4].

Integration of PV and agriculture was first proposed by Goetzberger and Zastrow[5] who performed a modeling exercise to calculate optimal panel arrangement for solar collection. Amaducci et al.[6] reported that PV panels have been applied to agricultural infrastructures including drying systems, water purification, and water pumping. Agrivoltaic systems have been examined using modeling approaches to answer questions regarding expected plant growth and development[7,8,9,10], and shade tolerant crops have been shown to grow under PV without significant yield reduction and with generated electricity to provide a 30% increase in economic value over conventional agriculture

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with lettuce[11] and 30-35% in tomatoes[12]. These reports identified that partial shading may be tolerated by some crops, and that solar arrays may help reduce water consumption[13]. Many reports present models and a growing number of reports evaluate plant growth under PV[3,14].

Various types of solar PV systems have been developed; the most common systems are ground-mounted or on structures where the angle of the panel to the sun maximizes light interception, either as fixed-tilt or tracking systems. Trackers maximize intercepted sunlight by maintaining direct exposure of the panels to the sun and may improve system output by 40% over fixed-tilt arrays[15]. Adjacent rows of trackers oriented north-south often shade each other in the morning and afternoon, therefore, spacing trackers further apart reduces this self-shading. Kanters and Davidsson[16] showed that for fixed tilt PV systems facing 30° south, 3–5% of the total amount of generated energy may be lost due to mutual shading effects. To minimize self-shading, small, PV tracking systems can require up to seven acres per megawatt of capacity-weighted land area[17]. Tracker spacing and movement also impact PAR available for plant production, wherein PAR is low directly under the trackers and high between the trackers, creating a heterogeneous environment that will influence the crops that are selected and how they are planted among the arrays.

Assuming that solar panels and trackers are economically viable over bare land, the agricultural production added to those profits would represent greater profit for the farmer. The core question is to identify which level of shade allows for such profitability. Costs to install PV systems continue to decrease and experience in the use of PV increases, thus such areas as agriculture are becoming economically attractive, which can have a significant impact on rural development[18]. Knowledge about the limitations of such PV applications, however, is still limited. Our objective was to identify whether economically viable agricultural crop production in the presence of solar PV equipped with trackers is possible. We conducted trials to identify whether it is feasible to have both electricity production as well as agricultural production, which tested crops might be more suitable than others, and in which positions among the trackers these crops grow best.

MATERIALS AND METHODS

Description of the Solar PV Facility

This study was conducted over 2017 and 2018 during the spring and summer growing seasons at the SunPower Research and Development Ranch located at 28058 Mace Blvd, Davis, CA 95618, 38.531751° latitude, -121.694959° longitude. While our focus was on plants and crop production, SunPower was engaged in various activities which were agnostic to our agricultural activities. They used the facility to test various facets related to energy and to showcase products to clients. At various times, the trackers were not moving while at other times they tracked the sun. This did have some impact on our plant production as noted below.

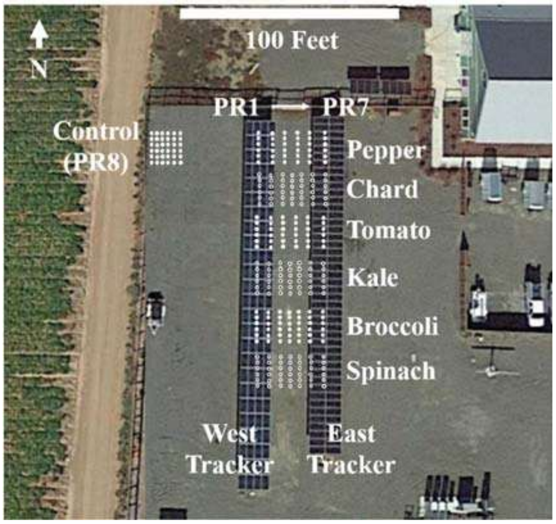


FIGURE 1. Layout of the shade treatments among the PV at the SunPower Research center in Davis, California. Circles show individual, container-grown plants of the indicated crops. Image source: Google Earth.

Since Davis, California, typically has winter conditions which limit plant production, we conducted our trials during the spring and summer. The first trial was from 4/12/2017 to 10/13/2017, and the second trial was from 3/28/2018 to 7/6/2018. In both trials, our research plots were positioned between the two assemblies as diagrammed in Figure 1. The West tracker measured 57.6 meters by 4.1 meters, with a pole height of 2.1 meters. The East tracker measured 47.6 meters by 4.1 meters with a pole height of 2.1 meters. The trackers were 9.8 meters apart, center to center. When panels were positioned fully flat, the area exposed between the panel arrays was 5.7 meters wide. The trackers did not touch the plants or pots during movement. The research area was fenced (see Figure 1).

Plants were grown in plastic containers filled with substrate positioned in a grid consisting of 6 replicates by 7 rows (42 pots) with the 7 rows running parallel to the axes of the trackers. The study plots consisted of 8 treatment positions relative to the trackers, labeled as panel rows (PR). Panel row 1 (PR1) was directly under the axis of the west tracker and PR7 was directly under the axis of the east tracker. Each successive PR was 1.63 meters apart in the west-east direction. Three sample plants and three non-sample plants per PR were 0.61 meters pot center to pot center for kale, chard, broccoli, and spinach, and 1.22 meters for peppers and tomatoes.

During the second trial we included a control position (PR8) as full sun irradiance located 9.8 meters west of PR1. This position was chosen such that the plants would be on the same gravel surface and with minimal shading by other obstructions. The West Tracker did shade PR8 for approximately 30 minutes after sunrise, but this shading reduced total daily PAR less than 0.001%. Likewise, the building in the Northwest corner also had minimal impact.

Biometeorology Analysis

A sensor array was deployed to the site prior the second trial (2018). These sensors were deployed at seven locations transecting the study area and included at each position three quantum sensors (SQ-110 SS, Apogee Instruments, Logan, UT), one pyranometer (SP-110 SS, Apogee Instruments, Logan, UT), two Type-T thermocouples, and one CS-215 temperature/RH probe (Campbell Scientific, Logan, UT). The thermocouples and RH probes were housed in a naturally aspirated, 6-plate, solar radiation shield. The quantum sensors measured PAR from 400 to 700 nm, and the pyranometers measured shortwave radiation from 380 to 1120 nm. The quantum sensors were positioned at 1.4 meters above the ground parallel to the ground pointing in the westward direction, parallel to the ground pointing in the eastward direction, and perpendicular to the ground pointing directly skyward. The pyranometers were also perpendicular to the ground. Temperature was measured at canopy height (0.3 meters) and at 1.4 meters above the ground. RH measurements were obtained at canopy height.

Plant Growth and Development

The study crops included kale (*Brasicca oleracea* cv. 'Toscano'), Swiss chard (*Beta vulgaris* cv. 'Bright Lights'), broccoli (*Brassica oleracea* cv. 'Arcadia'), bell peppers (*Capsicum annuum* cv. 'King Arthur'), tomato (*Solanum lycopersicum* cv. 'Big Beef'), and smooth leaf spinach (*Spinacia oleracea* cv. 'Seaside'). Seeds were sown in February of both years, one seed per cell into 6-pack cell trays filled with 'UC Mix' potting media. UC mix is a 1:1:1 mix of sand, composted redwood sawdust, and sphagnum peat moss. Each cell holds approximately 0.052 L. After sowing, the cell trays were placed in the Environmental Horticulture greenhouse facility at the University of California, Davis. Temperature was maintained between 17°C and 24°C, RH was 56% on average, CO_2 averaged 392 ppm, and the daily light integral was 16 mol m^{-2} d^{-1}. No supplemental lighting was administered. The seedling trays were top-watered with normal tap water for one week until appearance of the first true leaves, then fertilized with a modified Hoagland's solution containing half-strength macro-nutrients and full strength micro-nutrients. The seedlings were grown in the greenhouse for approximately three weeks, at which time they were selected for uniformity and transferred to 13.2 L pots containing 'UC Mix'. They were acclimated for an additional week in greenhouse conditions, then transferred to the study site. In both trials, the plants at the study site were irrigated by a drip system with Scotts Miracle-Gro® fertilizer mixed at 15 mL dry power per 3.79 L of water. Fertilizer was applied weekly. From March 28 through June 15, the plants were watered four minutes three times daily, and from June 15 through harvest, the plants were watered six minutes four times daily at a rate of 15 L per hour.

The plants were destructively harvested when the crops reached maturity (spinach and broccoli) or after two or more harvests for continually harvested crops (kale, chard, peppers, and tomatoes). Results presented here include total whole leaf dry mass for kale, chard, and spinach, and fresh mass of the reproductive structures for broccoli, pepper, and tomatoes. Statistical analysis was performed in SAS Online for Academics Proc GLM procedure with the LSMeans model.

RESULTS

Biometeorology

In 2018, we measured a peak PAR value of 60.2 mol $m^{-2} d^{-1}$ at our control position on Day 172 (Figure 2) with the direct, skyward sensor. During the same period, PR1 and PR7 measured 2.7 mol $m^{-2} d^{-1}$, PR2 and PR6 measured 33.5 and 30.1 mol $m^{-2} d^{-1}$, while PR3, PR4, and PR5 measured 50.8 mol $m^{-2} d^{-1}$. Over the course of the experiment, the shading impacts of the panel array resulted in values of 7% of control in PR1 and PR7, PR2 and PR6 were 62% and 55% of control, respectively, and PR3 to PR5 were 85% of control.

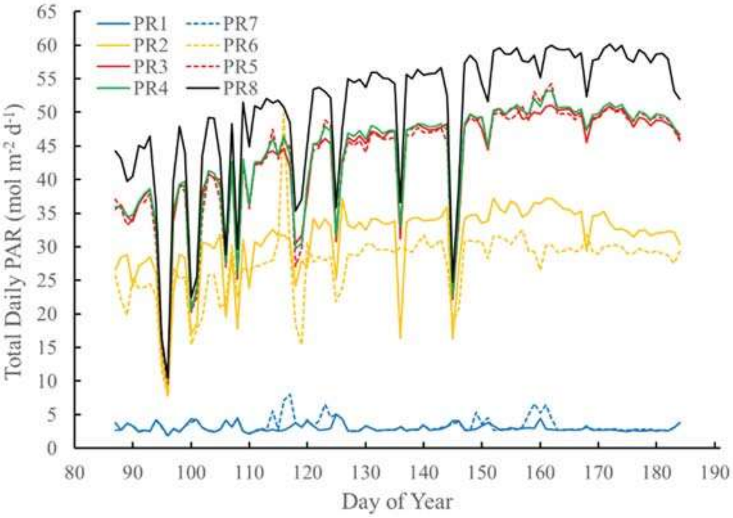
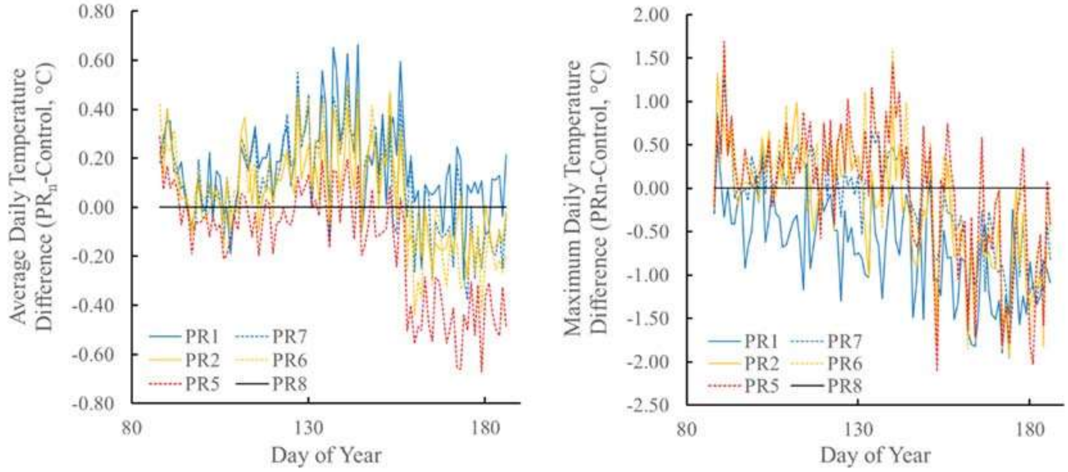


FIGURE 2. Overhead daily PAR during the experiment from March to July, 2018



(a) (b)

FIGURE 3. Average daily temperature (a) and maximum daily temperature (b) at each PR position relative to control during the second trial, 2018

The differences in average daily air temperature at canopy height across the PRs were minimal throughout the trial (Figure 3a). Maximum daily temperatures were similar to control through the third week of May (~ Day 145), except PR1, which remained cooler than control throughout the study (Figure 3b). In the last week of May, maximum daily air temperatures under the panels transitioned to be cooler than control, in relation with increases in ambient air temperatures. PR1 was as much as 2.1°C cooler, while the other PR positions were as much as 1.5°C cooler.

Across the 24-hour day, average ambient air temperatures at all positions under the panel array increased during the morning and decreased in the afternoon relative to control (Figure 4a). The temperature profiles were synchronized with the shading caused by the movement of the panels (Figure 4b). Canopy air temperatures for all positions were 1 to 2°C warmer than control while in the shade of the panels, but were 1°C (PR1 and PR7) to 3°C (PR5 and PR6) cooler than control during the hot part of the day, especially as the summer progressed into the hot period of the year.

There were no substantial differences in relative humidity across the PRs throughout the experiment.

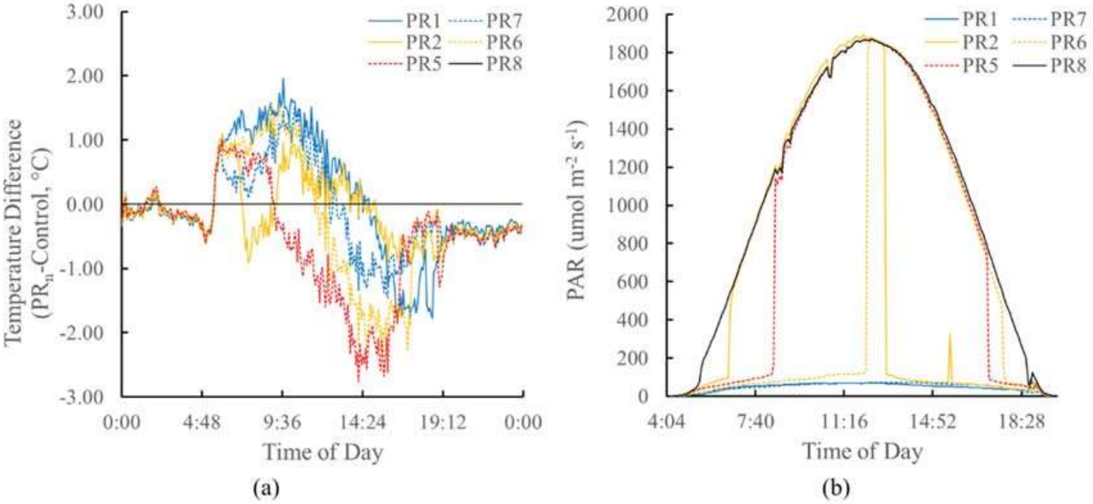


FIGURE 4. Canopy temperature profile over a 24-hour day (USA, Pacific Standard Time) at 5-minute intervals averaged across the week from 18 June to 24 June, 2018 (a) and daily profile for PAR on 18 June, 2018 (b).

Plant Growth and Development

Panel angle data provided by SunPower for 2017 showed that the west and east panels tracked properly 41% and 62% of the time during daylight hours throughout the growing season. When not tracking, the panels were flat 44% and 29% of the time, angled westward 13% and 6% of the time, and angled eastward 2% and 3% of the time. In 2018, panel tracking operated properly throughout the experiment. Thus, PR1 and PR7 continuous shade, PR2 and PR3 saw afternoon shade, PR4 was shaded equally in the morning and the afternoon, and PR5 and PR6 saw morning shade.

TABLE 1. 2017 total biomass accumulation with least significant difference (LSD) where means followed by a common letter are not significantly different (Alpha = 0.05); All weights in grams; n = 3

Panel Row	Kale		Chard		Broccoli		Pepper		Tomato	
	DW	LSD	DW	LSD	FW	LSD	FW	LSD	FW	LSD
PR1	57.3	c	133	b	5.3	d	310	bc	282	b
PR2	68.1	abc	174	ab	40.7	bcd	352	abc	927	a
PR3	64.0	bc	227	a	97.7	abc	626	a	663	ab
PR4	83.5	ab	150	ab	119	ab	n/a	n/a	n/a	n/a
PR5	86.1	a	249	a	160	a	560	abc	661	ab
PR6	68.2	abc	193	ab	42.3	bcd	602	ab	619	ab
PR7	61.8	c	171	ab	17.0	cd	280	c	635	ab
PR8	Not used in first trial (2017)									

Over two harvests in 2017, kale accumulated the highest amount of leaf dry biomass in PR4 and PR5 between the two panels (Table 1). Biomass in PR5 was significantly greater than PR1, PR3, and PR7, while PR2, PR4, PR5, and PR6 were all similar. PR1 and PR7 averaged 69% of PR5. Chard was harvested six times. Cumulative leaf dry mass of plants in the PR4 position were similar to PR1 and PR7, while PR3 and PR5 had the highest yield (Table 1). Except PR1, all positions produced similar leaf biomass. PR1 and PR7 averaged 61% of PR5. Broccoli produced minimal head fresh biomass in all but the middle three positions (PR3, PR4 and PR5) with the highest yield in PR5 (Table 1). Compared to PR5, yield in PR1 and PR7 averaged 7%, while yield in PR2 and PR6 averaged 26%. Peppers showed the greatest fresh biomass accumulation in PR3, but PR2, PR3, PR5, and PR6 were not significantly different (Table 1). PR1 and PR7 produced significantly less pepper fresh biomass than all other positions, and were 53% of PR5. Tomato fresh biomass yield was highest in PR2, but was similar across all positions except PR1 (Table 1).

During the second year (2018), a control plot was added outside the array because observations during 2017 showed that the center area between the trackers experienced about 15% shade. Over three harvests, kale leaf dry biomass among PR2 to PR5 ranged from 77% to 85% of control (PR8), but there was no statistical difference (Table 2). PR1 and PR7 resulted in significantly smaller leaf biomass at 35% and 39% of control. Chard was harvested three times. Biomass in positions PR2 to PR6 and control were not statistically different; PR2 and PR6 did yield 74% and 81% of control. PR1 and PR7 resulted in significantly smaller leaf biomass at 17% and 42% of control, respectively. As in 2017, broccoli produced relatively small heads in all but the middle three positions, with PR4 producing the highest yield (Table 2). PR1 and PR7 failed to produce any broccoli heads, PR2 and PR6 were 19% and 4% of control, respectively. The positions in 85% full sun (PR3, PR4, and PR5) produced the highest yield; head fresh mass in these positions were 127%, 146%, and 119% of full sun, respectively. Pepper fresh fruit biomass showed no significant differences in response to treatment in PR3, PR5, PR6, and control. PR1, PR2, and PR7 produced significantly less pepper fresh biomass than all other positions. Tomato fresh fruit yield in 2018 was similar among all PR positions except PR1 and PR7; PR1 was the poorest yielding position. Spinach growth in 2018 was strongly influenced by PR position with the full sun control producing the greatest amount of leaf biomass (Table 2). With each progressive increase in shade, biomass accumulation decreased. Yield was similar across positions PR3, PR4, and PR5, and all were significantly less than control. PR2 and PR6 were similar and significantly less than the middle three positions. Spinach plants in PR1 and PR7 produced 1% and 5% of control, respectively.

TABLE 2. 2018 total biomass accumulation with least significant difference (LSD) where means followed by a common letter are not significantly different (Alpha = 0.05); All weights in grams; n = 3

Panel Row	Kale		Chard		Broccoli		Pepper		Tomato		Spinach	
	DW	LSD	DW	LSD	FW	LSD	FW	LSD	FW	LSD	DW	LSD
PR1	21.8	c	12.1	b	0.0	d	127.8	c	505.3	c	0.1	c
PR 2	50.9	ab	54.2	a	18.0	c	365.1	bc	1462.0	a	3.8	c
PR 3	53.5	ab	62.0	a	117.7	ab	691.6	a	1451.3	a	8.1	b
PR 4	50.1	ab	68.0	a	135.0	a	n/a	n/a	n/a	n/a	9.5	ab
PR 5	50.0	ab	72.4	a	110.7	ab	653.9	a	1665.7	a	7.7	b
PR 6	48.6	b	59.5	a	3.7	c	515.0	ab	1156.2	ab	3.5	c
PR 7	24.9	c	30.8	b	0.0	d	165.3	c	903.5	bc	0.6	c
PR 8	63.2	a	73.2	a	92.7	b	763.7	a	1542.5	a	11.9	a

DISCUSSION

The tracking system in 2017 operated inconsistently due to activities in which SunPower was engaged. This reduced the amount of shading experienced by the plants in 2017, particularly in full shade (PR1 and PR7), and this was reflected in the biomass accumulation results for those positions. For example, biomass values for pepper, chard, and kale relative to PR5 were 20% to 30% more in 2017 than they were in 2018. Despite these differences, plant growth response to position within the array was generally the same over both years.

Harvested biomass was strongly influenced by the varying levels of shade of the PV array. Across the crops over two field seasons, biomass accumulated as a function of PAR but not linearly and with a different relationship for different species. Kale yield was similar in all PAR conditions from 55% to 85% of full sun; although not statistically different, yield was up to 23% less than control. Chard also yielded slightly less than control at 55% and 62% of full sun, but yield was similar to control in PAR 85% of full sun and greater. Broccoli required 85% full sun irradiance and greater to produce harvestable heads, indicating that too much shade would render this crop unproductive. Peppers generated harvestable biomass at PAR of 55% of full sun or less but yielded more in 85% and greater. This showed that peppers can be planted throughout the array, but with a substantial yield penalty when light was less than 85% PAR, potentially due to floral abortion induced by the shade[19]. Tomato biomass was similar in PAR levels 55% of full sun and greater, suggesting that some shade can be tolerated when planted under solar panels. Spinach was strongly sensitive to PAR level, yielding poorly under low PAR, but increasing in biomass as PAR increased.

Multiple studies have shown that different species, crops, and cultivars are more shade or temperature tolerant than others[20,21]. In our study, differences in biomass accumulation across all tested crops was largely correlated with variations in PAR at the different positions in the array, but the influences of temperature may have also contributed. While average daily air temperature among the positions were similar throughout the experiment, consistent with other research[3], our data showed maximum daily temperatures to be up to 3°C cooler than control under the panel array during the hot, dry periods of the summer (May to August, 2018). This was influenced by position, where deeper shade experienced cooler maximum air temperatures relative to control. Maximum daily temperatures were also consistently up to 2°C warmer than control through the cool months of spring.

Profiles across the 24-hour day showed a diurnal temperature pattern where all PRs were warmer than full sun in the morning and cooler than full sun in the afternoon throughout the experiment. Of particular note was the impact of the shade caused by the movement of the panels. PRs that saw no direct irradiance remained warmer than control through midday in synch with the panels as they tracked the sun. PRs that experienced abrupt transitions from shade to direct irradiance, however, saw abrupt transitions in their temperature profiles, as well. This was especially noticeable in PR5, which transitioned to cooler than control conditions at the time it experienced direct irradiance and remained that way into late evening.

The reduction in temperature as a result of sudden irradiance in the partial shade positions was not expected. However, it has been shown that when sun begins to warm air, water vapor from the air begins to evaporate. This process increases the latent heat which decreases the sensible heat of the air, thus causing a drop in air temperature[22]. This was particularly noticeable in PR2 and PR5, which experienced direct irradiance in the morning before the ambient air had gained thermal momentum. PR6 also showed a reduction in temperature, but because direct irradiance did not fall on PR6 until midday after the ambient air had gained thermal momentum, the transition was not abrupt. Warmer than control conditions throughout the morning in all positions when in the shade of the panels may have been due to sensible heat accumulating under the panels through direct solar irradiance on the panels or reflected irradiance from the gravel surface. The accumulation was not subsequently removed by evaporation or air movement. Dew formation can be inhibited under PV arrays, and because evaporation of dew reduces temperature, temperatures may have been higher compared to control and gap areas[23].

SUMMARY

All shade is not equal even when PAR levels are the same because of microclimate variation under the PV arrays. Adequate PAR, moderated temperature extremes, and the influence of diurnal temperature patterns on plant physiology can couple to produce crop yields in reduced PAR environments similar to and in some cases better than those in full sun. Results from our study showed that careful attention must be made when developing agrivoltaic systems, including the PV configurations, tracking algorithms, and the crops grown among them. Our findings suggest that crops like kale, chard, and tomatoes can be planted throughout the solar array with only limited yield penalty as long as light levels are at least 55% of full-sun irradiance. Other crops like spinach are not advisable among solar panel arrays due to their strong dependence on high irradiance for best crop yields. Many more crops, light levels, and temperature variations need to be evaluated to effectively couple PV with agriculture.

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