Installation of an agrivoltaic system influences microclimatic conditions and leaf gas exchange in cranberry

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Abstract

Agrivoltaic systems utilize the same area for both solar power generation and agricultural production. Our goal was to conduct a preliminary study to look at the changes in microclimatic conditions, plant ecophysiology, fruit quality, and yield under a cranberry agrivoltaic system. The study was conducted on a 'Stevens' cranberry bog in Carver, Massachusetts, USA. Two treatments were evaluated, an uncovered control area and a replica agrivoltaic system with three prototype solar arrays made out of plywood in a north-south orientation that mimicked a solar tracking system. The solar arrays were spaced 3.5 m apart, 6.0 m in length, and 1.5 m wide at a height of 3.0 m above the plant canopy. Microclimatic sensors were installed under solar arrays, between solar arrays, and in the uncovered control. Seasonally accumulated photosynthetically active radiation (PAR) was reduced by 41% under solar arrays and 29% between solar arrays compared to the control. On a clear sunny day, net carbon assimilation was reduced under the solar arrays at mid-day (12:30) and between solar arrays at mid-morning (09:46) and mid-afternoon (15:46) compared to the uncovered control. On a hot day (max temperature 30.9°C), canopy temperature was reduced by 3.5°C under the solar panels at mid-day and 3.0°C between solar arrays at mid-afternoon. Volumetric soil water content was increased under solar arrays and between solar arrays compared to the uncovered control. Leaf wetness was reduced under solar arrays and between solar arrays compared to the uncovered control. Fruit color measured as total anthocyanin content was not affected by the installation of an agrivoltaic system. Titratable acidity was reduced under the agrivoltaic system, in contrast, total soluble solids were increased.

Keywords: canopy temperature, fruit quality, leaf wetness, photosynthetically active radiation

INTRODUCTION

Agrivoltaics is the practice of co-locating solar photovoltaic power and agriculture. The concept of agrivoltaics was first proposed by Goetzberger and Zastrow (1982). Agrivoltaic systems address the challenges of maintaining both renewable energy and food security under ever-changing climatic conditions (Barron-Gafford et al., 2019). Agrivoltaic systems modify light conditions by reducing the amount of photosynthetically active radiation (PAR) reaching the plant canopy. The change in light conditions under an agrivoltaic system has the potential to affect ecophysiological plant functions and canopy microclimatic conditions (Barron-Gafford et al., 2019).

Cranberry production is vital to the economy of Massachusetts (MA). As of 2019, MA was the second largest producer of cranberries in the USA, accounting for 27% of total production (USDA, 2020). Over the last decade, the price of cranberry has decreased by 49%, from a high of USD $58 per barrel (45.4 kg) in 2008 to a low of USD $29.30 in 2018 (USDA, 2010, 2020). As a result, cranberry growers in MA are looking for alternative income streams to remain profitable.

The Massachusetts Department of Energy Resources launched the Solar Massachusetts

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Renewable Target (SMART) program in 2018. Under this program, renewable energy and agriculture are encouraged to work together with financial incentives available for agrivoltaic systems. There is no previous research on the effect of the installation of agrivoltaic systems on cranberry bogs (Sandler et al., 2019). The objective was to conduct a preliminary study on the effect of the installation of agrivoltaic system on cranberry canopy microclimate, leaf gas exchange, plant nutrient concentration, yield, and fruit quality.

MATERIALS AND METHODS

Study site, plant material, and treatments

The study was conducted on a 'Stevens' cranberry bog located in Carver, Massachusetts, USA (41.49° N, 70.45° W). The cranberry bog was managed under normal commercial cultural practices for irrigation, pest, and fertilizer management during the study (Ghantous et al., 2018). Two treatments were evaluated, an uncovered control and an agrivoltaic system with three replica solar arrays (solar arrays, hereafter) made out of plywood. The solar arrays were fabricated from 1 cm thick plywood sheets supported by standard lumber posts. In an attempt to simulate an articulating tracking system, three panels were arranged in a 'X' pattern with a vertical panel going through the center (Figure 1). The solar arrays were 6.0 m in length, 3.0 m above the plant canopy, and spaced 3.5 m apart. Solar array orientation was north to south. The solar arrays were installed during the spring of 2019 (northern hemisphere), with the construction completed by 1 July 2019.

Figure 1. Prototype agrivoltaic system installed on a 'Stevens' cranberry bog at Carver, Massachusetts, USA.

Microclimate measurement

Sensors to measure changes in microclimatic conditions were installed underneath the solar arrays, in between solar arrays and the control (no solar arrays). Depending on the angle of the sun, the area underneath and in between solar arrays is shaded at different times during the day resulting in two different microclimatic zones. Changes in microclimate conditions were measured using photosynthetically active radiation (PAR) sensors (Apogee Quantum Sensor, Apogee Instruments, Logan, UT), temperature and relative humidity (RH) sensor

(ATMOS 14, METER Group, Inc. Pullman, WA, USA), leaf wetness sensor (PHYTOS 31, METER Group, Inc. Pullman, USA), and volumetric soil moisture sensor (TEROS 11, METER Group, Inc. Pullman, WA, USA). The sensors were connected to an advanced cloud data logger (ZL6 METER Group, Inc. Pullman, WA, USA). The PAR, temperature and RH, and leaf wetness sensors were installed at the same height as the top of the plant canopy (≈10 cm above ground). The volumetric soil moisture sensor was installed 10 cm below the ground. An automated data logger collected data from all the sensors at 15-min intervals. The PAR sensors were installed after full bloom (19 July 2019) and removed before the bog was flooded for harvest on 22 September 2019. All the other sensors were installed on 28 August 2019 and removed on 22 September 2019. The sensors were installed under solar arrays, in between solar arrays, and in the control.

Yield and fruit quality

Yield was estimated by picking all fruit within a 930 cm^2 template as described by Suhayda et al. (2009). Fifteen samples were collected from each treatment. The fruit samples were then sieved through an 8-mm opening to remove undersized berries, and the remaining berries represented marketable berries. Average weight of marketable berries from each sample was calculated by dividing the total weight with the number of marketable berries. Fruit firmness was measured on ten fruits per sample using a fruit texture analyzer (FirmTech 2, Bioworks Inc., Wamego, KS, USA).

Fifteen additional 500 g samples were collected from each treatment for fruit quality analysis. Total anthocyanin content (TAcy) was determined on 200 g of fruit from the additional sample using a modified protocol from Fuleki and Francis (1968). Juice was extracted by blending 150 g of fruit in a commercial juice extractor (Waring® 6001C, Torrington, CT, USA) and used to measure total soluble solids and titratable acidity. Total soluble solids were measured using a hand-held refractometer (PAL-Easy ACIDF5, Atago CO, Tokyo, Japan). Titratable acidity was determined by titrating 10 g of juice with 0.1 N NaOH with an automated titrator (EasyPlus Titrator, Mettler-Toledo LLC, Columbus, OH, USA) until an end-point of 8.2.

Ecophysiological measurements

Leaf gas exchange measurements were done three times on a clear sunny day, in the morning (09:44), at solar noon (12:40) and in afternoon (15:30). Spot readings were taken underneath solar arrays, in between solar arrays, and in the control (no solar arrays). Depending on the angle of the sun, the area underneath and in between solar arrays is shaded at different times during the day resulting in two different microclimatic zones. Measurements were done using a portable photosynthesis system (CIRAS-3, Amesbury, MA, USA). The complete methodology for leaf gas exchange measurements in cranberry is described in Jeranyama et al. (2017).

Plant nutrient analysis

Plant tissue samples were collected on 22 September 2019 following the cranberry guidelines (DeMoranville and Ghantous, 2018). The top 5 cm of cranberry uprights comprising new growth was collected for analysis. Ten samples were collected from each treatment. The plant tissue was rinsed and air-dried before being shipped overnight for analysis.

Data analysis

Two-sample t-tests were used to determine treatment differences of yield, fruit quality, and plant nutrient data at 0.05 significance level using OriginPro 2019b (OriginLab Corporation). For leaf gas exchange, mean values and standard error of the mean were calculated for the data.

RESULTS AND DISCUSSION

On a sunny day, PAR was reduced by 40.1% under the solar array and 27.5% between the solar arrays (Figure 2). In terms of shading characteristics, there were 3.3 h of shading under the solar array at noon and 0.5 h in the early morning and late afternoon from the adjacent solar array. In between the solar arrays, there were 2.5 h of shading from adjacent arrays. Across the whole season, there was 41.5% shading beneath solar arrays and 29.3% between solar arrays (data not shown).

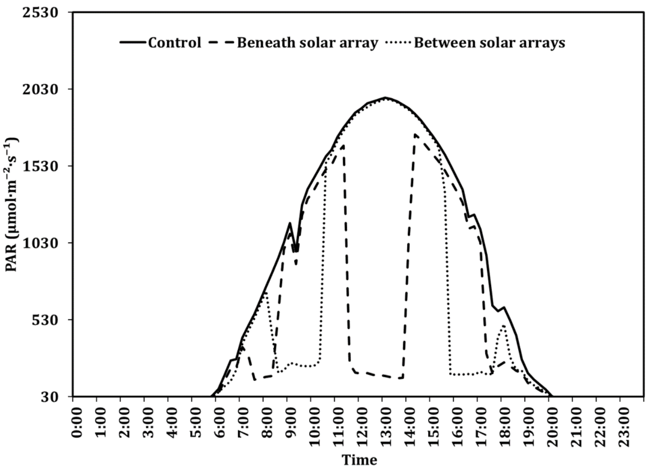

Figure 2. Diurnal change in photosynthetically active radiation (PAR) beneath and between solar array prototype compared to an uncovered control measured on a clear sunny day (20 September 2019) in 'Stevens' cranberry bog at Carver, Massachusetts, USA. Data was logged at 15 min intervals.

On a hot day (max temp 31.3°C) ambient canopy temperature was reduced by 3.8°C (08:45), 4.2°C (12:45) and 2.3°C (16:45) beneath the solar arrays compared to the control (Figure 3). In between the solar arrays, ambient canopy temperature was reduced by 4.1°C (10:15) and 3.4°C (16:00). The lower ambient temperature under solar arrays may be beneficial in the reduction of fruit surface temperature and consequently, the development of sunscald.

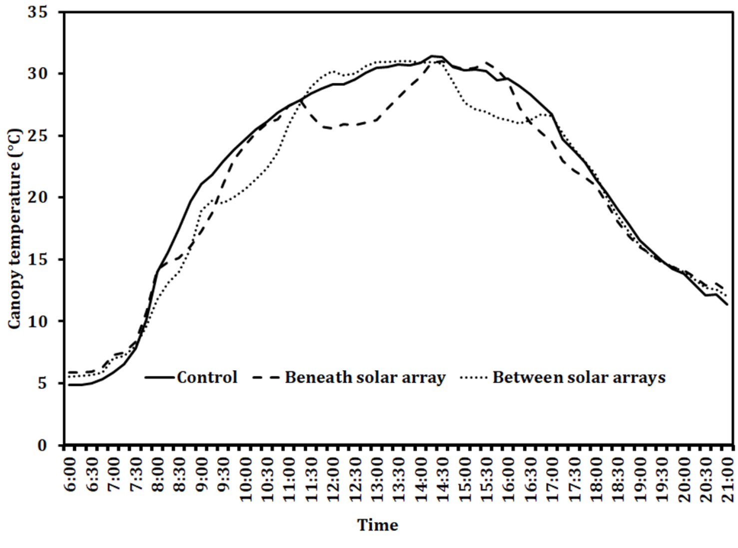

Figure 3. Diurnal change in ambient canopy temperature beneath and between solar array prototype compared to an uncovered control measured on a hot day (21 September 2019) in a Stevens' cranberry bog at Carver, Massachusetts, USA. Data was logged at 15 min intervals.

On a cold night, the temperature beneath solar array was warmer by 2.9°C (00:00) compared to the control (Figure 4). In between the solar arrays, the temperature was 1.3°C warmer. The increase in ambient temperature under the solar arrays could be due to arrays creating a 'greenhouse' effect by reducing convective heat loss and also preventing radiative cooling. The experiment did not collect data on wind speed which could have explained explain changes in airflow under the solar arrays.

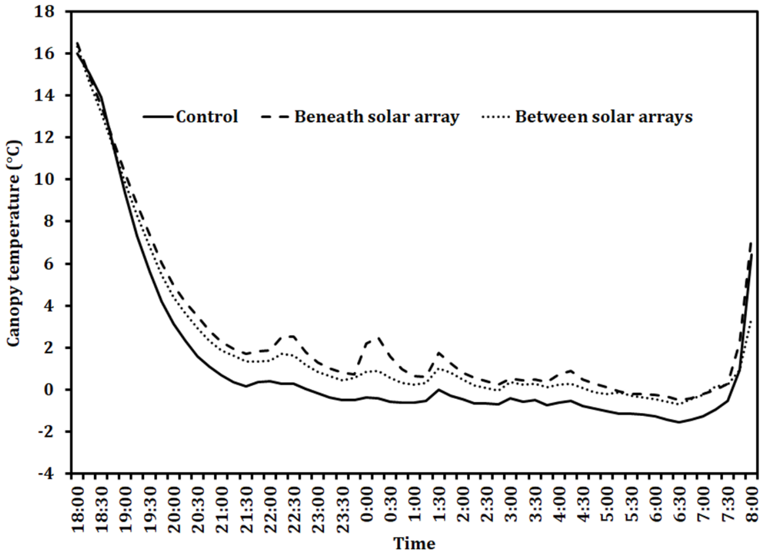

Figure 4. Nocturnal change in ambient canopy temperature beneath and between solar array prototype compared to an uncovered control measured on a cold night (19-20 September 2019) in Stevens' cranberry bog at Carver, Massachusetts, USA. Data was logged at 15 min intervals.

Leaf wetness was reduced under solar arrays and between solar arrays compared to the uncovered control (data not shown). The reduced leaf wetness can be explained the warmer ambient canopy temperature under the solar arrays. The reduction in leaf wetness has potential implications for diseases and infections that thrive under wet conditions. Also, the reduction in leaf wetness will lessen the possible risk of ice formation on a cold night which results in damages to flower buds. Cranberry bogs are traditionally placed in lowland areas such as swamps and marshes, cold air tends to drain from the adjacent high ground into the low areas on calm nights with no wind (Demoranville, 2008).

Volumetric soil moisture content was consistently higher beneath and between the solar arrays compared to the control (Figure 5). The observed differences in volumetric soil water content can possibly be explained by the reduced evapotranspiration due to shading from the solar arrays. The increase in soil moisture under an agrivoltaic system has also been previously reported by Hassanpour Adeh et al. (2018) and Barron-Gafford et al. (2019). Potential water savings under solar arrays may be important in future scenarios under global warming.

Net carbon assimilation between solar arrays was significantly reduced in the morning compared to control and beneath solar arrays (Figure 6). At solar noon, net carbon assimilation was significantly reduced beneath solar arrays pared to the control and between solar arrays. In the afternoon, net carbon assimilation was significantly reduced between solar arrays compared to control and beneath solar arrays. Results from our study show that net carbon assimilation is reduced at different times of day in a cranberry agrivoltaic system depending on the area being shaded. The values for net carbon assimilation obtained in our study were comparable to previous values for 'Stevens' cranberry (Jeranyama and Sack, 2017; Kumudini, 2004.) Also, as the shadow moves, net carbon assimilation is able to recover as shown between and beneath solar panels.

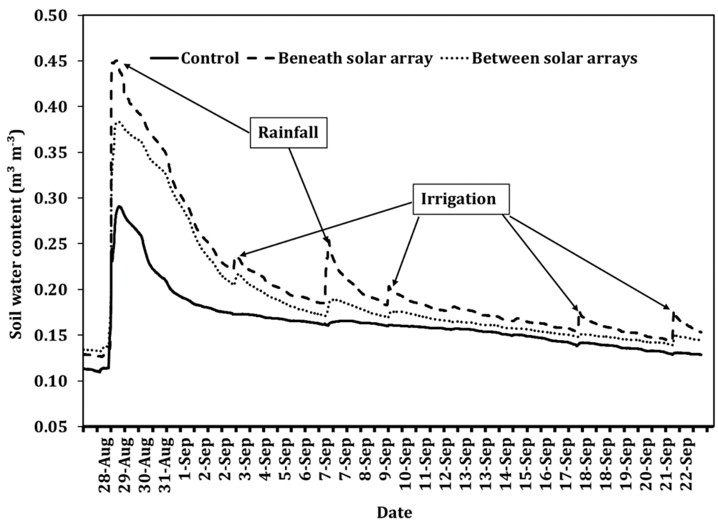

Figure 5. Volumetric soil water content beneath and between a prototype solar array compared to a control without solar arrays in 'Stevens' cranberry at Carver, Massachusetts, USA. Data was logged at 15 min intervals.

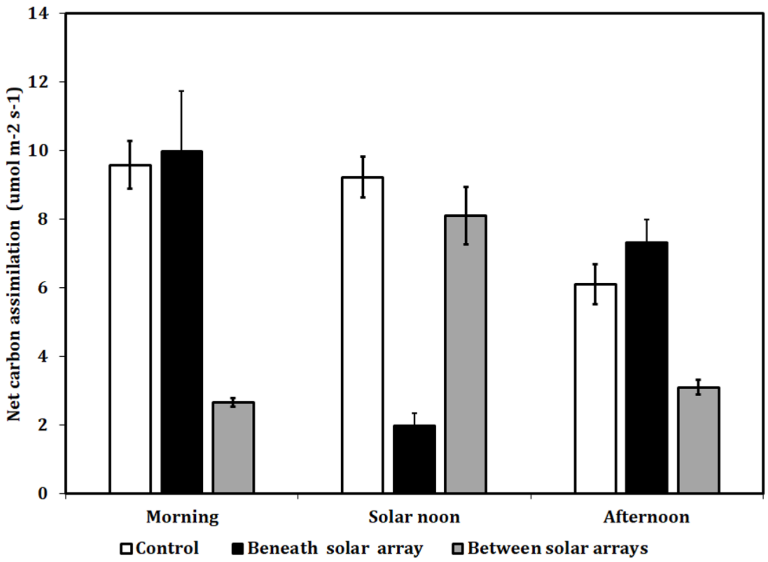

Figure 6. Differences in net carbon assimilation beneath and between a prototype solar array compared to a control without solar arrays in 'Stevens' cranberry at Carver, Massachusetts, USA. Spot measurements were done at morning (09:44), solar noon (12:40), and afternoon (15:30).

The installation of an agrivoltaic system significantly reduced yield, fruit firmness, fruit weight and total soluble solids (Table 1). Titratable acidity was significantly increased under an agrivoltaic system compared to the control. Fruit color was not affected by the installation of an agrivoltaic system.

The installation of an agrivoltaic system significantly increased the total nitrogen, phosphorous, potassium, calcium and magnesium (Table 2). The levels of zinc and copper detected in collected cranberry leaf tissue were significantly higher under the agrivoltaic system compared to the control, while manganese, iron and born levels were not affected (Table 3). The changes in macronutrients and micronutrients under an agrivoltaic system warrants further investigation and may necessitate modification of fertilizer applications under such system.

Table 1. Effect of a prototype agrivoltaic system on mean (n=15) yield, fruit firmness, fruit weight, total soluble solids, titratable acidity, and fruit color in 'Stevens' cranberry at commercial harvest.

Treatment	Yield (t ha^{-1})	Firmness (g mm^{-1})	Weight (g)	TSS (°Brix)	TA (%)	TAcy (mg 100 g^{-1})
Control	16.50	759.03	1.42	9.24	2.48	25.20
Agrivoltaic	9.56	710.67	1.29	8.74	2.71	25.33
P value	**	***	*	**	*	NS

Means for each parameter measured were separated by a two-sample t test (NS = not significant, *P≤0.05, **P≤0.001, ***P≤0.0001).

Table 2. Effect of a prototype agrivoltaic system on mean (n=10) concentration of macronutrients in 'Stevens' cranberry. Vines for tissue analysis were collected before commercial harvest in Massachusetts, USA.

Treatment	Total nitrogen (N) (% DW)	Phosphorus (P) (% DW)	Potassium (K) (% DW)	Calcium (Ca) (% DW)	Magnesium (Mg) (% DW)
Control	0.82	0.12	0.44	0.81	0.17
Agrivoltaic	0.95	0.14	0.47	0.94	0.18
P value	***	***	*	***	*
Optimum range	0.90-1.10	0.10-0.20	0.40-0.75	0.30-0.80	0.15-0.25

Means for each parameter measured were separated by a two-sample t test (NS = not significant, *P≤0.05, **P≤0.001, ***P≤0.0001). DW = dry weight.

Table 3. Effect of a prototype agrivoltaic system on mean (n=10) concentration of micronutrients in 'Stevens' cranberry. Vines for tissue analysis were collected before commercial harvest in Massachusetts, USA.

Treatment	Zinc (Zn) (ppm DW)	Copper (Cu) (ppm DW)	Manganese (Mn) (ppm DW)	Iron (Fe) (ppm DW)	Boron (B) (ppm DW)
Control	16.09	5.03	1063.45	72.80	29.29
Agrivoltaic	24.68	5.40	1045.58	67.00	31.31
P value	***	*	NS	NS	NS
Optimum range	15-30	4.0-10	10-500	>20	15-60

Means for each parameter measured were separated by a two-sample t test (NS = not significant, *P≤0.05, **P≤0.001, ***P≤0.0001). DW = Dry weight.

CONCLUSIONS

The installation of a prototype agrivoltaic system modified the microclimate on a cranberry bog. PAR was reduced under an agrivoltaic system with the highest shading occurring under the solar arrays compared to between solar arrays. Yield, fruit firmness and berry weight were also significantly reduced under the agrivoltaic system. The reduction in yield might be explained by the reduction on photosynthesis from shading and the damage during installation of the prototype agrivoltaic system. Cranberry plants form perennial trailing vines on the ground which can be easily damaged during installation. Yield results from additional consecutive years needs to be collected to assess the recovery of the canopy.

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