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**xx.** Investigating Dual-Use Solar on a Wild Blueberry Field in Rockport

### **OBJECTIVES**

- Document the impact of solar array construction on wild blueberry.
- Determine the impact that array shading has on wild blueberry productivity.

**LOCATION:** Rockport, ME

**PROJECT TIMEFRAME:** 2020 – 2024

### **INTRODUCTION**

*For a full explanation of the interest in developing solar photovoltaic projects on agricultural land, please see the 2021 report, page 123, “Wild Blueberry Phenology”.*

Dual-use solar is the installation of solar panels installed in such a way that agricultural activities such as crop production and animal grazing can occur simultaneously. Such arrays may include higher panel heights and increased row spacing to allow enough sunlight to reach the crop underneath and for equipment and workers to maneuver. While farming wild blueberries under solar panels is not yet economical, perhaps a future incentive program would make it so. Solar companies continue to approach wild blueberry growers with development offers, and this research explores the impact of shade and array construction on wild blueberry productivity and evaluates the costs associated with continuing to farm under the panels.

There are three commercial cranberry bogs in Massachusetts that have dual-use solar systems installed (Shemkus, 2022; Mupambi, 2020), and these solar installations were installed with the lowest panel edge more than 8 – 10 feet off the ground, to best enable continued crop growth and management (Clean Energy Extension, 2022). No specific regulations guide the spacing of panels, but developers must use a Shading Analysis Tool to ensure that the maximum reduction in sunlight due to shading from panels on any square foot of land underneath the dual-use system may not exceed 50% during the growing season (Clean Energy Extension, 2022).

Agrivoltaic installations are not unique to the United States. An exciting project was developed in France, where rotating solar panels were installed above rows of wine grapes and the system was designed to prioritize grape production over energy production (Crellin, 2021). Much like wild blueberry, wine grapes are cultivated in well-suited local climates and these slow-growing plants cannot easily adapt to sudden changes in climatic conditions. The panels benefit the grapevines by mediating ground temperatures during times of extreme heat or cold, and some of this benefit is due to direct shading by the panels (Crellin, 2021). Another French agrivoltaic system was co-located in a lettuce field and delays in plant growth were observed in areas with more shade coverage (Marrou et al., 2013). Lettuce differs greatly from wild blueberry, but it is probable that any disruption in plants’ ability to utilize sunlight to photosynthesize will impact plant health and productivity. Research into the impact of varied shade amounts and types of ultraviolet light allowed through shade (by controlling both factors using shade cloths) on the health of highbush blueberry has shown that reducing available sunlight by approximately 50% promotes plant photosynthetic characteristics and leaf traits, by increasing leaf chlorophyll levels and reducing leaf temperature (thereby improving photosynthetic efficiency) (Lobos et al., 2011). Taken together, the studies on shading in lettuce, grape, and highbush blueberry make it clear that research

on the impact of shade on specific crops is necessary to understanding the impact that agrivoltaic shade may have on each cropping system.

Construction of this solar array caused obvious disturbance to the blueberry cover and soil, as mechanical equipment was used to de-rock, level, and drill post driven ground mounts across the site. These direct impacts, which include death of above ground plant stems, compaction of soil, possible weed seed bank mixing, cooler soil and above ground temperatures in the shade, and water falling to the ground along drip lines are some examples of possible impacts to the future health and yield of wild blueberry plants. Indirect impacts are more difficult to quantify and may take several seasons to fully understand. This solar array was completed in 2021 and continued data collection will articulate what harms or benefits the wild blueberry are subject to as the blueberry underneath the panels continues to recover from installation and be commercially managed.

(Information on how growers can start exploring options for solar development on their land can be found under the “Current Recommendations” header.)

## **METHODS**

### Installation (completed by the construction team)

During construction of the 40-acre site, 12 acres were set aside for this research and panel installation was done in one of three ways within the research section. The three construction methods were named Standard, Mindful, and Careful. In Standard: construction and installation methods were unaltered from industry and company standards. Equipment could drive and operate anywhere and was not restricted from turning or rotating, and foot traffic was not limited. In Mindful: equipment could only enter and exit the site along one path, equipment could only rotate 90°, and foot traffic was limited to as few paths as possible. In Careful: poly mats (Figure 1) were placed on top of the blueberry plants to work and drive equipment on. Poly mats could remain in place for only four weeks at a time in spring and as summer progressed the mats could only be in place one workday at a time. Equipment could only turn 90° if the equipment was situated fully on plywood (otherwise, equipment could only drive straight in and straight out), and foot traffic was allowed only along one path.

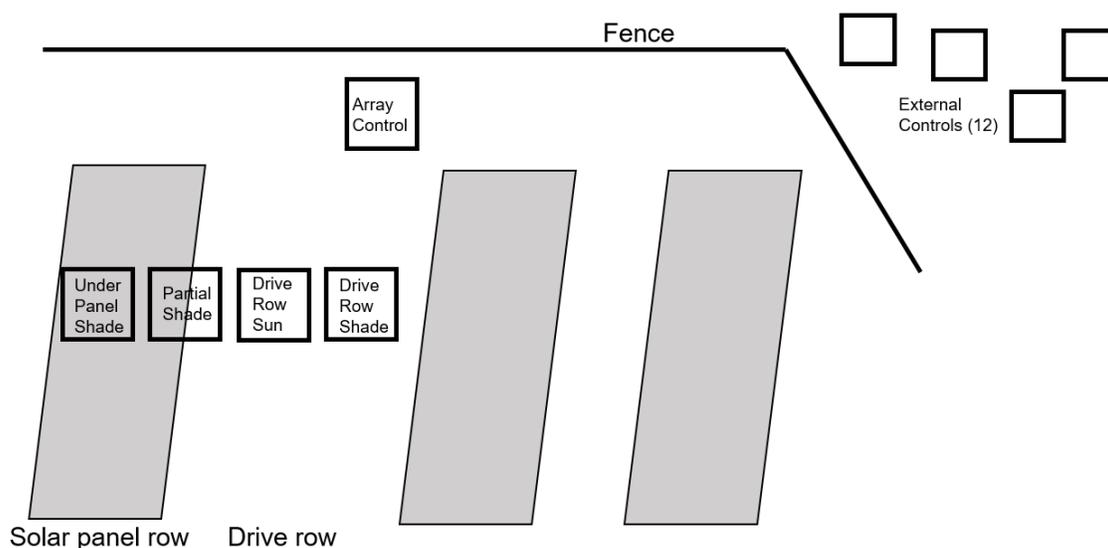
Monofacial and bifacial panels were installed in this array. Monofacial panels are standard panels that have solar receptors only on the sun-facing side of the panel and generate energy just from that side. Bifacial panels are a newer technology with solar receptors on both sides of the panel that can generate energy from both sides. Bifacial panels allow more sunlight through the panel and generate energy from solar energy reflected off the surface underneath the panels. Monofacial panels were installed in the area constructed with the Standard treatment. Bifacial panels were installed in the areas constructed with Mindful and Careful treatments. Additionally, it's worth noting there are terrain differences between steep slope where the bifacial panels are located and the shallow slope at the bottom of a hill, where the monofacial panels are located.

### Data collection (completed by University of Maine Team)

Onset HOB0 (Onset Computer Corporation, Bourne, MA, USA) temperature and relative humidity sensors (MX2300) were installed on wooden stakes driven into the ground to continuously track these metrics over time. One sensor was installed under monofacial panels, one under bifacial panels, and one in the array control underneath no panels.

Multiple Photosynthetically Active Radiation (PAR) sensors with data loggers (ZL6 from METER group, Pullman, WA) were installed on wooden stakes on June 27, 2022. These wooden stakes also supported

the temperature and humidity sensors described above. These sensors measured, in 15-minute intervals, the amount of sunlight penetrating the solar panel array; this light was assumed to be available to wild blueberry plants growing underneath the panels. Sunlight penetrating the panels was measured directly under panels, called “shade under panel”, partial shade (in drive rows behind panels, called “shade drive row”), and full sunlight conditions (in drive rows between solar arrays, called “sun drive row”). There were 4 sensors (full shade, partial shade, full sun, and a localized control, called “array control”) installed in each construction category (Standard, Mindful, Careful), for a total of 12 PAR sensors (Figure 1, below). No PAR sensors were installed in the control plots situated outside of the array perimeter (called “external control”). PAR sensors in full sunlight provided the localized control value, or “light quantities,” for comparison with the partial and full shade conditions.



**Figure 1.** Example of one replication plot layout in the field where black squares represent quadrats where data collection occurred.

A 0.37 m<sup>2</sup> quadrat was used at each of the three PAR sensor locations totaling 16 quadrat sample locations per construction method for a total of 48 quadrats within the array. In addition, there were 12 external control quadrat plots, for a total of 60 quadrat plots across the entire project. All 60 quadrats were flagged for repeated measurements in the same locations throughout the season.

Wild blueberry health was evaluated within each quadrat by ranking overall blueberry cover using the Daubenmire Cover Scale of 0-6, where 0 = not present, 1 = ≤1-5% coverage, 2 = 6-25% coverage, 3 = 26-50% coverage, 4 = 51-75% coverage, 5 = 76-95% coverage and 6 = 96-100% coverage (Daubenmire, 1959). Weed presence was evaluated using the Daubenmire rank, totaling the number of weeds present, and listing the top three weed species present. Disease presence was evaluated by counting the number of blueberry stems showing signs of disease, listing the top three diseases present, and ranking the severity of the disease observed. Numbered stem tags were placed on three stems within each quadrat and these three stems were visited repeatedly to count the number of buds and fruit that developed. These blueberry coverage, bud/fruit count, weed presence, and disease presence measurements were all taken three times in 2022, on May 17, June 14, and July 20.

Wild blueberry plant health was further evaluated by gathering SPAD and TDR data. SPAD (Soil Plant Analysis Development) is a measure of how much chlorophyll is present in the leaves of the plant and

was measured using a handheld chlorophyll meter (SPAD 502; Minolta Corp., Osaka, Japan). The higher the value calculated by the meter, the healthier the plant. SPAD values were taken in pairs on the same stem, reading the value on a lower and upper leaf. These pairs were taken on 4 randomly selected stems within each quadrat. TDR (Time Domain Reflectometry) is a measure of soil moisture content and temperature and was measured using a FieldScout TDR 150 Soil Moisture Meter (Spectrum Technologies, Inc., Aurora, IL, USA) to measure soil conditions to a depth of 12 cm. TDR samples were taken twice in each quadrat. SPAD samples were gathered on June 14 and July 20, 2022. TDR samples were gathered on May 17 and July 20, 2022.

Fruit was harvested July 20, 2022 by hand-raking within each quadrat and measuring the weight of the harvested fruit. The fruit samples were then combined by treatment type (sun, full shade, partial shade) and 100 random berries were selected, combined and weighed to calculate the “100 berry weight”; this information can give a sense of whether fruits were large or small in size. After calculating the 100 berry weight, a sample of fruit was removed from each combined treatment sample and macerated before being measured for Brix, a measure of sugar content.

### Data analysis

Computations were carried out using JMP Version 16.0 (SAS, Cary, NC, USA) statistical software. All data collected via multiple samplings throughout the field season (soil moisture, soil temperature, SPAD, pest measures and blueberry cover) were analyzed using a repeated measures full factorial, followed by a Tukey’s Pairwise comparison. Larger data sets of environmental conditions collected on a 24hr basis, including PAR, air temperature, humidity and dewpoint were shortened to 10 AM – 2 PM (peak growing hours) and analyzed using an REML mixed model with date and treatment. PAR was converted from units of  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  PPFD to %PAR relative to the average PAR received by the control outside of the array ( $1380 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  PPFD). Single date measures (blueberry phenology, yield and Brix) were analyzed using a one-way ANOVA and a Tukey’s Pairwise comparison (following any necessary transformations). Multivariate and bivariate regressions were run to assess the degree of relation between the dependent variable yield and independent variables: air temperature, relative humidity, PAR, soil moisture, soil temperature and SPAD. Linear regression plots are presented below for variables with significant linear relationships following the bivariate regression analysis.

Due to the nature of count data collected in the field (which often has a high number of zeros, creating a skewed distribution) much of our data failed the assumptions of normality and equal variance often required to run parametric statistical tests. Data that did not meet the statistical assumption of normal distribution included: soil moisture, soil temperature, relative humidity, pest data, Brix, blueberry phenology and cover. These data were transformed using a square root transformation. The transformed data improved visually in their distribution but continued to statistically fail for normality. Statistical tests were carried out despite non-normality after establishing there were no serious problems with the data. When data met statistical assumptions (including air temperature, dewpoint, and yield), data were not transformed prior to statistical testing. Regressions were performed on untransformed data.

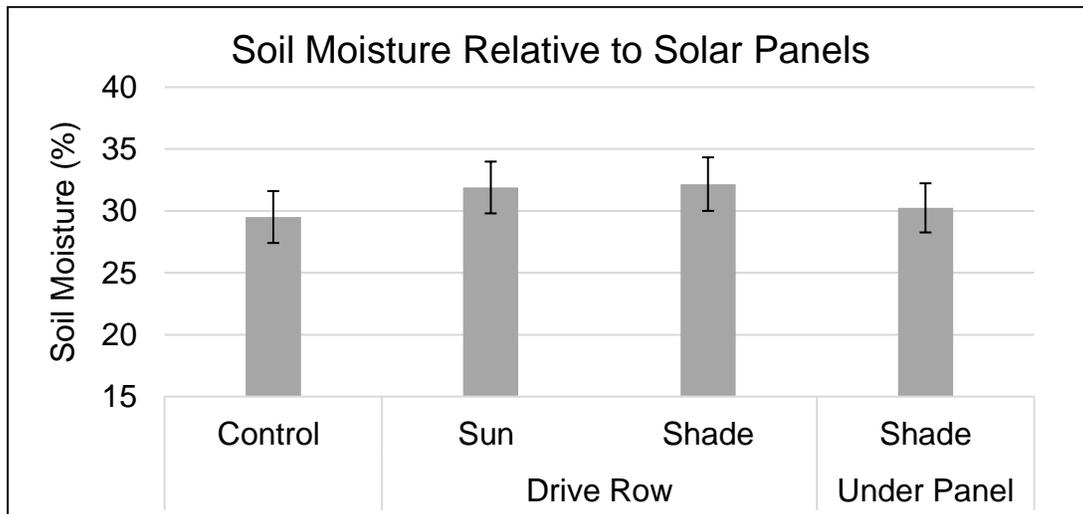
## **RESULTS**

### Environmental Conditions (Soil, Air, Sunlight)

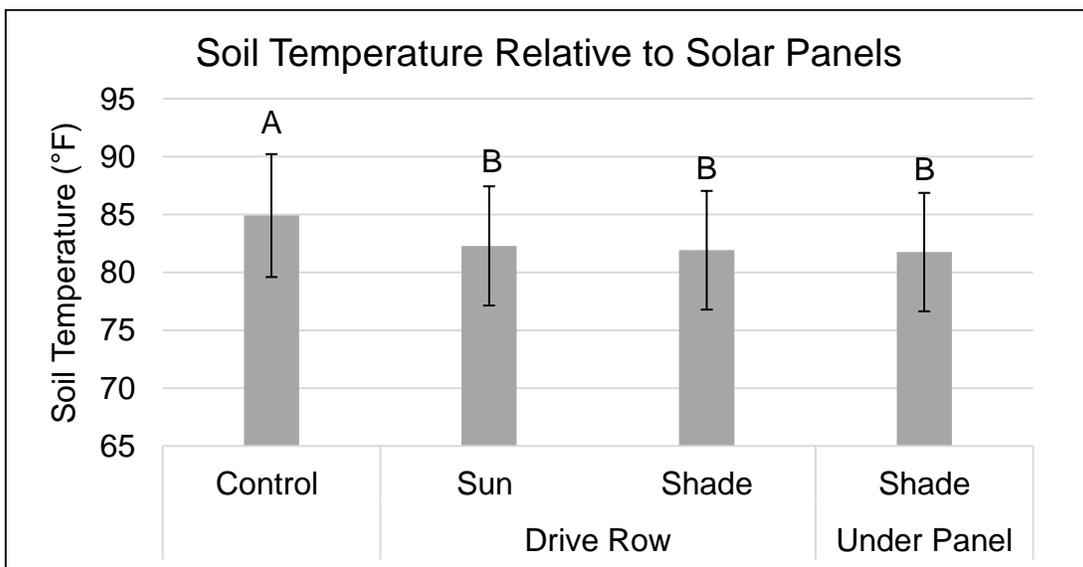
While not significant, there were trends in soil moisture where the control experienced the lowest average soil moisture (29.5%), the shade under panel was slightly greater (30.3%), and greater still in the sun drive row (31.9%) and shade drive row (32.2%) (Figure 1). This may be due to the location of

the drive row (being between the panels) where regular precipitation and panel run off is concentrated but the panels still shade and trap moisture from the sun.

The shade under panel experienced the lowest average soil temperature (81.7°F), close to the temperature of the shade drive row (81.9°F) (Figure 2). Soil temperatures in the sun drive row were 82.3°F and significantly higher at 84.9°F in the control. The average control temperatures were significantly warmer when compared to the treatments, which makes sense as the ground in the control experiences full sun.

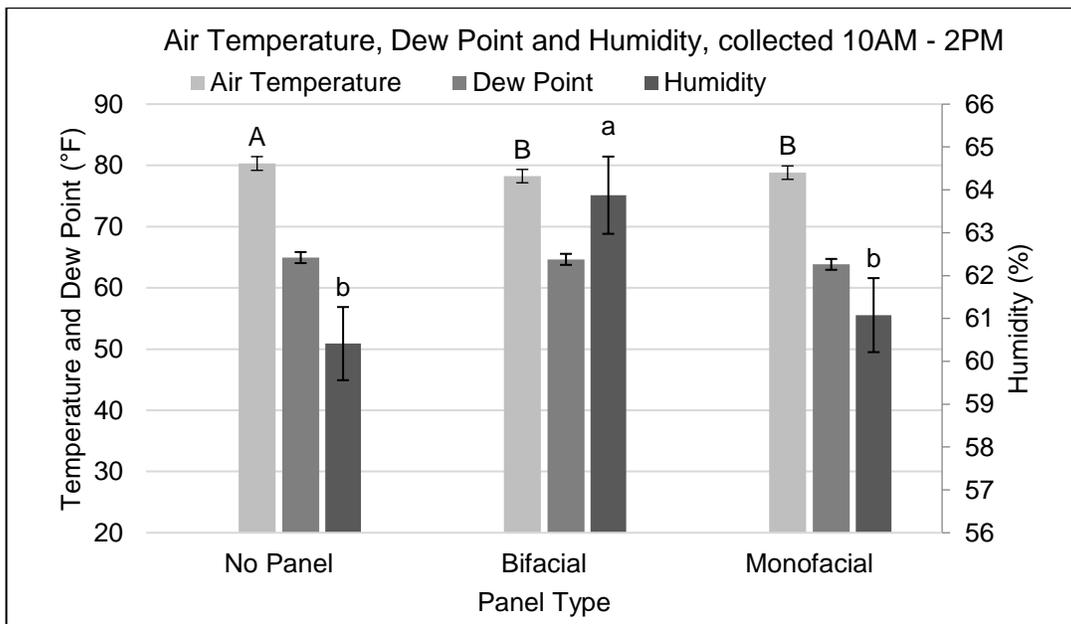


**Figure 1.** Average soil moisture relative to the amount of shading from the panels, measured on May 17 and July 20, 2022. The 'shade drive row' location received partial sun exposure depending on the time of day. Treatment differences (shading from panels) were not significant. Error bars represent the standard error of the mean.



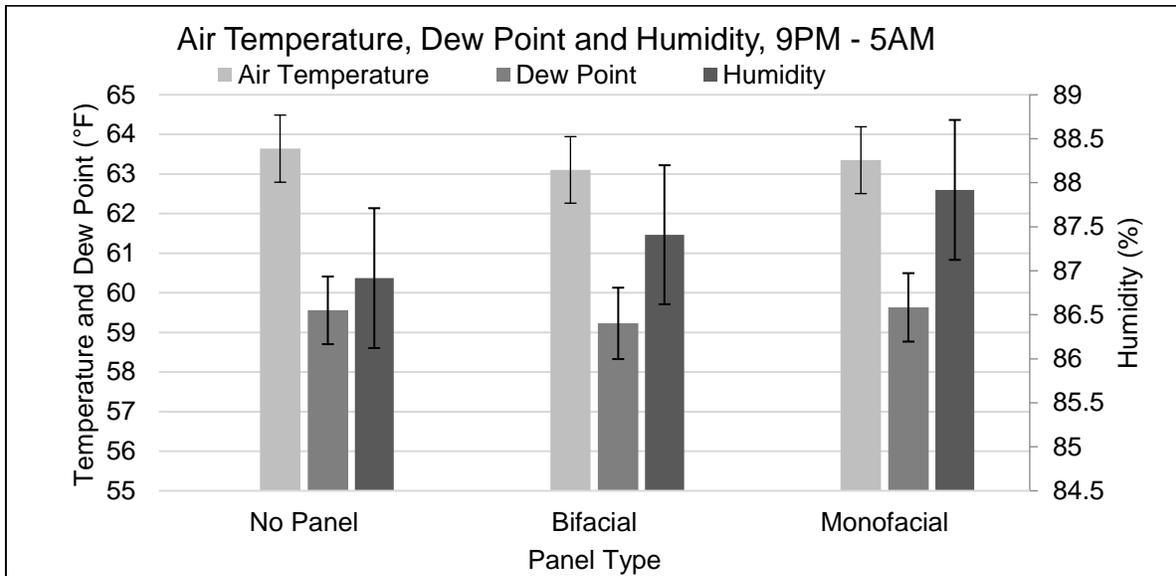
**Figure 2.** Average soil temperature relative to the amount of shading from the panels, measured on May 17 and July 20, 2022. The 'shade drive row' location received partial sun exposure depending on the time of day. Letters indicate significant differences at the 0.05 level of significance. Error bars represent the standard error of the mean.

Air temperature, dew point, and humidity were measured from 10 AM – 2 PM daily (most direct sun exposure) for the control and both panel types: monofacial and bifacial (Figure 3). Air temperatures were significantly higher outside of the panels (80.3°F), and lower underneath the bifacial panels (78.3°F) and monofacial panels (78.8°F). Dew point exhibited no significant treatment differences, with average dewpoint values of 64.9°F, 64.7°F, 63.8°F, in the control, bifacial and monofacial treatments, respectively. The bifacial panels experienced significantly greater average humidity (63.9%) than the average humidity observed under the control (60.4%) and monofacial panels (61.1%). The bifacial panels allow greater light penetration than the monofacial panels. The higher humidity under the bifacial panels suggests that the light penetration encourages evapotranspiration from the leaves and soil but also acted as a physical barrier to trap that humidity.



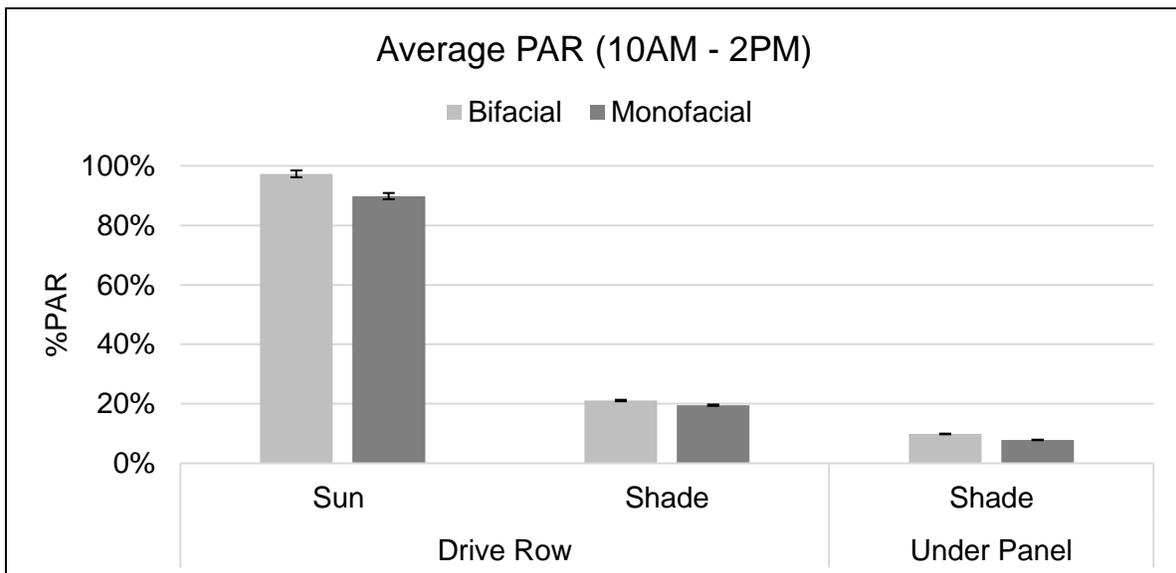
**Figure 3.** Average temperature (°F), dewpoint (°F), and humidity (%) relative to the amount of shading from the panels, measured from June 27 to August 31, 2022. Letters indicate significant differences at the 0.05 level of significance. Capital letters are to be compared separate from lowercase letters. Error bars represent the standard error of the mean.

Air temperature, dew point, and humidity were measured from 9 PM – 5 AM (overnight) for the control and both panel types: monofacial and bifacial (Figure 4). Air temperatures were highest outside of the panels (63.6°F), and slightly lower underneath the bifacial panels (63.1°F) and monofacial panels (63.3°F), although not significantly different. Average dew points were relatively similar across treatments, being 59.6°F, 59.2°F, and 59.6°F in the control, bifacial and monofacial treatments, respectively. Average humidity observed in the control was 86.9%, 87.4% under the bifacial panels, and 87.9% under the monofacial panels, although not significantly different. A lack of significant treatment differences in the nighttime hours when compared to the daytime hours suggests sunlight is the driving factor in the significant differences observed in Figure 3.



**Figure 4.** Average temperature (°F), dewpoint (°F), and humidity (%) relative to the amount of shading from the panels, measured from June 27 to August 31, 2022. Treatment differences (shading from panels) were not significant. Error bars represent the standard error of the mean.

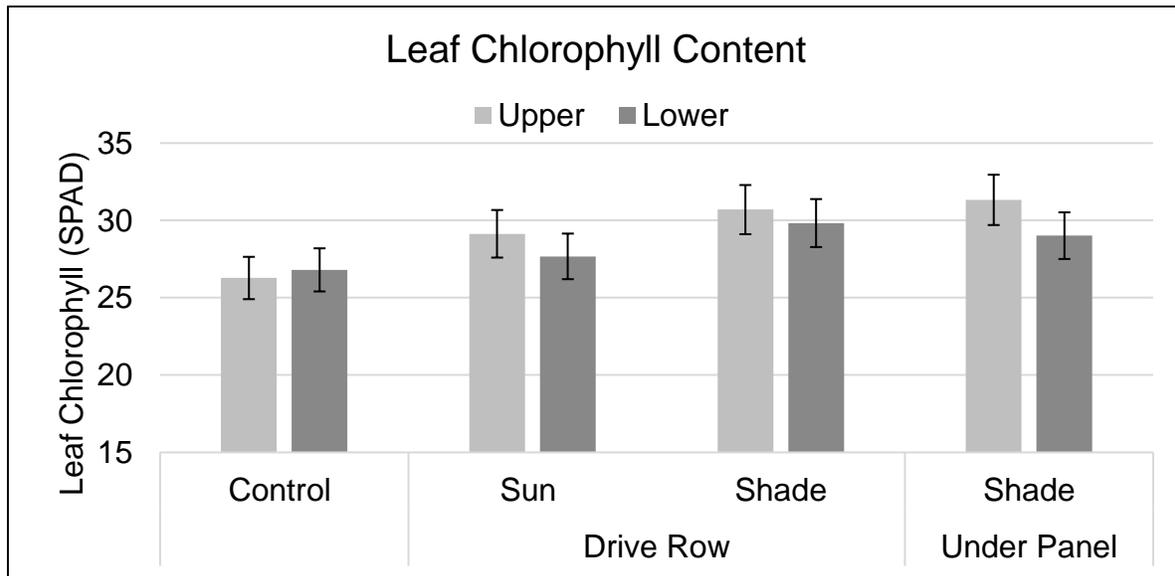
PAR received by plants in each of the treatments was dramatically different. Areas underneath bifacial panels had slightly higher PAR levels than those with monofacial panels. All units for PAR are micromoles per meter per second ( $\mu\text{mol}/\text{m}^{-2}/\text{s}^{-1}$  PPFD) and indicate how much usable light energy reaches an area. The base level for full sunlight was  $2000 \mu\text{mol}/\text{m}^{-2}/\text{s}^{-1}$  PPFD with sensors maxing out at  $2325 \mu\text{mol}/\text{m}^{-2}/\text{s}^{-1}$  PPFD. The control received an average of  $1380 \mu\text{mol}/\text{m}^{-2}/\text{s}^{-1}$  PPFD from 10a-2p each day May 18 to August 31, 2022, including both sunny and cloudy days. The control PAR level was used as the upper threshold for establishing %PAR in all other treatments. Relative to the average PAR observed in the control, bifacial areas received 90%PAR, 19%PAR, and 9%PAR in the sun drive row, shade drive row, and shade under panel, locations, respectively (Figure 5). The monofacial areas received slightly less than the bifacial with average levels of 83%PAR, 18%PAR and 7%PAR in the respective sun drive row, shade drive row, and shade under panel locations.



**Figure 5.** Average photosynthetically active radiation (PAR) presented as %PAR (of the control; 1380  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  PPFD) observed in wild blueberry relative to the amount of shading from the panels, measured from May 18 to August 31, 2022. The 'shade drive row' location received partial sun exposure depending on the time of day. Error bars represent the standard error of the mean.

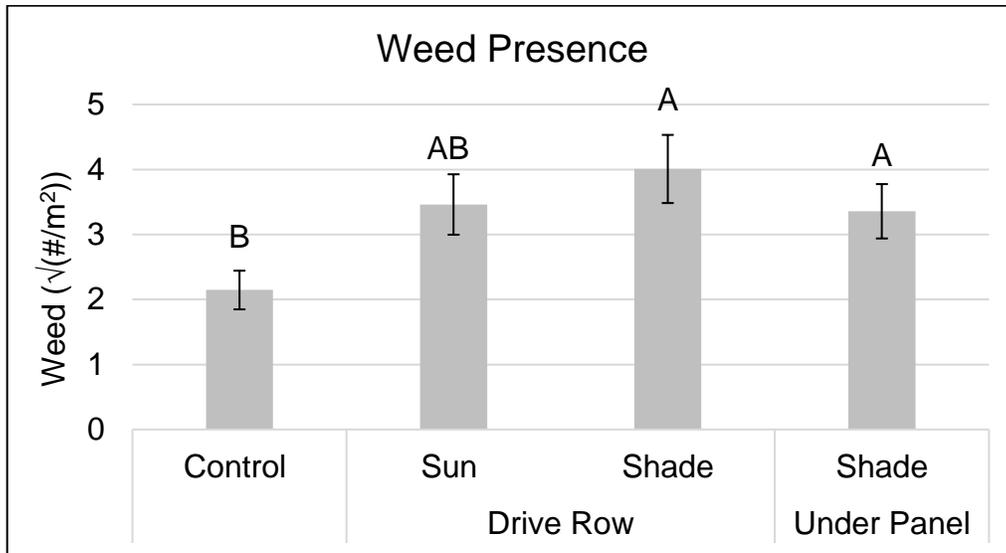
Plant Health

Leaf chlorophyll content in the shade drive row treatments were greatest in both the upper and lower leaves (upper 30.7 SPAD, lower 29.8 SPAD), while the lowest leaf chlorophyll content occurred in the control (upper 26.3 SPAD, lower 26.8 SPAD) (Figure 6). Although not significant, all treatments within the array exhibited greater leaf chlorophyll content in both the upper and lower leaves when compared to the control.

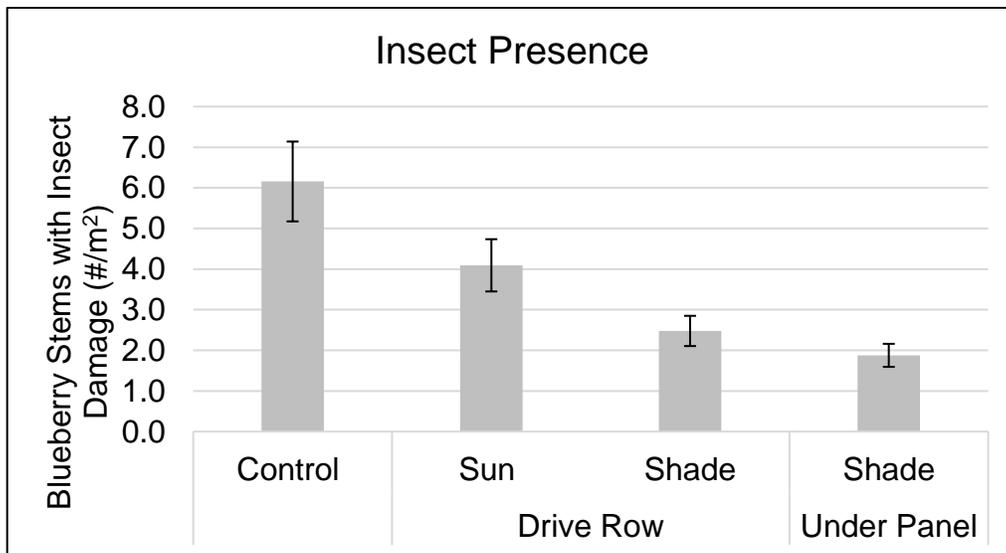


**Figure 6.** Average upper leaf and lower leaf chlorophyll content (SPAD) relative to the amount of shading from the panels, measured on June 14 and July 20, 2022. The 'shade-drive row' location received partial sun exposure depending on the time of day. Treatment differences (shading from panels) were not significant. Error bars represent the standard error of the mean.

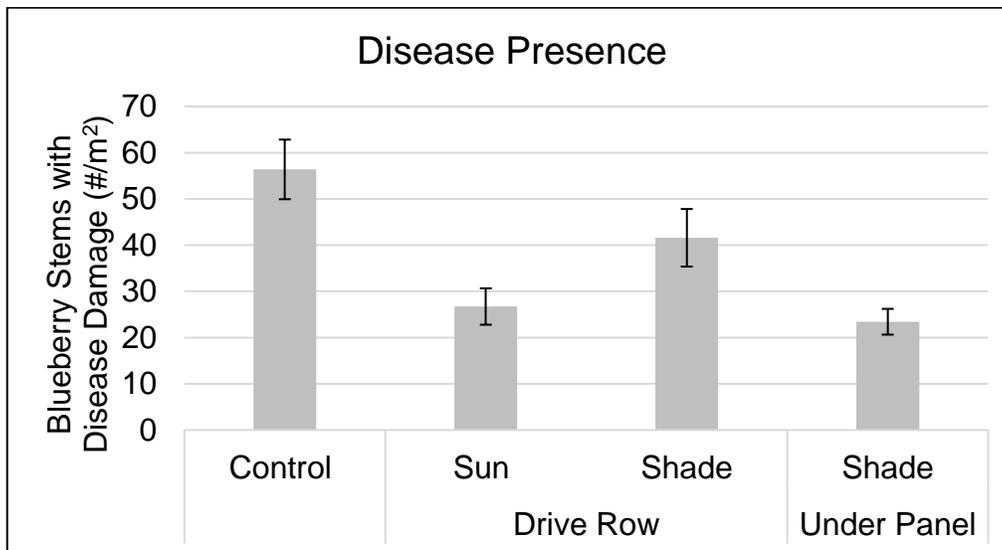
Weed presence was greater within the array relative to the control (Figure 7). The shade drive row treatment (43 weeds/m<sup>2</sup>) and the shade under panel treatment (28 weeds/m<sup>2</sup>) had significantly greater weed numbers than the control (14 weeds/m<sup>2</sup>). Although not significant, the treatments with the greatest number of blueberry stems with insect damage were the control (6.2 stems /m<sup>2</sup>), followed by the sun drive row (4.1 stems /m<sup>2</sup>), the shade drive row (2.5 stems /m<sup>2</sup>), and the shade under panel (1.9 stems /m<sup>2</sup>) (Figure 8). Disease presence also did not demonstrate significant treatment differences (Figure 9). However, the control exhibited the highest number of blueberry stems with disease (56.4 stems/m<sup>2</sup>), followed by the shade drive row (41.6 stems /m<sup>2</sup>), the sun drive row (26.7 stems /m<sup>2</sup>), and the shade under panel (23.4 stems /m<sup>2</sup>).



**Figure 7.** Average weed presence (transformed:  $\sqrt{\#/m^2}$ ) relative to the amount of shading from the panels, measured on May 17, June 14 and July 20, 2022. The 'shade drive row' location received partial sun exposure depending on the time of day. Letters indicate significant differences at the 0.05 level of significance. Error bars represent the standard error of the mean.



**Figure 8.** Average blueberry stems with insect damage ( $\#/m^2$ ) relative to the amount of shading from the panels, measured on May 17, June 14 and July 20, 2022. The 'shade drive row' location received partial sun exposure depending on the time of day. Treatment differences (shading from panels) were not significant. Error bars represent the standard error of the mean.

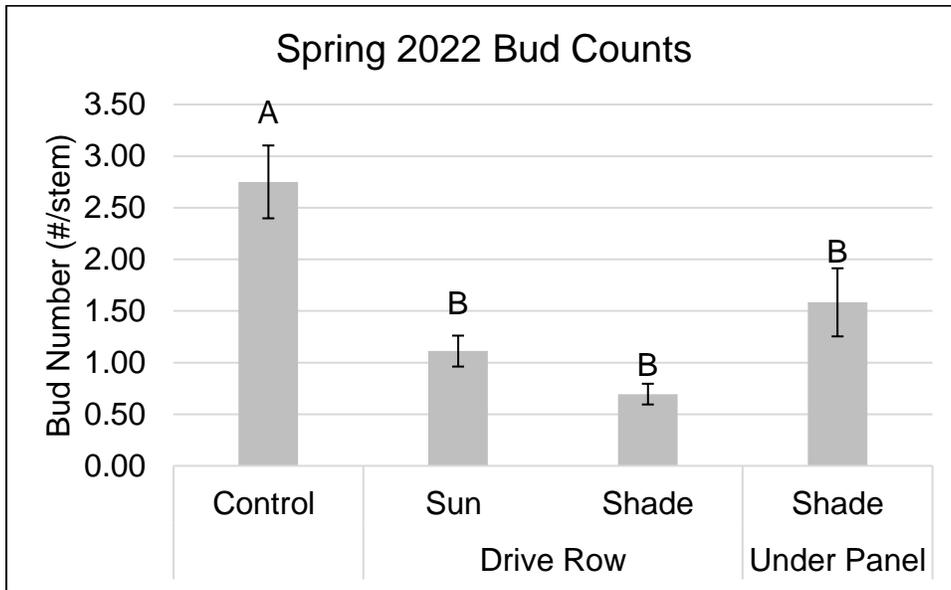


**Figure 9.** Average blueberry stems with disease damage (#/m<sup>2</sup>) relative to the amount of shading from the panels, measured on May 17, June 14 and July 20, 2022. The 'shade drive row' location received partial sun exposure depending on the time of day. Treatment differences (shading from panels) were not significant. Error bars represent the standard error of the mean.

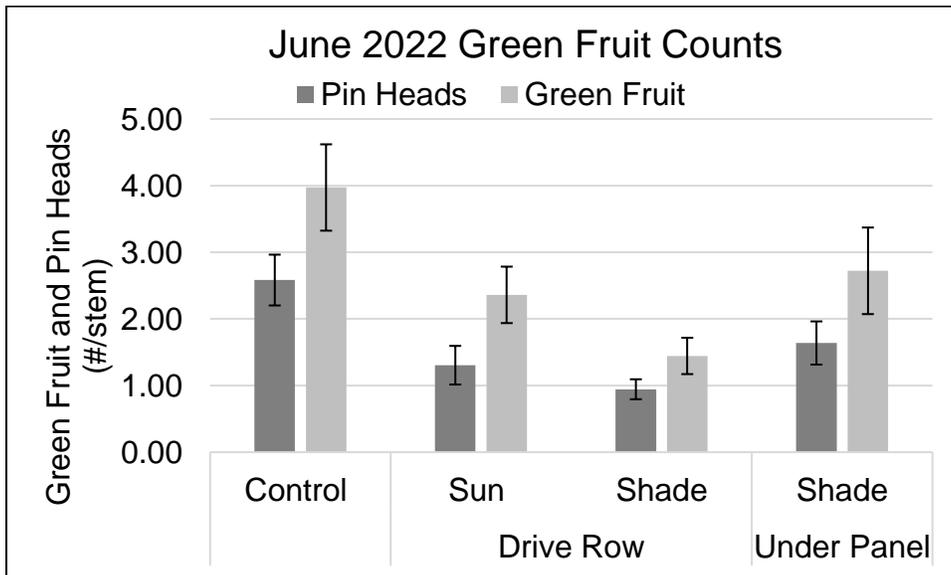
### Phenology

On May 17, 2022, the blueberry stems in the control exhibited significantly higher bud numbers (2.8 buds/stem) compared to all other treatments (Figure 10). The stems in the shade drive row treatment exhibited the lowest average bud numbers (0.7 buds/stem). On June 14, 2022, treatment differences in phenological development were not significant (Figure 11). However, it is worth noting that blueberry stems in the control exhibited the highest number of pin heads (2.6 pin heads/stem) and green fruit (4.0 green fruit/stem). Similar to bud number, the lowest counts of pin heads (0.9 pin heads/stem), and green fruits (1.4 green fruit/stem).

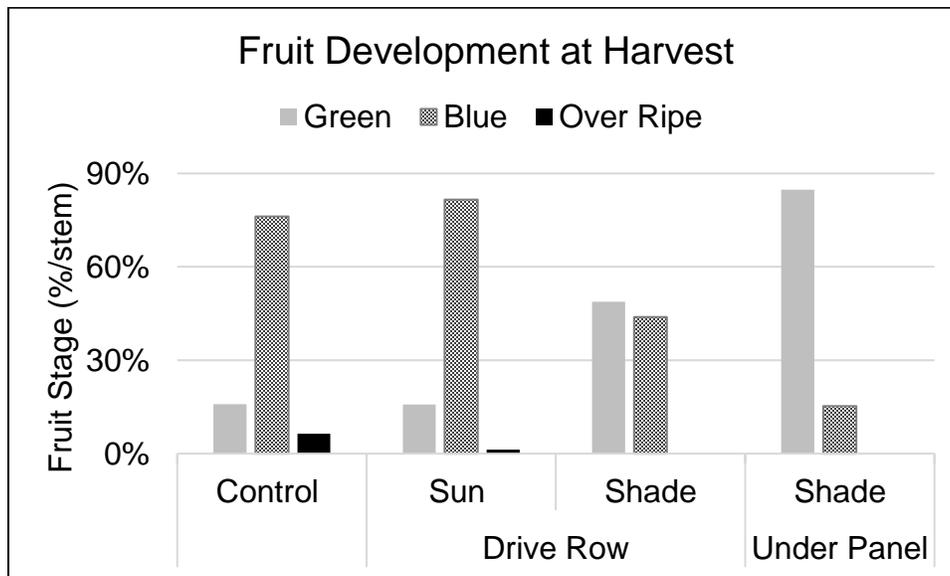
At harvest on July 20, 2022, the greatest number of blue fruits occurred in the control (76%) and the sun drive row (82%) treatments (Figure 12). In contrast, the shade drive row and shade under panel were primarily dominated by the green fruit stage, with green fruit comprising 49% and 85% of the total fruit, respectively. These differences in fruit ripeness ratios by treatment suggest that the shaded treatments were behind in phenological development relative to the treatments receiving more sun. Additionally, the control may have been developmentally ahead of the treatments within the array, with 6% of the fruit counted as overripe (unmarketable) fruit.



**Figure 10.** Average bud numbers (#/stem) relative to the amount of shading from the panels, measured on May 17, 2022. The 'shade drive row' location received partial sun exposure depending on the time of day. Letters indicate significant differences at the 0.05 level of significance. Error bars represent the standard error of the mean.



**Figure 11.** Average green fruit and pin head numbers (#/stem) relative to the amount of shading from the panels, measured on June 14, 2022. The 'shade drive row' location received partial sun exposure depending on the time of day. Treatment differences (shading from panels) were not significant. Error bars represent the standard error of the mean.



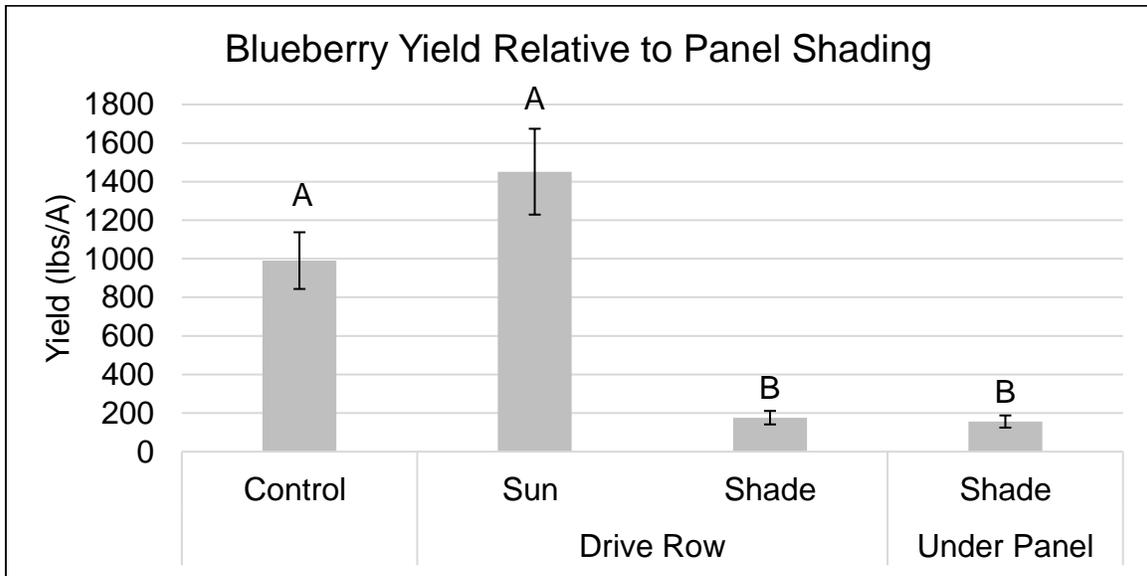
**Figure 12.** Average fruit development (%/stem) relative to the amount of shading from the panels at the time of harvest measured on July 20, 2022. The ‘shade drive row’ location received partial sun exposure depending on the time of day.

#### Fruit Yield & Quality

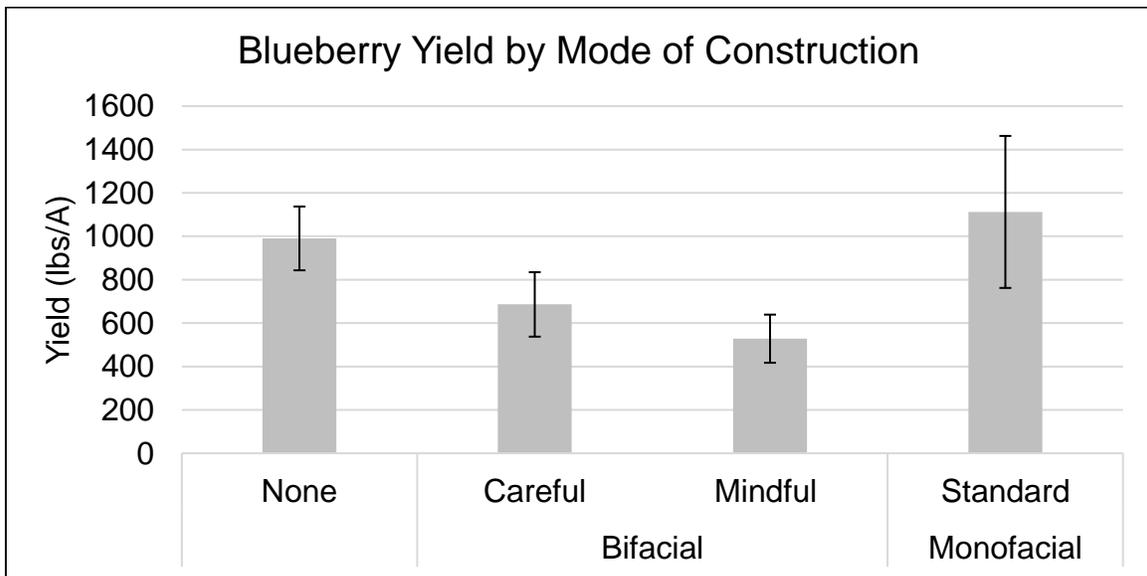
Fruit yield dramatically varied by treatment, with the greatest average yield harvested from the sun drive row treatment (1451 lbs/A), exceeding that harvested in the control (990 lbs/A) by 461 lbs/A (Figure 13). The yields of shade drive row (176 lbs/A), and the shade under panel (156 lbs/A) were significantly lower than that of the control and sun drive row treatments. The shade drive row and shade under panel yields were 87% and 89% less than the higher yielding treatment (sun driver row), respectively. While the higher percentage of green fruit in the shaded treatments suggests these treatments were developmentally behind, the low blueberry yield suggests lack of productivity in general.

When comparing blueberry yield by panel construction, the greatest yields were harvested in the standard-construction monofacial treatment (1112 lbs/A), exceeding that harvested in the control (990 lbs/A), the careful-construction bifacial treatment (686 lbs/A), and the mindful-construction bifacial treatment (528 lbs/A) (Figure 14). Treatment differences were not significant. Higher yields were hypothesized to occur under the bifacial panels due to the greater potential for light infiltration, however, the standard construction that occurred under the monofacial panels had a higher level of disturbance which the blueberry may have responded well to.

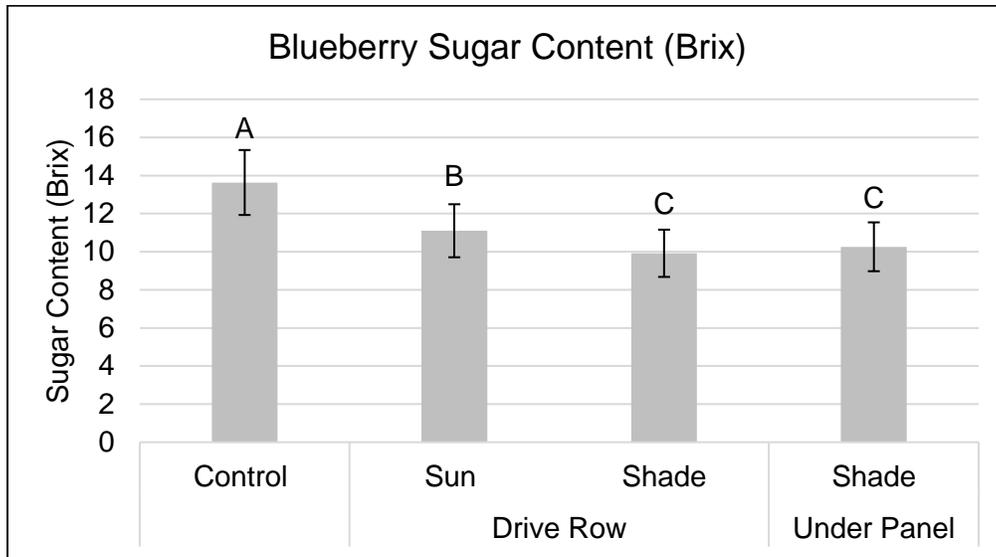
The highest berry sugar content, measured in Brix, was measured in the control (13.6 Brix), compared to the sun drive row (11.1 Brix), shade under panel (10.3 Brix), and shade drive row (9.9 Brix) (Figure 15). This corresponds to the ratios of phenological development, where a higher blue fruit ratio would inherently have higher berry sugar content.



**Figure 13.** Average yield (lbs/A) relative to the amount of shading from the panels, harvested on July 20, 2022. The 'shade drive row' location received partial sun exposure depending on the time of day. Letters indicate significant differences at the 0.05 level of significance. Error bars represent the standard error of the mean.



**Figure 14.** Average yield (lbs/A) relative to the mode of construction, harvested on July 20, 2022. The 'shade drive row' location received partial sun exposure depending on the time of day. Treatment differences by mode of construction and panel type were not significant. Error bars represent the standard error of the mean.



**Figure 15.** Average berry sugar content (Brix) relative to the amount of shading from the panels, harvested on July 20, 2022. The 'shade drive row' location received partial sun exposure depending on the time of day. Letters indicate significant differences at the 0.05 level of significance. Error bars represent the standard error of the mean.

A multivariate analysis evaluating the influence of independent variables (air temperature, relative humidity, PAR, soil moisture, soil temperature and SPAD) on the dependent variable of yield, exhibited a significant relationship for the model ( $p < 0.0001$ ) with an  $R^2$  of 0.56 (1.0 would be a perfect 1:1 relationship; Table 1). Within the model, PAR had the greatest influence on yield ( $p < 0.0001$ ;  $t = 5.89$ ). A series of bivariate regressions provided a more in-depth view of each independent variable relative to yield (tested on an individual basis; Table 2). Here, PAR exhibited the most significant relationship ( $p < 0.0001$ ;  $R^2 = 0.44$ ), followed by soil temperature ( $p < 0.0104$ ;  $R^2 = 0.14$ ) and leaf chlorophyll content (SPAD;  $p < 0.0298$ ;  $R^2 = 0.10$ ).

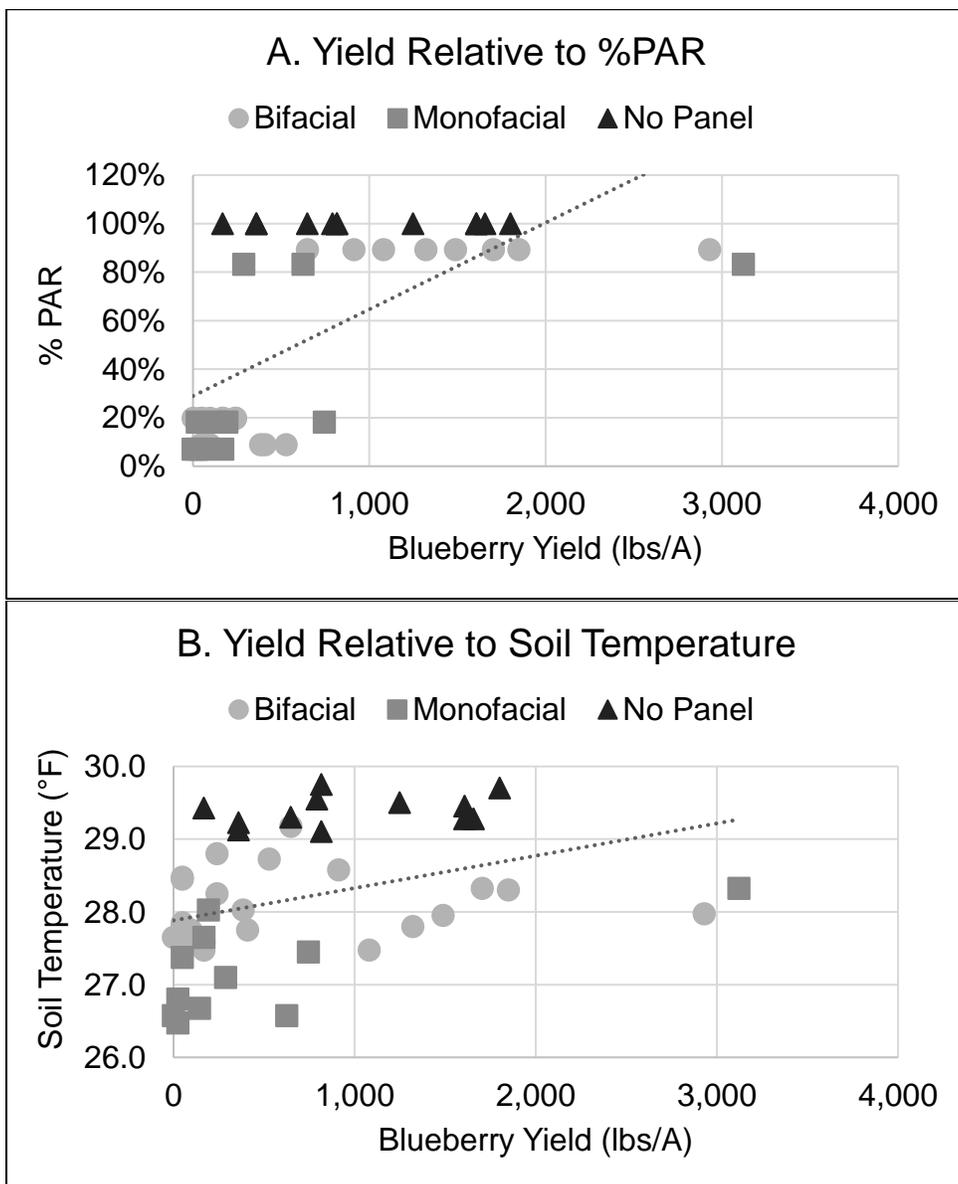
The linear regressions show the degree and the direction of the independent variables which had a significant relationship in the bivariate regressions (Figure 16). These variables included PAR, soil temperature and SPAD relative to yield (across all treatments).

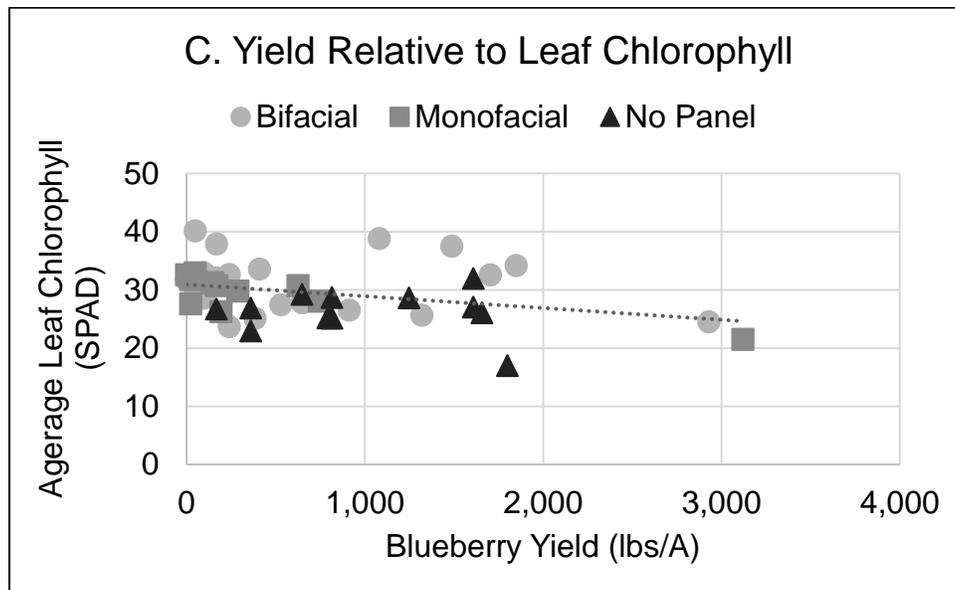
**Table 1.** Predicted influence of the independent variables (air temperature, relative humidity, PAR, soil moisture, soil temperature and SPAD), evaluate using a multivariate linear regression. Bold text indicates a significant linear relationship at the 0.05 level of significance.

Multivariate	Dependent Variable: Yield		
	R2	F-value	$p$
ALL	<b>0.56</b>	<b>8.6</b>	<b>&lt; 0.0001</b>
Independent Variables:	t-value	$p$	
Air Temperature	-1.97	0.0559	
Relative Humidity	-1.15	0.2577	
PAR	5.89	<b>&lt;0.0001</b>	
Soil Moisture	0.19	0.8528	
Soil Temperature	0.98	0.3318	
SPAD	-1	0.3224	

**Table 2.** Predicted influence of the independent variables (air temperature, relative humidity, PAR, soil moisture, soil temperature and SPAD), evaluate using a bivariate linear regression. Bold text indicates a significant linear relationship at the 0.05 level of significance.

Bivariate Independent Variables:	Dependent Variable: Yield	
	R2	p
Air Temperature	4.70E-02	0.1426
Relative Humidity	0.01741	0.3766
PAR	0.44132	<b>&lt; 0.0001</b>
Soil Moisture	5.86E-05	0.9593
Soil Temperature	<b>0.13727</b>	<b>0.0104</b>
SPAD	<b>0.10069</b>	<b>0.0298</b>





**Figure 16.** Average blueberry yield (lbs/A) relative to average %PAR (Figure 16A; observed 10 AM - 2 PM), soil temperature (Figure 16B; °F) and average leaf chlorophyll (Figure 16C; SPAD). The dashed line represents the significant linear relationship between the two parameters. Datapoints are coded by panel type vs. control for additional descriptive detail.

## DISCUSSION

This particular solar array in Rockport, ME was designed for energy output with farming as a secondary priority. Because of this, the rows between panels and height of panels were only slightly extended from standard array spacing. Our biggest take-home message for landowners considering a solar array is to determine whether the project is primarily for energy production or crop production.

### Environmental Conditions (Soil, Air, Sunlight)

This array contains both monofacial and bifacial panels. Higher humidity levels under the bifacial panels during the time of maximum direct sun exposure could be an indication that more moisture from active plant respiration is trapped underneath the panels and this extra moisture is then heated further by the sunlight. This slight greenhouse effect was more pronounced in the 10 AM – 2 PM (maximum direct sun exposure) window under the bifacial panels and was more pronounced under the monofacial panels during the 9 PM – 5 AM (overnight) window. This suggests that there is more of a greenhouse effect on plants under monofacial compared to bifacial panels.

Research on highbush blueberries has identified the minimum threshold for good fruit yield from the plants as being 60% of full sunlight (2,000 PPF) (Kim et al., 2011), or approximately 1,200  $\mu\text{mol}/\text{m}^2/\text{s}^{-1}$  PPF. These highbush blueberries grew under a range of sunlight conditions and there were significant differences in physical plant structure depending on the amount of sunlight received. Shaded plants produced fewer but longer shoots, more and larger leaves, thinner leaves with fewer stomata (which lowers the rate of photosynthesis), leaves with more chlorophyll, fewer flowers and thus fewer fruits. Some shading of the plant can prove beneficial since shade during hours of direct sunlight (10 AM – 2 PM) can improve plants' photosynthetic efficiency (Lobos et al., 2011), however, continual shade (of high shade intensity, so low sunlight intensity) may fail to produce these same benefits as we saw in Rockport this year.

The most sunlight reached the control since the only shading received there was from passing clouds. Sun drive row saw much more sunlight than the shade drive row and shade under panel rows, as expected. That the sun drive row received less sunlight than the control indicate there is still some shading from panels in sunny parts of the array. This experiment was not designed to approximate the amount of sunlight that was reaching the plants but the results show that the shading present was enough to reduce fruit yield significantly. The percent reduction from the control to shade was 91% and 93% for the bifacial and mono respectively much more than the functional 50% reduction in shade that allowed highbush blueberry to continue productivity (Lobos et al., 2011).

### Plant Health

SPAD levels were highest where plants received the least amount of sunlight. Plants produce more chlorophyll in low-light conditions to maximize their potential to produce energy from the limited light. Generally, plants have higher SPAD levels on their lower leaves for this reason, but this trend was only observed in control this year. It is possible that the limited indirect light received by the plants underneath panels did not stimulate plants to produce more chlorophyll in those lower leaves. Perhaps producing more chlorophyll in low-light conditions was too costly for the plants.

### Pests

There were significantly more weeds in treatments compared to the control, possibly because treatments were disturbed during construction, so weed seeds from the weed seed bank may have sprouted. Since the controls were situated outside of the area that experienced any construction and disturbance in the past few years, the wild blueberry is better-established and weeds are reduced in those control areas, possibly from chemical weed management techniques which have not yet been applied to areas cultivated within the solar array. The most weeds were measured in the shade drive row. The most insect damage was observed in the control and sun drive row, which are areas that received the most sunlight. Reasons for this need to be explored further, however some insects target healthy plants that were present in sunnier locations.

### Phenology & Yield

The control produced the most buds (when measured in May), which correspondingly produced the most pin heads and green fruit a month later. The control then had high rates of blue fruit (76%) and the highest rate of overripe fruit (6%) of all treatments. However, the highest yield was harvested in the sun drive row, which contradicts the expectation that the undisturbed, unshaded control would have the highest yield. Therefore, it is possible the control did not have the highest yield because the fruit in the full sun, undisturbed conditions caused the fruit to overripen and drop from the stem before harvest.

Shade drive row produced the fewest buds in May and thus the fewest pin heads and green fruit a month later; at harvest, the fruit was nearly evenly split between green fruit and blue fruit. The shaded conditions prevented the plants from producing many buds and then delayed fruit development significantly. The final fruit yield was 9% of the fruit harvested in the drive sun row (the greatest yield).

Areas under the panels produced the second most buds and, correspondingly, the second most pinheads and green fruit a month later, but at harvest, nearly all the fruits were green fruit. Despite producing so many buds early in the season, the final fruit yield was so low that it was only 8% of the fruit harvested in the drive sun row (the greatest yield).

Wild blueberry is a plant that thrives best in full sun conditions. Introducing consistent shade over the plants impacted plant development and success in producing fruit. It was clearly observed that full and

partial shade delayed plant development and reduced fruit yield to a fraction of the yield collected in full sun. Plants in the shade underneath the panels had fruit ripening profiles inverse to those of the sun drive row: full shade plants were 85% green and 15% blue at harvest but shade drive row was 16% green and 82% blue fruit at harvest. Therefore, the amount of sunlight received by plants in partial shade is more likely to result in ripe fruit at harvest than in full shade conditions.

The most fruit was harvested within standard monofacial areas and the control, far exceeding the yield in the careful and mindful bifacial areas. Though the bifacial panels, by design, allow more sunlight to penetrate the panels, the bifacial panels are situated on a steeper slope than monofacial panels. The inconsistent slope of the ground beneath the panels confounds the results and makes it impossible to clearly understand why yields varied by panel type.

### Fruit Quality

Brix levels were significantly higher in the control compared to treatments, likely because the control plots contained more overripe fruit. As fruit ripens, sugar content within the fruit increases, and as the control was the only treatment to observe overripe fruit, the Brix levels from the sampled fruit were higher. The other treatments had more green fruit (low Brix level) and no overripe (high Brix level) fruit. As most wild blueberry growers harvest entire fields simultaneously, rather than harvesting one plant at a time during peak ripeness, the variability in fruit ripeness and corresponding Brix levels is important for growers regardless of the form in which berries are sold.

### **CURRENT RECOMMENDATIONS**

- When considering a solar array, decide if it the main goal is food or energy production.
- If managing the crop underneath, plan to manage for weeds and pests underneath the panels.
- If managing the crop underneath, plan to manage for harvest in the sun drive row between panels. Additional complexities and labor associated with harvesting directly underneath the panels will make the extra effort unprofitable.

### **NEXT STEPS**

- Continue data collection through 2024
- Compile cost-benefit analysis in 2023 and 2024

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