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RESEARCH ARTICLE

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Environmental Co-Benefits of Maintaining Native Vegetation With Solar Photovoltaic Infrastructure

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Key Points:

- Agrivoltaics can be an effective climate mitigation strategy along with providing location specific co-benefits
- Effect of vegetation-induced panel cooling on electricity generation are rather site-specific and depend on climate and soil properties
- Our findings provide foundational data for site preservation and for optimizing agrivoltaic designs by targeting site specific co-benefits

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Co-locating solar photovoltaics with vegetation could provide a sustainable solution to meeting growing food and energy demands. However, studies quantifying multiple co-benefits resulting from maintaining vegetation at utility-scale solar power plants are limited. We monitored the microclimate, soil moisture, panel temperature, electricity generation and soil properties at a utility-scale solar facility in a continental climate with different site management practices. The compounding effect of photovoltaic arrays and vegetation may homogenize soil moisture distribution and provide greater soil temperature buffer against extreme temperatures. The vegetated solar areas had significantly higher soil moisture, carbon, and other nutrients compared to bare solar areas. Agrivoltaics in agricultural areas with carbon debt can be an effective climate mitigation strategy along with revitalizing agricultural soils, generating income streams from fallow land, and providing pollinator habitats. However, the benefits of vegetation cooling effects on electricity generation are rather site-specific and depend on the background climate and soil properties. Overall, our findings provide foundational data for site preservation along with targeting site-specific co-benefits, and for developing climate resilient and resource conserving agrivoltaic systems.

1. Introduction

Solar photovoltaics (PV) is one of the fastest growing renewable technologies that is often preferred for its low emission, scalability, and ease of off-grid deployment in rural areas. In the US, solar technologies are expected to account for as much as 45% of the national electricity supply but occupy a maximum land area equivalent to 0.5% of the contiguous U.S. surface and only 10% of suitable disturbed lands (US Department of Energy Solar Energy Technologies Office, 2021). However, due to the suitability of farmlands for PV development (Adeh et al., 2019), competition for these lands may grow as more farmland is converted to PV development to meet the swelling electricity demand (Grout & Ifft, 2018). Extensive landscape modification by utility-scale PV such as vegetation removal, land grading, refilling topsoil, and compaction for the construction of conventional PV plants may have negative impacts on the ecological functions and may provide challenges for reintroducing native vegetation or crops during or after the 25–30 years lifetime of solar plants (Beatty et al., 2017; Choi et al., 2020; De Marco et al., 2014; Hernandez et al., 2014). Furthermore, agriculture and energy production coupled with climate change are impacting habitat loss around the world with implications for pollinators and biodiversity (Raven & Wagner, 2021). Many native species and pollinators will not be able to migrate in pace with the impacts of climate change (Warren et al., 2018), and habitat fragmentation and alteration from large conventional solar installations may put additional pressure on the biodiversity and insect-pollination activities (Rafferty, 2017).

Co-location of utility-scale PV installations with a complementary land-occupying activity such as restoration of native flora or cultivation of profitable crop, fodder, or biofuel is being evaluated as a strategy to minimize the negative consequences of PV deployment (Dupraz et al., 2011; Hernandez et al., 2019; Macknick et al., 2013; Pascaris et al., 2021; Ravi et al., 2014, 2016). PV—agriculture co-location (Agrivoltaics or Agrophotovoltaics) has the potential to abate the cost of solar power generation with agricultural income and may also provide several co-benefits, including increased PV cell efficiency from cooler microclimate induced by underlying vegetation, employment generation, rural electrification in remote areas, and renewable electricity sources for processing agricultural products locally (Adeh et al., 2018; Barron-Gafford et al., 2019; Choi et al., 2021; Marrou et al., 2013; Ravi et al., 2014, 2016; Weselek et al., 2019). In addition to creating different microhabitats, PV arrays may also delay and prolong growing season for plants (Graham et al., 2021), which may reduce the chance

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of phenological mismatch between the plants and the pollinator species (Graham et al., 2021) and increase crop yield and enhance the ability of some crops to expand beyond their current geographical and seasonal range limits (Adeh et al., 2018; Barron-Gafford et al., 2019; Walston et al., 2018). Evapotranspiration (ET) from co-located vegetation may reduce the temperature of the overlying PV system (Barron-Gafford et al., 2019) and increase the PV cell efficiency (Evans & Florschuetz, 1978). While decreased panel temperature has been observed in a small-scale desert setting (Barron-Gafford et al., 2019), it has not been linked to higher PV electricity production in a co-located utility-scale facility.

Several modeling and pilot-scale field experiments that explored the techno-economic and environmental feasibility of co-location approaches have indicated that co-located land uses have higher land use efficiency than the single-component land uses (Adeh et al., 2018; Barron-Gafford et al., 2019; Beatty et al., 2017; Dinesh & Pearce, 2016; Dupraz et al., 2011; Elamri et al., 2018; Majumdar & Pasqualetti, 2019; Marrou et al., 2013; Ravi et al., 2014, 2016; Trommsdorff et al., 2021). However, field-level investigations on the mutual interactions between PV and underlying soil-vegetation in the context of co-location of crops or native vegetation with utility-scale PV plants are limited (Armstrong et al., 2016; Beatty et al., 2017). No study exists yet to identify and quantify separate contributions of PV arrays and different site management choices at commercial utility-scale solar installations to the soil moisture, microclimate, and soil nutrient characteristics. The scarcity of studies on these topics presents a critical research gap, and the prospect of unforeseen environmental consequences may become a potential roadblock to the widespread implementation of optimally designed co-located systems and deployment of PV in natural or agricultural lands. To address this research gap, we use a combination of sensor data analysis and field and laboratory measurements to investigate the role of site-specific conditions on the environmental co-benefits and trade-offs between PV and underlying vegetation, in the context of designing resource conserving and climate resilient integrated solar energy and food/fodder systems.

2. Materials and Methods

2.1. Site Description

The study area was a 1.2 ha portion of a 9.5-MW PV plant (located at 45.451148, −92.907255) in Chisago City, Minnesota, USA, that started operating in October of 2016 (Enel Green Power North America (EGP-NA)) (Supporting Information S1). This region's climate is characterized as warm-summer humid continental (Köppen climate type Dfb). The panels were installed on a tracking system at a hub height of 2 m and the distance between the center of the arrays were 7.5 m. Prior to the construction of the PV facility, approximately 74% of the land area was agricultural, and 17% was temperate forest. The remaining portion of the land was categorized as developed/urban (approximately 6%), recently disturbed/modified (approximately 2%), flooded and swamp forest (approximately 1%), and boreal forest (<1%). To retain the lands' ability to cultivate crops after the decommissioning of the facility, land grading or any other construction techniques that would remove a significant portion of the topsoil was avoided during the construction of the facility. Native flora was planted in 2018 on the intact soil in a portion of the facility following the construction. To separate the effects of vegetation and PV panels, three treatments were established in the study area. The bare PV treatment was established in the PV arrays where the ground was maintained bare after construction, whereas the vegetated PV (veg PV) treatment was established within the same PV array in an adjacent location, but was revegetated with native flora. The control was established in an adjacent area without PV arrays that was revegetated with the same native flora as the veg PV treatment. The entire site was exposed to light sheep grazing for 2–3 weeks per year since 2019. The condition of the veg PV and the bare PV treatments are shown in Figures 1a and 1b. The list of plant species at the study site is included in Supporting Information S1.

2.2. Field Measurements

The meteorological stations were installed in September of 2018. The analyzed microclimate data were from the growing season of 2019 (May–August). The microclimatic variables, except solar radiation, were measured every 15 s and recorded every 15 min (Campbell Scientific, USA: CR6 Measurement and Control Datalogger).

The locations of soil moisture and temperature measurements (25-cm depth, Campbell Scientific, USA: CS655 Water Content Reflectometers) at each PV treatment were directly below the center of the PV panel ("BP" for "below panel"), below the western edge ("WE" for "western edge") of the panel, in the central location between

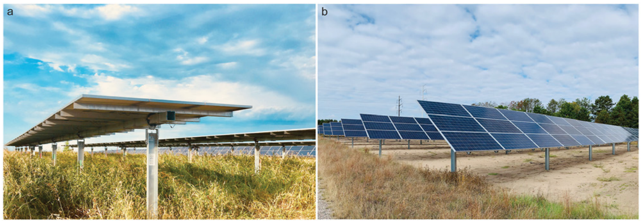

Figure 1. (a) Vegetated and (b) bare photovoltaics treatment in Chisago, MN.

two rows of PV panels ("IS" for "interspace"), and finally, below the eastern edge ("EE" for "eastern edge") of the adjacent row of panels (Figure 2a). Relative humidity and air temperature (Campbell Scientific, USA: EE181 Temperature and Relative humidity probe) were measured at 0.5 m from the ground at the IS of veg PV and bare PV treatment and also in the control. Relative humidity was sampled and recorded every 15 min. Wind speed (minimum, maximum, mean, and standard deviation) and direction (Campbell Scientific, USA: 03002 Wind Sensor) were measured at 1.5 m from the ground at the IS. PV module temperatures were measured using back-of-the-module temperature sensors (Campbell Scientific, USA: CS240).

Soil moisture and temperature at the control treatment were measured only at two locations that were placed 8 m away from each other along an east-west trending line. Relative humidity, air temperature, wind speed, and wind

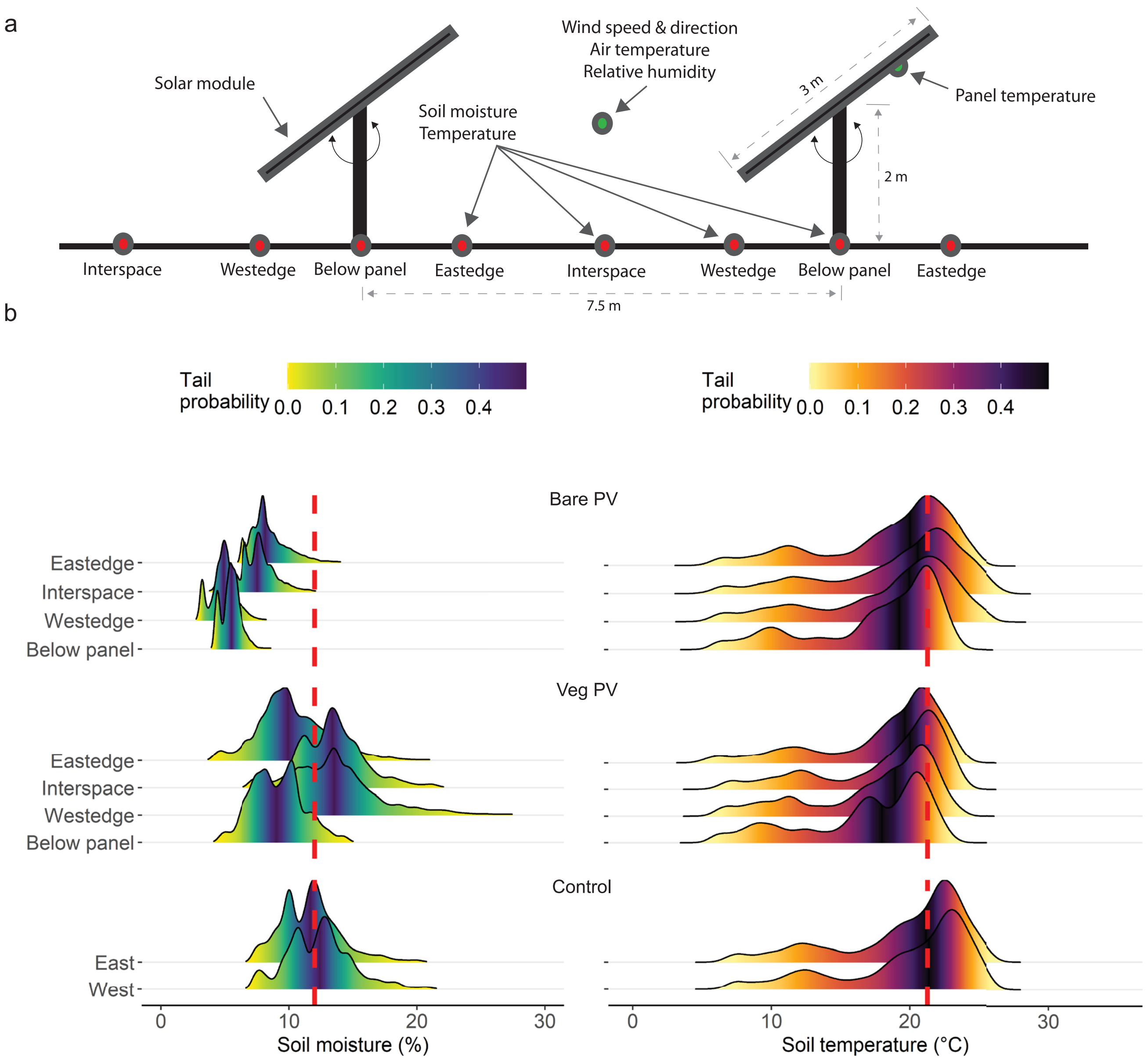

Figure 2. Soil moisture and temperature (a) Monitoring locations (b) Distribution of soil moisture (left) and soil temperature (right) at different relative positions over the experimental period (growing season). The dashed red line indicates the median value at the control.

direction were also measured the same way at the control treatment at the midpoint of the east-west line. Precipitation depth (Campbell Scientific, USA: TE525 Tipping Bucket Rain Gage) was recorded over 15-min intervals. Radiation intensity (Campbell Scientific, USA: CS320 Digital Thermopile Pyranometer) was sensed every 10 s and averaged over an hourly interval.

Soil samples (n = 100, top 5-cm) for nutrient and particle size analysis were taken from veg (n = 40), bare (n = 40) and control (n = 20) treatments. For the veg and bare PV treatments soil samples were taken from each of the four relative positions (n = 10 per position). Soil samples for bulk density measurements were taken using a standard 2-inch bulk density cup and cap sampler (AMS, USA).

2.3. Laboratory Methods

The air-dried soil samples were sieved using a 2-mm sieve and split into sub-samples using a riffle sampler (Humboldt Mfg. Co. Il, USA). The dry particle size distribution of the soil samples were determined using a laser diffraction particle sizing analyzer (LS 13320 with tornado dry powder system, Beckman Coulter, Inc. CA, USA) with a grain diameter measurement range of 0.4–2,000 μm. Total soil carbon (TC) and total soil nitrogen (TN) were determined with a standard combustion method (McGeehan & Naylor, 1988; Nelson & Sommers, 1996). Other analysis includes pH, Organic Matter, estimated Nitrogen release, Bray I Phosphorus, Exchange Capacity, % base saturation of Cation, Available Nitrogen, and Mehlich III Extractable Phosphorous, Manganese, Zinc, Boron, Iron, Sulfur, Calcium, Magnesium, Potassium and Sodium (Brookside Laboratories, INC. New Bremen, USA).

2.4. Statistical Analysis

Analysis of variance (ANOVA) and Tukey post hoc test (at $\alpha = 0.05$) were performed for mean TC, TN, grain sizes, and sorting to detect any significant differences among the bare PV treatment, the veg PV treatment, and the control. Kolmogorov–Smirnov (KS) tests (at $\alpha = 0.05$) were applied to compare distributions of soil moisture, air temperature, air humidity and wind speed from the bare PV treatment, the veg PV treatment, and the control. Both statistical tests were performed with R ver. 4.0.4 (R Core Team, 2021). The results of the KS tests are in Text S5 in Supporting Information S1.

2.5. Electricity Production Data

Electricity production data at the PV facility was provided by EGP-NA. The bare PV treatment and the veg PV treatment were connected to inverters that contained 1,044 modules (328.9 kW_p). Production data were recorded every 15 min.

3. Results

3.1. Soil Moisture and Temperature

The compounding effect of PV arrays and vegetation can homogenize soil moisture distribution and provide greater soil temperature buffer against extreme temperatures at vegetated solar sites. The treatment with the traditional management (bare PV) consistently had the lowest average volumetric soil moisture content (25 cm depth), while the treatment with native vegetation (veg PV) and the adjacent undisturbed area (control) had similar average moisture content (Figures 2a and 2b). The PV treatments showed heterogeneity in soil moisture distribution among their relative locations with respect to panel position. All locations corresponding to panel edges except for the WE in bare PV had higher soil moisture compared to BP (Figure 2b). Among the three treatments, the control had the highest median soil temperature, and the maximum soil temperature of the two positions of the control were higher than that of all the relative positions in the two PV treatments except the EE, the WE, and the IS in the bare PV treatment (Figure 2b). While the median temperatures of the PV treatments were not significantly different, the bare PV treatment had a wider range of soil temperatures than did the veg PV treatment. The below panel had the lowest median soil temperature at the bare PV and veg PV treatments.

3.2. Microclimate: Wind Speed, Air Temperature and Relative Humidity

The air temperature, relative humidity and vapor pressure deficits were not significantly different between the treatments (Figures 3a and 3b; Text S2 in Supporting Information S1). The vegetated solar site showed slower and more homogenous wind speeds over all directions compared to those in the bare solar site (Figure 3c). The

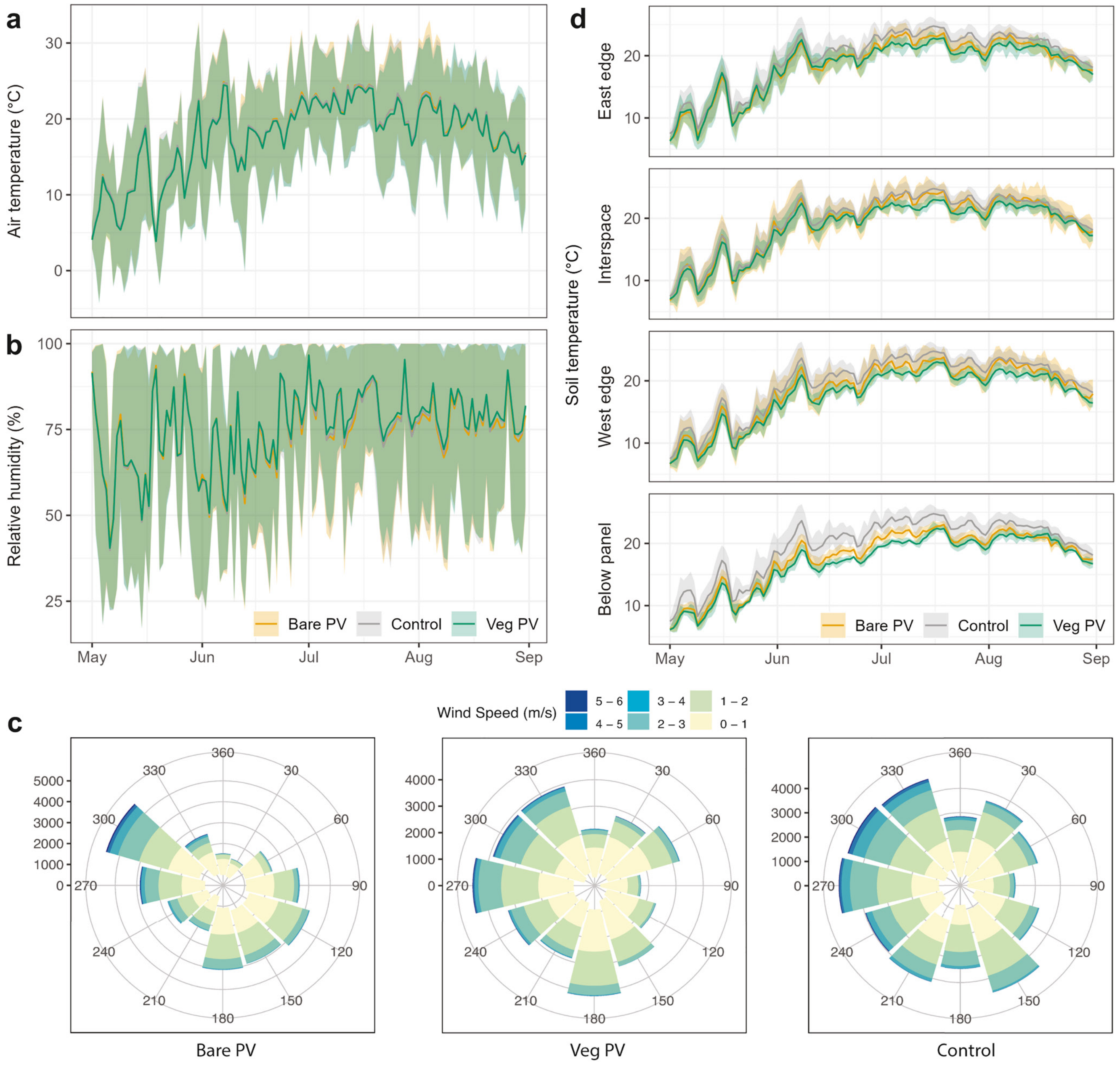

Figure 3. Microclimate: (a) Air temperature (mean, maximum and minimum) (b) relative humidity (mean, maximum and minimum), (c) Rose diagram showing distribution of wind directions and speeds over the growing season. Each concentric circle represents number of events and the length of each spoke around the circle indicates the amount of time that the wind blows from a particular direction with that speed range (colors), and (d) soil temperature (mean, maximum and minimum) for the three treatments.

distribution of mean, maximum, and minimum wind speeds were significantly different among the treatments ($p < 0.05$). Compared to those in the control, the wind speed was lower in all directions in the vegetated solar site (Figure 3c). The veg PV treatment had the narrowest diurnal variations in soil temperatures (Figure 3d).

3.3. Soil Properties: Carbon, Nitrogen, and Grain Size Distribution

The bare PV treatment had significantly ($p < 0.05$) lower total soil carbon (TC) and total soil nitrogen (TN) levels than the control and the veg PV treatment (Figure 4a). However, the TC and the TN levels were not significantly ($p > 0.05$) different between the veg PV and the control. Also, TC and TN levels were not significantly ($p > 0.05$)

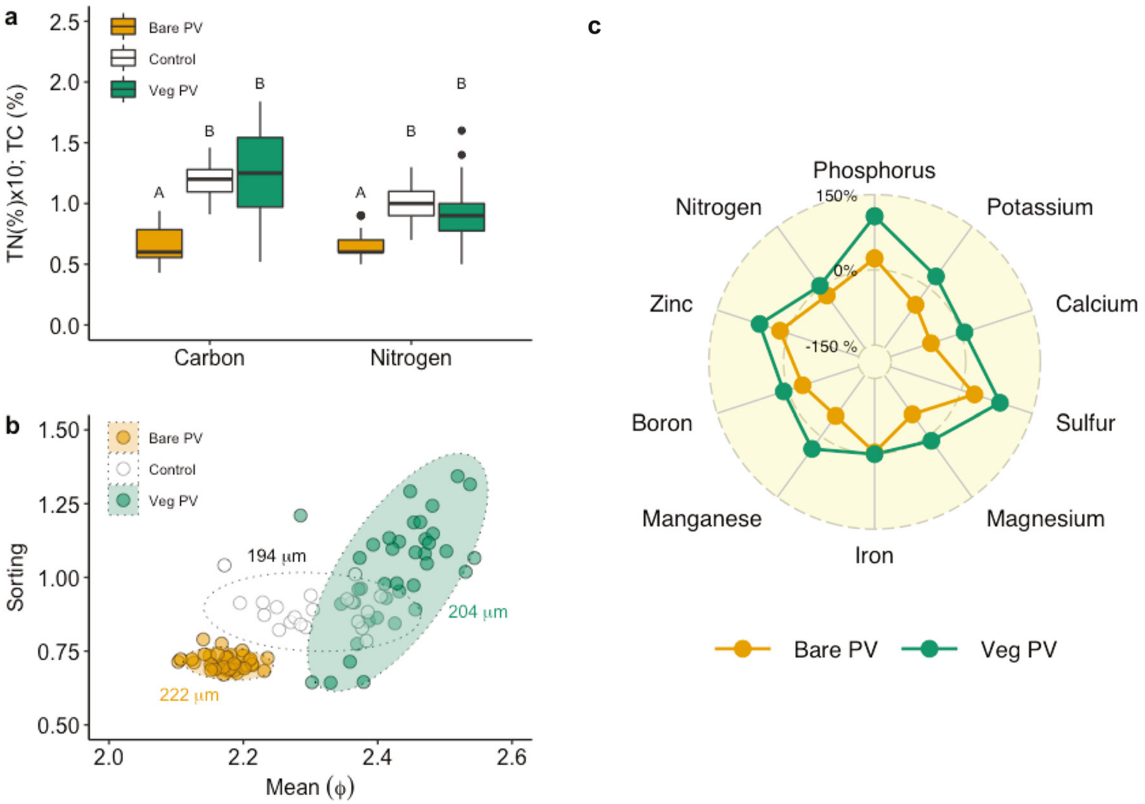

Figure 4. Soil properties: (a) Total carbon and total nitrogen in soil at the three treatments. The horizontal bar represents the median, and the lower and the upper box boundaries represent the 25th and the 75th percentiles. The whiskers represent the 5th and the 95th percentiles. Treatment categories share letters if pairwise comparisons did not identify significant differences between means; (b) Sorting and mean of soil particle size ($\phi = -\log_2 d$, where d is grain diameter in mm) at different sites. The median grain size is shown; and (c) Percentage increase (+) or decrease (−) in major soil macro and micronutrients (Phosphorus, Potassium, Calcium, Sulfur, Magnesium, Iron, Manganese, Boron, Zinc, and Available Nitrogen) important for plant growth in the vegetated and bare photovoltaics treatments relative to undisturbed control (0%).

different between the relative locations both in the vegetated and bare sites. The median soil grain sizes at the bare site were significantly ($p < 0.05$) larger than those at the veg PV treatment and the control. The veg PV treatment had the largest variation in grain sizes (φ size-scale $= -\log_2$ (diameter in mm)) and sorting (Figure 4b). Other macronutrients important for plant growth were significantly higher in the vegetated treatment than in the bare PV treatment compared to the control (Figure 4c). Mean bulk densities of the soil in the bare PV treatment, the veg PV treatment, and the control were 1.48, 1.27, and 1.39 g cm^{-3} respectively.

3.4. Electricity Generation

During the growing season (May–August), the PV arrays in the bare PV treatment produced 198.4 MWh, and the ones in the vegetated PV treatment produced 193.1 MWh, which was equal to 2.7% less electricity generated in the veg PV treatment. The times when the bare PV treatment produced more power than the veg PV treatment were between 6–10 and 15–18 during the study period, which accounted for 99.3% of the production discrepancy (5.3 MWh) between the two treatments (Figure 5a). Panel temperature was higher in the bare PV treatment than in the veg PV treatment during the hours 5–9, 14, and 20, which roughly coincide with the times at which the bare PV treatment produced more power than the veg PV treatment.

4. Discussion

Our results show that the construction and maintenance of PV arrays can alter soil moisture, microclimate, and soil physicochemical properties. Maintaining natural vegetation on solar sites may mitigate the negative environmental impacts of PV installation and operation on soil conditions and vegetation diversity; such mitigation

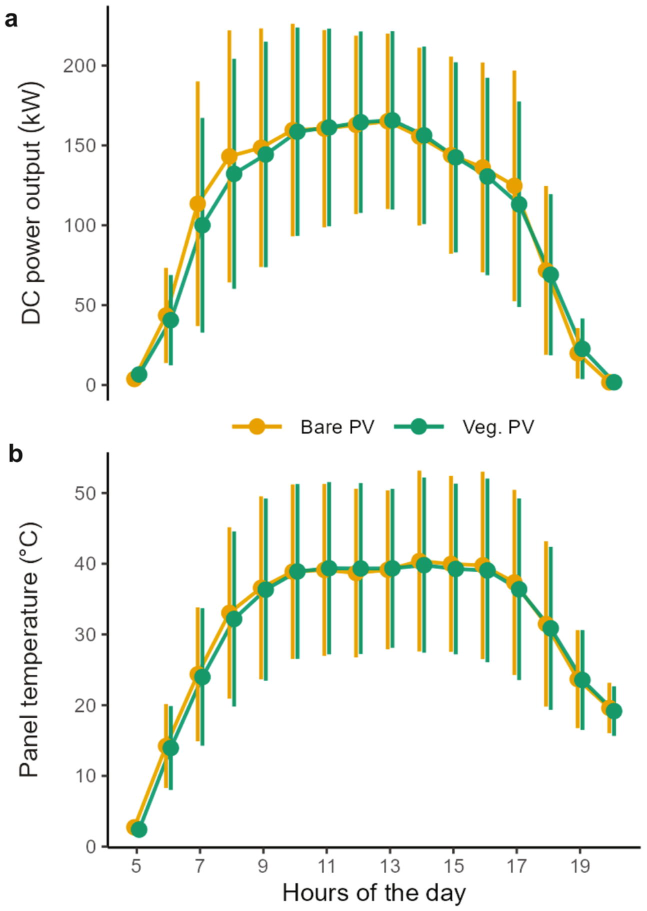

Figure 5. Electricity generation: (a) Average hourly DC power output (kW) and (b) panel temperature (°C). Error bars represent standard deviations, the line and point colors represent treatments, and the blue numbers represent the sample size for each hour. The points that belong to the two treatments are horizontally offset for visibility even though the data from the two treatments are recorded simultaneously.

may also benefit pollinators that comprise an integral part of the landscape. Interestingly, our results demonstrate that the positive impact of ET-induced cooling by vegetation on electricity generation may not be applicable in all climatic zones or for all vegetation types. Overall, our study provides foundational data on the potential to improve multiple ecosystem services by maintaining native vegetation at PV sites.

4.1. Implications for Site Preservation

The elevated soil moisture in the veg PV treatment and the control may be a combination of several mechanisms that link vegetation cover with higher soil moisture. First, solar panels intercepted and redistributed precipitation and generated spatial variability of soil moisture (Figure 2b). Positive feedbacks exist between vegetation and soil moisture, leading to transport of water to vegetated areas (Cramer et al., 2017), mostly through soil-water diffusion toward the root zone. Thus underlying vegetation can homogenize or mitigate the soil moisture variability through root uptake of water for transpiration, which can compensate for spatial variability in soil moisture by extracting water from wet regions at a high rate (Breazeale, 1930; Guswa, 2012; Ivanov et al., 2010; Katul et al., 1997). Also, the lower soil moisture levels in the bare PV treatment may be explained by higher soil temperature and less shading that would result in higher evaporation rate from bare soils compared to the vegetated surface in the veg PV treatment and the control (B. Li et al., 2016). Furthermore, vegetated soils may retain more water than bare soil because rooted soils have higher suction than do bare soils (Leung et al., 2015). The homogenizing effect of plant uptake on soil moisture can enhance transpiration and ecosystem productivity. These effects are especially significant in water-limited environments (Katul et al., 1997), which presents motivation for similar research on co-located systems in arid climates.

The lower median and maximum soil temperatures and the reduced soil temperature ranges in the PV treatments compared to the control during the growing season are attributed to the interception of incoming shortwave and longwave radiation by the PV panels (Adeh et al., 2018; Armstrong et al., 2014, 2016). Additionally, our comparison between the two PV treatments is in line with previous findings that vegetation can further reduce the median and maximum soil temperature and narrow the range of soil temperature fluctuations (Oliver et al., 1987). Our data shows that compound effect of PV arrays and vegetation may produce even greater temperature buffer against the extreme temperatures than would a native grassland, which may benefit various species of crops whose growth and quality are negatively impacted by thermal stress (Aldous & Kaufmann, 1979; Al-Khatib & Paulsen, 1999; Rivero et al., 2001).

The lower sorting index and the high mean Phi ($\phi = -\log_2 d$, where d is grain diameter in mm) values in the bare PV soil samples imply that the lower TC and TN contents in the soil samples in those soils are likely caused by the preferential loss of fine soil particles that act as substrates for TC and TN from the bare PV treatment in the absence of vegetation (Bashagaluke et al., 2018; J. Li et al., 2008; Quinton et al., 2010; Sharpley, 1985; Wang et al., 2011; Zhang et al., 2004; Zougmoré et al., 2009). The faster speeds and homogenized wind directions, as observed in the bare PV, have been linked to increased soil erosion in some systems (Dupont et al., 2014). Assuming a soil bulk density of 1.3 g cm^{-3}, the deficit of 0.6% in TC and 0.03% in TN observed in the bare PV are equivalent to a deficit of 3.9 Mg ha^{-1} of TC and 0.2 Mg ha^{-1} of TN in the top 5-cm of the soil, after the construction of the PV facility in 2016. Over the lifetime of the PV facility with bare soil cover, which may be 20–30 years, continued loss of fines in the bare soil may lead to even greater deficit of TC and TN and degrade the soil's ability to retain any added nutrients. Our analysis makes a strong case for vegetating PV sites for site preservation. Land appropriation for intensive farming practices have resulted in substantial loss of carbon from agricultural and grassland soils globally (Sanderman et al., 2017). Improving carbon sequestration in agricultural areas with carbon debt using innovative site management practices such as co-location of PV and perennial native vegetation (often with managed grazing) as in our study sites can be effective climate mitigation strategies along with revitalizing agricultural soils, generating income streams from fallow land, and providing pollinator habitats.

4.2. Implications for Developing Agrivoltaic Systems

Possibly favorable microclimatic conditions for the growth of vegetation created by the PV arrays, and the evidence for the erosional buffer created by the presence of vegetation imply that co-locating vegetation with PV arrays can be beneficial for PV projects in some climatic zones where conservation of the soil and their potential for biological production is a concern. However, in our study the panel temperature data and the electricity production data from the growing season imply that the co-located vegetation may not always positively impact the performance of the PV arrays in a humid, continental climate. Therefore, the microclimatic interaction between PV arrays, soil, and vegetation is not consistent across varying landscapes and climates. Consequently, the considerations for co-locating vegetation with PV arrays in any climate should include a site-specific assessment of the tradeoffs between resultant microclimatic determinants stemming from the presence of vegetation.

In our study, since both power production and panel temperature were slightly higher in the bare PV treatment than in the veg PV treatment in the early morning and in the late afternoon (Figures 5a and 5b), the panels in the bare PV treatment may have received more solar radiation than those in the veg PV treatment during these times. Had the PV arrays in the two treatments received the same amount of solar radiation, the higher panel temperatures in the bare PV treatment should have coincided with lower power output due to higher cell efficiency (Evans & Florschuetz, 1978), which is not the case. Therefore, it is more likely that the panel temperature in the bare PV treatment was higher because it simply received more solar radiation than did the veg PV treatment. This power output discrepancy may have largely contributed to the veg PV treatment's electricity production deficit over the observation period. A likely explanation for the veg PV treatment's potential solar radiation deficit is shading due to tall vegetation: since the PV arrays were mounted 2 m above ground and were 3 m along their east-west axis, 1-m-tall plants may have shaded as much as the bottom 0.3 m of the arrays when they were at a 45°-tilt in the beginning and at the end of the day. The obstruction from the co-located vegetation can be avoided by choosing plant species that do not grow tall enough to shade the panels, increasing the height on the mounting system, or mowing, though less preferred (Macknick et al., 2022). Another approach is to open the facility for sheep grazing, which can increase the soil nutrient content and generate extra revenue without modification of the array mounting system (Macknick et al., 2022; Towner et al., 2021).

Contrary to a previous study that observed lower panel temperatures in arrays with co-located vegetation (Barron-Gafford et al., 2019), distribution of panel temperatures between the bare PV and the veg PV treatments did not differ over the entire daylight hour or during the hours 10–15 ($p < 0.05$) (Text S3 in Supporting Information S1), and the distribution of power production in these time windows were also not significantly different between the treatments ($p < 0.05$). While the inverter data cannot conclusively disprove the previously hypothesized benefit of vegetation cover on the PV systems (Barron-Gafford et al., 2019), our analysis of the inverter data suggests that the impact of the vegetation-driven conductive cooling of the PV panels in some temperate climates may not be large enough to overcome the opposing effects, such as slower winds due to increased surface roughness. Furthermore, higher relative humidity in the study area when compared to arid regions (Barron-Gafford et al., 2019) could have decreased the power output of the PV cells by increasing the water vapor and condensed water droplets on the cell surface that scatter solar radiation (Kazem & Chaichan, 2015), which may have negated the elevated cell efficiency from lower panel temperatures.

Another explanation for the lack of significant difference in the panel temperature between the two treatments may be a comparison of ET rates between the two PV treatments. Crop evapotranspiration ET_c can be estimated as per the following equation: $\mathrm{ET}_c = \mathrm{ET}_{\mathrm{ref}} \times K_c$, where $\mathrm{ET}_{\mathrm{ref}}$ is reference ET, and K_c is crop coefficient (Allen, Pruitt, et al., 2005). This model of ET divides the ET process into energy-limited (or atmosphere controlled) Stage 1 and water-limited (soil controlled) Stage 2. For the study sites where the average rainfall interval during the growing season is between 1 and 2 days and soil surface is consistently wet, K_c for the bare PV treatment can be higher than or comparable to that of a vegetated surface (Figure 6a), and the resulting evaporation may exceed or equal the ET rate in the vegetated PV treatment. The soil surface is consistently kept moist by frequent rainfall events, thereby maintaining evaporation at or near the rate of free-water evaporation. Therefore, in a

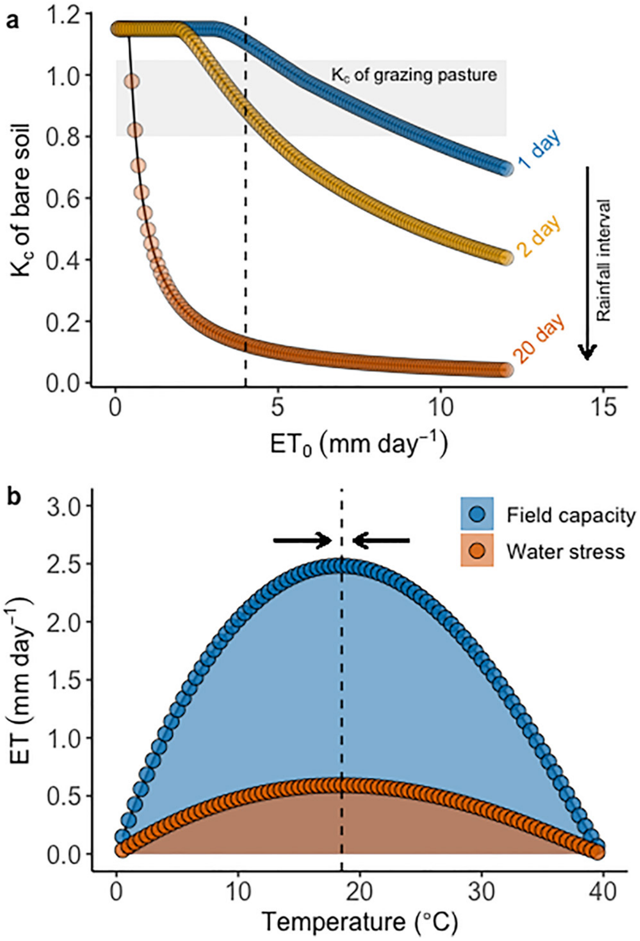

Figure 6. Evapotranspiration (ET)-driven panel cooling effects are site specific: (a) Crop coefficient (K_c) of bare soil as a function of reference ET depth and rainfall intervals. The shaded area represents the typical range of K_c for grazing pastures, and the vertical dotted line represents an example daily value of growing season reference ET in the study region (modified from Allen, Pruitt, et al. (2005) and Allen, Walter, et al. (2005)); (b) Evapotranspiration as a function of air temperature at high soil moisture (field capacity) and water stress conditions (Penman–Monteith equation combined with Stewart (1988) model of leaf conductance to include environmental controls on canopy resistance). The vertical dotted line represents the optimal air temperature for ET.

temperate climate with a wet growing season, the magnitude of ET-driven diversion of net radiation into latent heat in a PV site with a bare soil may be comparable to that of a PV site with underlying vegetation, resulting in slightly higher but still comparable temperatures in the non-vegetated PV. In water-limited environments with long duration between rainfall events, K_c of the bare soil will be significantly lower than that of a vegetated surface (Figure 6a), and the difference in panel temperature will likely be significantly larger in the opposite direction. Vegetation can maintain much higher transpiration rates by utilizing root zone soil moisture even after soil evaporation is drastically reduced (Stage 2) as the surface soil dries out. Even though ET-driven panel cooling was negligible during the study period, crop coefficient during Stages 1 and 2 for the veg PV treatment at this site may increase in the future growing seasons as the vegetation becomes more established (increase in leaf area index), which may result in a cooling effect large enough to create a discernible increase in the productivity of the overlying PV arrays. This possibility prompts the need for a multi-year study with a similar experimental design.

Recent pilot-scale studies have demonstrated the effect of vegetation on PV panel cooling, however the actual benefits to electricity generation and irrigation requirements need to be investigated. To determine whether co-location is worth the cost of irrigation and soil quality improvements in arid regions, one should consider its benefits to the vegetation (shading, water use efficiency) and the extent of improvement in electricity generation. To demonstrate the effects of water limitations and temperature on crop ET, we used the Stewart model (Stewart, 1988) of leaf conductance and the Penman–Monteith model (Dingman, 2015) to compare the transpiration rate from the canopy for soil-moisture deficits. Even though the leaf conductance nonlinear functions for environmental controls on canopy conductance (incident short-wave radiation, specific humidity deficit, air temperature and soil moisture deficit) used in this example are not specifically for grassland species, it is instructive to visualize the significance of water limitations and temperature on ET (Figure 6b). The detailed description and inputs of the model are provided in the Text S4 in Supporting Information S1. In arid and semiarid systems, maintaining higher vegetation ET may result in panel cooling and potential increase in electricity generation. However, bringing the soil to field capacity to maximize the ET in such an arid climate will require additional irrigation (Figure 6b), which also comes at a cost in water-limited systems. Further, water for cleaning panels and for dust suppression can be a significant component of the water budget of solar facilities in desert regions (Ravi et al., 2014), and it may place a major demand on the already scarce local water resources.

The fact that the soil temperatures were lower in the veg PV and the bare PV treatments than they were in the control site during the growing season (Figure 2b) implies that the shading from the PV arrays may cool the underlying soil-vegetation. Since photosynthesis declines at temperatures exceeding 30°C for C_3 plants and 35°C for C_4 plants and stops increasing at solar radiation exceeding certain threshold, partial shading by the PV panels may benefit the vegetation. It is well understood that partial shading can increase yield, nutritional quality, and/or survival rate of some crops, such as lettuce, tomatoes (Wolff & Coltman, 1990a, 1990b), cherry tomatoes (Rosales et al., 2011), while this is untrue for other crops, such as broccoli (Kläring et al., 2001), or peanuts (Wolff & Coltman, 1990b). The variability in shade response across different types of plants imply that the selection of suitable vegetation or crop for co-location as per the background condition is essential for the viability of co-location. As with the panel-cooling effect, the shading from the PV panels may be more beneficial for vegetation in arid and semi-arid regions with high air temperature and abundant solar radiation, and utility-scale PV facilities may even be used to expand areas with temperature range and radiation intensity that are ideal for certain crops. Further, shading by panels can decrease ET and thereby increase irrigation water use efficiency. In our study the vegetated solar sites had lower diurnal variations in soil temperatures even though the vapor pressure deficits were not significantly different between the treatments. On the other hand, the partial shading from the PV arrays may decrease crop yields in temperate regions which have considerably less net radiation than arid regions, and the only way to increase plant-available solar radiation in these areas may be to increase the spacing between the PV arrays or the PV panels. However, lower PV density will result in lower energy production and a reduced ground-cover ratio, which can affect economic viability as profit margins for PV are currently higher than most agricultural crops. Therefore, our findings show that agrivoltaics in temperate regions may be suited for maintaining the multiple ecological functions of the soil with native vegetation or providing supplemental income with cultivation of shade-tolerant crops or pastoral activities.

5. Conclusions

Agrivoltaics in areas with soil carbon debt can be an effective climate mitigation strategy along with revitalizing agricultural soils, generating income streams from fallow land, and providing pollinator habitats. The compounding effect of PV arrays and underlying vegetation may homogenize soil moisture distribution and provide greater soil temperature buffer against extreme temperatures. The effect of vegetation-induced panel cooling on electricity generation are rather site-specific and can be predicted using background climatic parameters and soil properties. We expect the temperature buffering and panel cooling effects to be greatly amplified in arid and semi-arid regions and may provide opportunities to expand agriculture to marginal lands, but with additional investments for irrigation and improving soil quality. Our findings provide foundational data for site preservation and for optimizing agrivoltaic designs by targeting site specific co-benefits and highlight the need to target site specific ecosystem services.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data used in our work can be found online (https://figshare.com/s/05ad6d8ea5449979a67e).

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