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Multi-year analysis of physical interactions between solar PV arrays and underlying soil-plant complex in vegetated utility-scale systems

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HIGHLIGHTS

- Vegetation-driven PV panel cooling was not observed in the humid temperate climate.
- PV arrays and vegetation may have compounding positive impact on preservation of the soil quality.
- Microclimatic modifications and soil quality improvements in co-located systems are site-specific.

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ABSTRACT

Concerns over the land use changes impacts of solar photovoltaic (PV) development are increasing as PV energy development expands. Co-locating utility-scale solar energy with vegetation may maintain or rehabilitate the land's ability to provide ecosystem services. Previous studies have shown that vegetation under and around the panels may improve the performance of the co-located PV and that PV may create a favorable environment for the growth of vegetation. While there have been some pilot-scale experiments, the existence and magnitude of these benefits of vegetation has not been confirmed in a utility-scale PV facility over multiple years. In this study we use power output data coupled with microclimatic measurements in temperate climates to assess these potential benefits. This study combines multi-year microclimatic measurements to analyze the physical interactions between PV arrays and the underlying soil-vegetation system in three utility-scale PV facilities in Minnesota, USA. No significant cooling of PV panels or increased power production was observed in PV arrays with underlying vegetation. Fine soil particle fraction was the highest in soils within PV arrays with the vegetation which was attributable to the lowest wind speeds from the compounding suppression of wind by vegetation and PV arrays. Soil moisture and soil nutrient response to re-vegetation varied between PV facilities, which could be attributed to differing soil texture. No statistically significant vegetation-driven panel cooling was observed in this climate. This finding prompts a need for site-specific studies to identify contributing factors for environmental co-benefits in co-located systems.

1. Introduction

Installed capacity of solar photovoltaics (PV) has been rapidly growing due to decreasing costs, increasing policy support, and the burgeoning demand for energy with low carbon emissions: In the US alone, the annual additions to the capacity of utility-scale solar energy (USSE) have increased from lower than 1 GW year^{-1} to >20 GW year^{-1} over the past decade [1–4]. Similarly, increasing numbers of farmers are investing in on-farm PV systems to power their farming operations or alternatively, leasing out their lands for USSE development to provide a reliable revenue stream independent from the volatility of agricultural markets [5–8]. While PV has low greenhouse gas (GHG) emission rates and may be sited on degraded lands [9], USSE construction and operation on an ecologically or agriculturally important land can affect ecological functions and agricultural productivity in multiple ways.

First, conventional construction practices of USSE modifies the landscape, which can include vegetation removal, soil removal, grading, and compaction of soil from the use of heavy machinery [10]. Removal of soil and vegetation decreases gross primary productivity and carbon sequestration capacities [10–13]. Decreased carbon sequestration and

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soil organic carbon stock may result in reduced aggregate stability of the soil, which may accelerate erosion and further loss of soil nutrients [14]. Soil compaction has been shown to limit rooting depth and root density in experiments that compacted soils to varying degrees by driving tractors over them [15]. In some construction practices, topsoil is moved into a stockpile and then redistributed so the underlying earth material can be graded without damaging the topsoil, but even this practice can cause reductions in organic carbon, nitrogen, and soil aggregate stability [16]. Second, maintenance of un-vegetated USSE plants can further degrade ecosystem services: Cook & McCuen (2013) has concluded that the operation and maintenance of solar facilities on a bare or gravel ground cover may increase peak stormwater discharge and soil erosion rates at the base of the PV panels by concentrating the intercepted rainwater into a flow with a higher kinetic energy [17], which was corroborated by a field study [13]. Soil erosion, especially of fine particles, may cause long-term damage to the soil's ability to retain life-supporting nutrients [18,19]. Additionally, Lovich and Ennen (2011) has suggested that the operation and maintenance of the PV facilities may cause habitat fragmentation and obstruct gene flow [20]. In short, the modification of the landscape from the construction of PV sites and the operation of un-vegetated USSE facilities can compromise the ecosystem services of the land. These potential environmental impacts may be a cause for concern for landowners who wish to use the land for farming or conservation efforts following the lease to solar developers. These concerns can be addressed by investigating the influence of PV arrays on the surrounding environment and the underlying soil, then using the findings to develop or refine mitigation strategies.

One strategy to reduce the land-use impacts of USSE is co-location of PV with beneficial vegetation, which was first proposed in 1982 as a technique for modifying the PV operation to grow crops from PV-occupied lands [21]. Studies have shown that a co-located system with proper crop selection for partial shading has potential to increase the land equivalent ratio compared to cropland or a ground-mounted PV system of equivalent land area [22,23] as well as create microclimatic zones with favorable temperatures that can extend the growing season for some crops [24–27]. Co-location practices that focus on restoring or maintaining native plants instead of crop production are sometimes referred to as "ecovoltaics", and they have the potential to improve the lands' ability to provide ecosystem services such as carbon sequestration and pollination, which may even benefit neighboring farmlands [28–31]. Furthermore, experiments in PV facilities co-located with native plants have shown only minimal reduction in aboveground net primary production and evapotranspiration underneath the panels despite significantly reduced light, implying that re-established plants may sufficiently grow even in the dynamic shading environment within PV arrays [30–32]. However, impact of PV construction may have lasting impacts on the soil: a study on the soils in an agrivoltaic site in Colorado, USA saw that fine fraction of the soil particles and total soil carbon (TC) and nitrogen (TN) contents in a conventionally constructed PV facility had not recovered to the reference levels after a decade even with sufficient vegetation cover in the array [13]. In contrast, another study in Minnesota, USA showed PV arrays with minimized land modification and reestablished native vegetation experienced reduced erosion of the fine soil particle fraction and retained total soil carbon and nitrogen to the reference levels in nearby undisturbed soil, while PV arrays with bare soil underwent loss in fine particle fraction, TC, TN, and various soil cations [33]. The relative abundance of these variables in the vegetated array may have been due to the avoidance of land modification as well as re-vegetation. Therefore, the extent of mitigated soil alteration due to avoided land grading needs investigation.

Studying the influence of PV arrays on the soil-vegetation component of co-located PV systems also provides opportunities to investigate the influence of vegetation on PV performance, the studies of which are relatively scarce. Barron-Gafford et al. (2019) observed lower panel temperatures and diurnal panel temperature fluctuations in agrivoltaic arrays compared to those in an adjacent PV array at a test site and concluded that the added evapotranspiration by the co-located vegetation increases the portion of incoming solar radiation that is converted to latent heat, thereby decreasing the sensible heat flux to the PV panels for an irrigated system in an arid region [26]. The findings of this study provide motivation for similar research in USSE installations, which currently represents the majority of ground-mounted PV installations [34]. Furthermore, vegetation-driven panel-cooling has not been observed in environments other than drylands, and the resulting increase in efficiency is yet to be confirmed by electricity production data from other climates. To address this gap, this study links multi-year microclimate and power production data in three USSE facilities in Minnesota, USA. Additionally, this study combines soil chemistry and particle size analyses of the soil samples from the PV facilities with the microclimate data to study the physicochemical impact of the PV arrays on the underlying soil-vegetation complex and its potential to conserve or improve the native productivity of the soils after the construction of PV arrays.

2. Methods

2.1. Description of the study sites and field data collection

Meteorological and soil data and samples were collected in three utility-scale solar PV facilities owned and operated by Enel Green Power North America (EGP-NA) located in Minnesota, USA (Fig. S1b). Details of the three facilities (Atwater, Chisago, and Eastwood) are listed in Table S1 in supporting information. Each facility contained three treatments: PV arrays on soil that was re-vegetated with native grasses, referred in this study as "vegetated PV" (veg PV), PV arrays with bare ground cover, or bare PV, and an adjacent undisturbed open-sky area with similar native grasses and forbs as the control. Part of the bare PV treatment at Chisago and the veg PV treatment at Atwater was graded, but the topsoil was removed and stockpiled on site prior to grading and redistributed after the fact. Due to the timeline of the study, soil data prior to the construction of the facilities was not available. However, because the control was adjacent to the treatments but outside of the direct construction, the soil conditions and other physical attributes of the control were considered a valid representation of those in the two treatment areas prior to the construction. Therefore, the soil and other physical data taken post-construction in the other two treatments would reflect the combined effects of the construction and the treatments.

In the veg PV and the bare PV treatments, soil moisture data measured as volumetric water content and soil temperature measurements were collected at a 25-cm depth in four locations: below the western edge (WE) of one of the PV arrays, in the interspace (IS) between the two rows of the arrays, below the eastern edge (EE) of the other PV array, and in the area below one of the PV trackers (BP) (Fig. S1d). In veg PV and bare PV, six 5-cm soil cores were randomly sampled from areas underneath the PV panels (area between a WE and EE of the same row) and another six from areas between the rows of PV panels with open sky. Six 5-cm soil cores were also sampled from the control as well. This depth was chosen to examine the effect of soil erosion and the resulting change in the soil nutrients. In addition to the 5-cm cores, three bulk core samples were collected from each treatment at all three facilities. The samples from the veg PV treatment and the bare PV treatments were taken in areas at least a meter away from posts or buried cables. Soils in areas directly under the panel edges and gaps between panels within a row where evidence of concentrated rainfall impact was observed were also not sampled.

Electricity production data from the bare PV and the veg PV treatments in all three facilities were provided by Enel Green Power North America (EGP-NA). The bare PV treatment and the veg PV treatment each contained an inverter that was linked to 1044 modules (328.9 kWp), whose total surface area was 2026 m^2. Production data were recorded every 15 min from January 1st, 2019 to December 31st, 2021. The power data (W_{dc}) were normalized by the solar irradiance (W m^{-2})

and the total surface area of the PV (m^{-2}). Any power data that coincided with the solar irradiance ≤0 were filtered out. Due to equipment failure, inverter data from Chisago before 2021 and between May 1st and June 10th in 2021 and those from Eastwood between May 30th and September 31st in 2021 were excluded from analysis.

2.2. Laboratory measurements

The soil samples were tested for a suite of soil nutrients including total soil carbon (TC), and total soil nitrogen (TN) with a standard combustion method, and also for phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn) using Mehlich III (Brookside Laboratories, INC. New Bremen, USA) [35]. For statistical procedures, any soil nutrient content that was reported as below detection limit was removed from analyses. In addition to the nutrient content, particle size distribution (PSD) of the soil samples was determined with a laser diffraction particle sizing analyzer (LS 13320 with aqueous liquid module, Beckman Coulter, Inc. CA, USA) with a grain diameter measurement range of 0.4–2000 μm. Prior to the PSD analysis, the samples were disaggregated (but not pulverized) with a soil crusher and sieved through a 2 mm sieve. Organic matter was removed from the samples by submerging the sample in a sodium hypochlorite solution (100 mL 2 M HCl to 1 l of sodium hypochlorite, 12.5%) for 24 h.

2.3. Analyses

The electricity production data of the PV modules in the veg PV treatment and those in the bare PV treatment were compared using the DC power record from the inverter data. Malfunctioning solar tracking system may put the PV array at a suboptimal angle, which may significantly decrease the power production of the array. To account for the tracking system malfunction, outliers ($1.5 \times IQR$) were removed to account for large differences in the power output due to instances in which the sunlight tracking systems malfunctioned in one of the two treatments. The exact timing of the tracking system malfunctions was unknown, so the data within the time window of tracker malfunction had to be visually identified and removed.

Since *t*-test on autocorrelated data may yield a type I error, a modified *t*-test was used to compare the means of continuous time series of DC power output from bare PV and veg PV treatments [36]. The t-test was performed on the data above the 10th percentile to exclude the readings during low sunlight periods and on those above the 50th percentile to focus on high insolation periods. Before performing the *t*-test, the Durbin-Watson (D—W) test was performed on the data to determine whether they constituted AR(1) time series [36].

Analysis of variance (ANOVA) and Tukey post hoc test (at $\alpha = 0.05$) were performed to determine the difference in the soil nutrient content among the treatments.

3. Results

3.1. PV temperature and power output

Over the three growing seasons, power output and panel

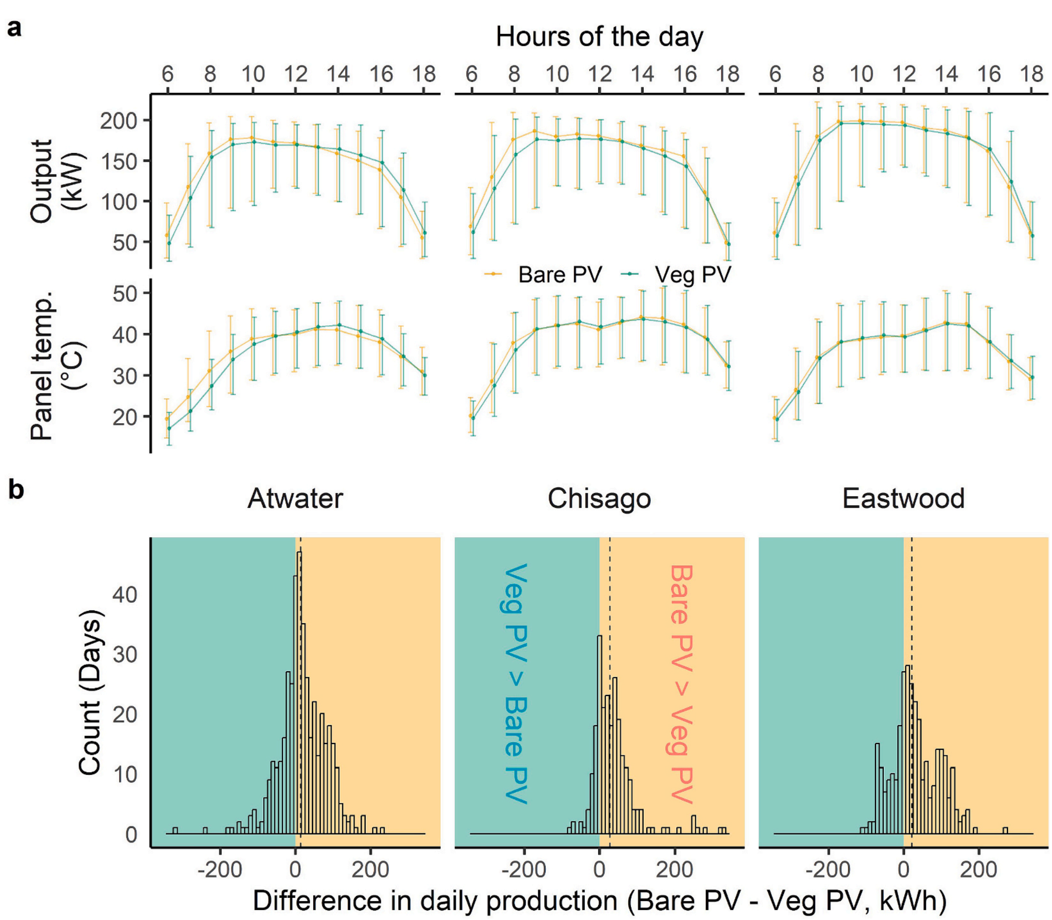

Fig. 1. a. Daily profile of median DC power output (kW) and median panel temperature (°C) over the growing seasons (between May and September of the years 2019, 2020, and 2021). The whiskers represent the 25th and the 75th percentiles; b. Histogram of raw difference (kWh) in daily production between Bare PV and Veg PV (Bare PV – Veg PV), separated by facility. The vertical dashed line represents the median, and the colored area represents the range in which the daily production of a treatment exceeds that of the treatment type. Throughout, bare PV is orange and veg PV is green.

temperature were similar in both treatments throughout the day. The times of the day when the difference in either were the most pronounced was in the early mornings (hours 6–9) and late afternoons (hours 14–18), and the power output and the panel temperature difference occurs in the same direction (Fig. 1a) The median difference in in daily electricity output (output difference = bare PV output – veg PV output) was positive in all three facilities, which meant that the bare PV produced more electricity in all three facilities (Fig. 1b). However, the *t*-test showed no significant difference ($p < 0.05$) in electricity output from the PV arrays between the bare PV and the veg PV treatments under all, 50th percentile, or 90th percentile of the irradiance levels (Table 1).

3.2. Microclimate

Overall, air temperature and relative humidity were not significantly different among the treatments in all facilities (Fig. 2). However, the median of the daily minimum temperatures was slightly higher in the bare PV treatment than in the veg PV treatment and the control, whereas the median of the daily minimum relative humidity was the lowest in the bare PV treatment. Additionally, the median of the daily maximum air temperature was slightly higher in the veg PV treatments than in the other two.

Higher wind speeds were more frequently recorded in the control than in the other two treatments in all three facilities over the growing seasons, and the veg PV treatment experienced the least frequent higher wind speed observations (Figs. 2 & 3). The bare PV and the veg PV treatments had lower mean wind speed and higher percentage of calm periods compared to the control. Between the bare PV and the veg PV treatments, the bare PV experienced higher wind speeds more frequently than the control in Atwater and Eastwood, while the opposite was true in Chisago.

3.3. Soil particle size distribution and nutrients

Overall, Chisago had the coarsest soil texture (sand), while Atwater (a sandy loam) and Eastwood (a silt loam) had finer soil textures (Fig. 4a, S2a, S2c). Eastwood had the highest total carbon (TC) and total nitrogen (TN) on average, and Chisago had the lowest at approximately half of those of Eastwood (4b). In all three facilities, the bare PV and the veg PV treatments had higher mean phosphorus (P) and zinc contents (Zn), but no other consistent pattern in the relative abundance of macro and micro soil nutrients emerged (Fig. 4c).

In Atwater, the control had the highest and the most variable mean grain sizes, and the bare PV and the veg PV had similar mean grain sizes, while sorting was similar in all three treatments (Fig. 4a). The TC and TN contents were similar in the bare PV and veg PV treatments but significantly higher in the control (Fig. 4b). The mean of the total exchange capacity (TEC) and the manganese (Mn) content were similar in all three treatments (Fig. 4c). The bare PV treatment had the highest mean potassium (K), phosphorus (P), and sulfur (S) contents. The mean zinc (Zn) content was higher in the bare PV and veg PV treatments compared to the control.

In Chisago, the bare PV treatment had the most homogenous grain size distribution (low sorting) and slightly higher mean grain size than the veg PV treatment and the control. The TC content in the control and the veg PV were similar but significantly lower in the bare PV treatment. The TN content was the highest in the control and the lowest in the bare PV treatment. In Chisago, the mean TEC was similar between the veg PV treatment and the control, but the veg PV had higher mean content of K, Mn, P, S, and Zn than the control did. The bare PV treatment had the lowest TEC, iron content, K, Mg, and Mn, but its P, S, and Zn contents were still higher than those of the control.

In Eastwood, the control had the largest mean grain size and the largest variation in grain sizes (highest sorting). The bare and the veg PV treatment had similar mean grain sizes, but the bare PV treatment had the most homogeneous grain sizes (lowest sorting). The TC and TN contents were similar in all three treatments. The bare PV treatment had significantly higher mean Zn content and around 400% of the mean P

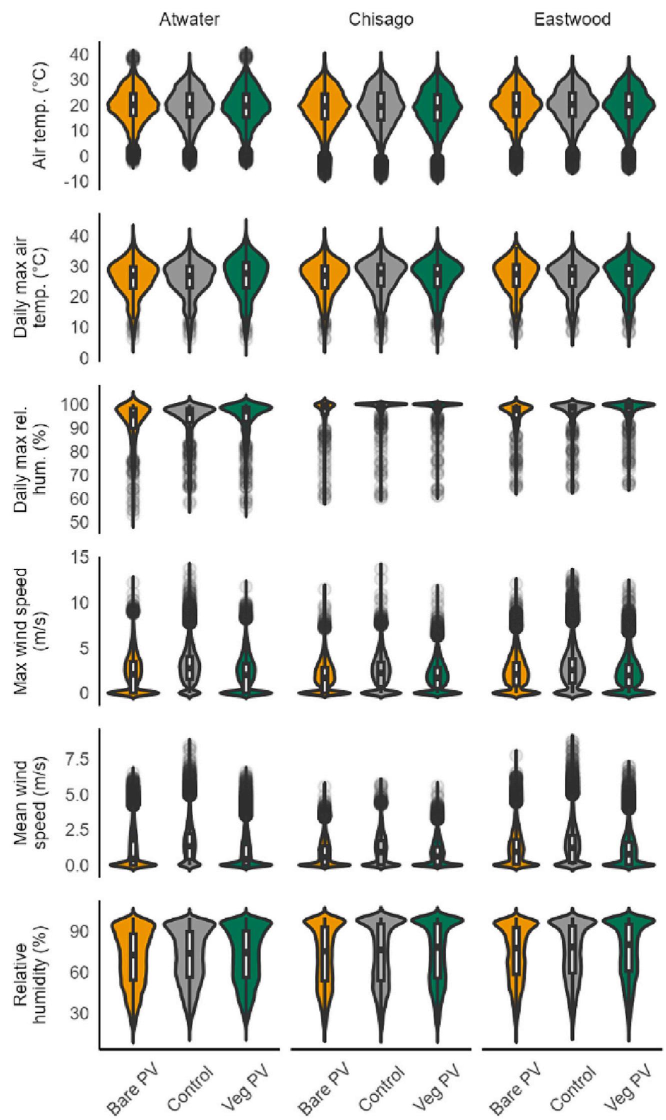

Fig. 2. Distribution of air temperature and relative humidity at each treatment over all three growing seasons of the study period. The colour under the curve indicates tail probability, which is 0 at the darkest and 50% (median) at the highest.

Table 1
Comparison of power output between the bare PV and the veg PV treatments using *t*-test ($p < 0.05$).

Facilities		Atwater			Chisago			Eastwood		
	Compared treatments	2019	2020	2021	2019	2020	2021	2019	2020	2021
Power output (kW_{dc}) at top 10% irradiance	Bare PV - Veg PV	0.7495	0.8650	0.7279	0.7834	0.9448	0.7163	0.3950	0.9278	0.6942
Power output (kW_{dc}) at top 50% irradiance	Bare PV - Veg PV	0.6032	0.8795	0.5564	0.8335	0.8143	0.9315	0.2297	0.9363	0.2228
Power output (kW_{dc}) at all irradiance levels	Bare PV - Veg PV	0.7361	0.9385	0.8618	0.7416	0.9709	0.8933	0.3151	0.9639	0.8662

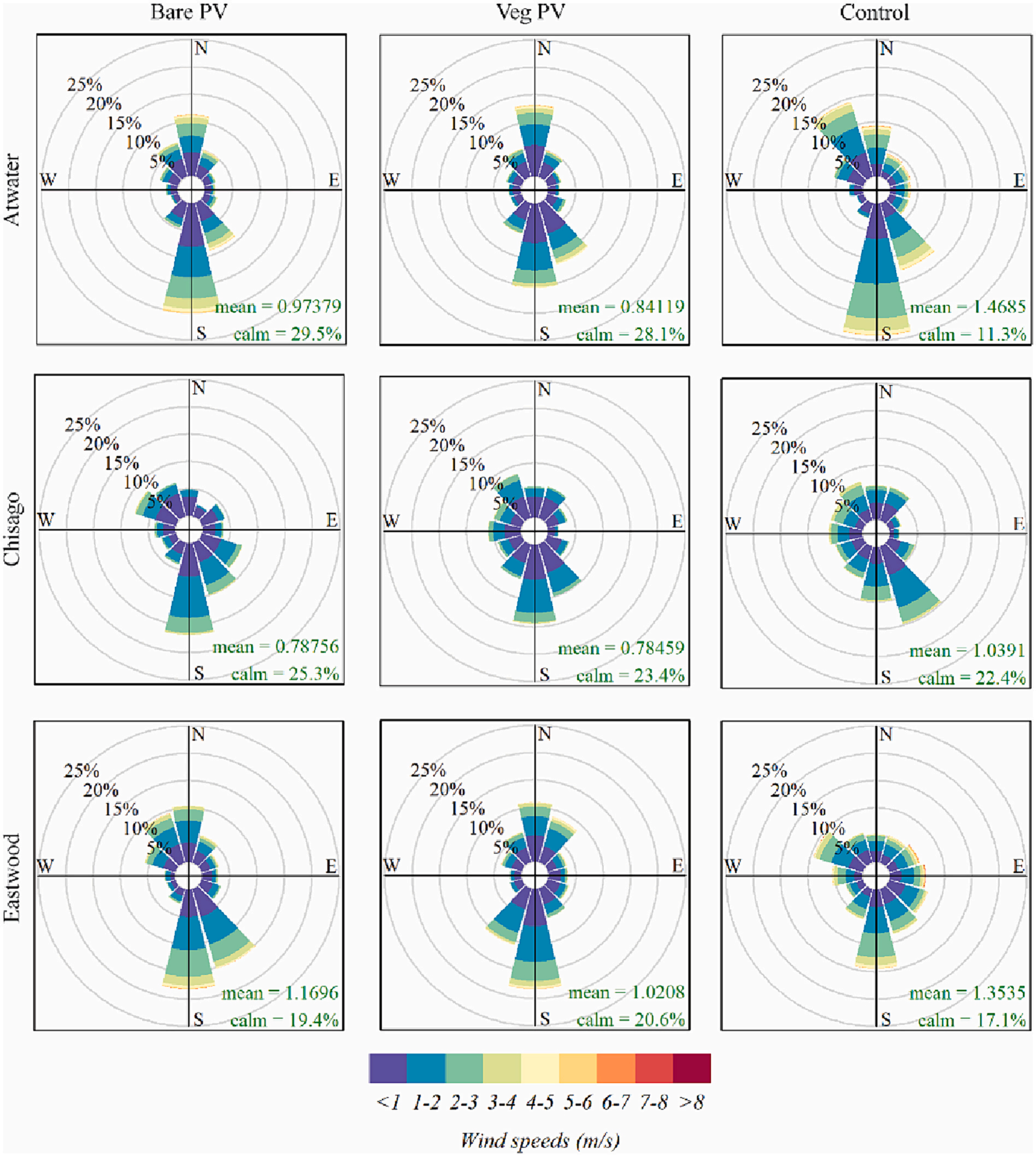

Fig. 3. Wind roses representing frequency of counts (%) by wind direction over the growing periods from 2019 to 2021. The thickness of the bands represents frequency of measurement, and the colors represent average wind speeds (m/s). The data is separated by facilities and treatments. Calm percentage represents the percentage of measurements for which the wind speed was lower than the minimum sensible speed of the wind speed measuring equipment.

content of that of the control. Conversely, TEC and other mean soil nutrients contents (Cu, K, Mg, Mn, and S) were lower in the bare PV than those in the control. The Fe content was similar in the bare PV treatment and the control. As in the bare PV treatment, the mean Zn and P contents in the veg PV were higher than those in the control, while the mean Cu, Fe, K, Mg, Mn, and S contents, and the TEC were lower than those in the control.

3.4. Soil moisture and temperature

Every subsequent growing season, precipitation decreased in frequency and depth, and the local minima of the soil moisture in the veg PV and the control prior to a precipitation event also decreased over the years (Fig. 5a). Within each treatment, the soil moisture distribution was heterogenous among the relative positions along the transverse profile through the solar arrays (Fig. 5b), but the pattern was not consistent in magnitude or direction across the treatments. On the other hand, the heterogeneous distribution of soil temperature among the relative position was consistent across both PV treatments and all three facilities. In Chisago and Eastwood, the soil moisture was higher in the veg PV treatment and the control than in the bare PV treatment, but Atwater showed higher soil moisture in the bare PV treatment and the control than the veg PV treatment (Fig. 5a and b). The soil moisture measurements in the vegetated PV treatment and the control drifted downwards

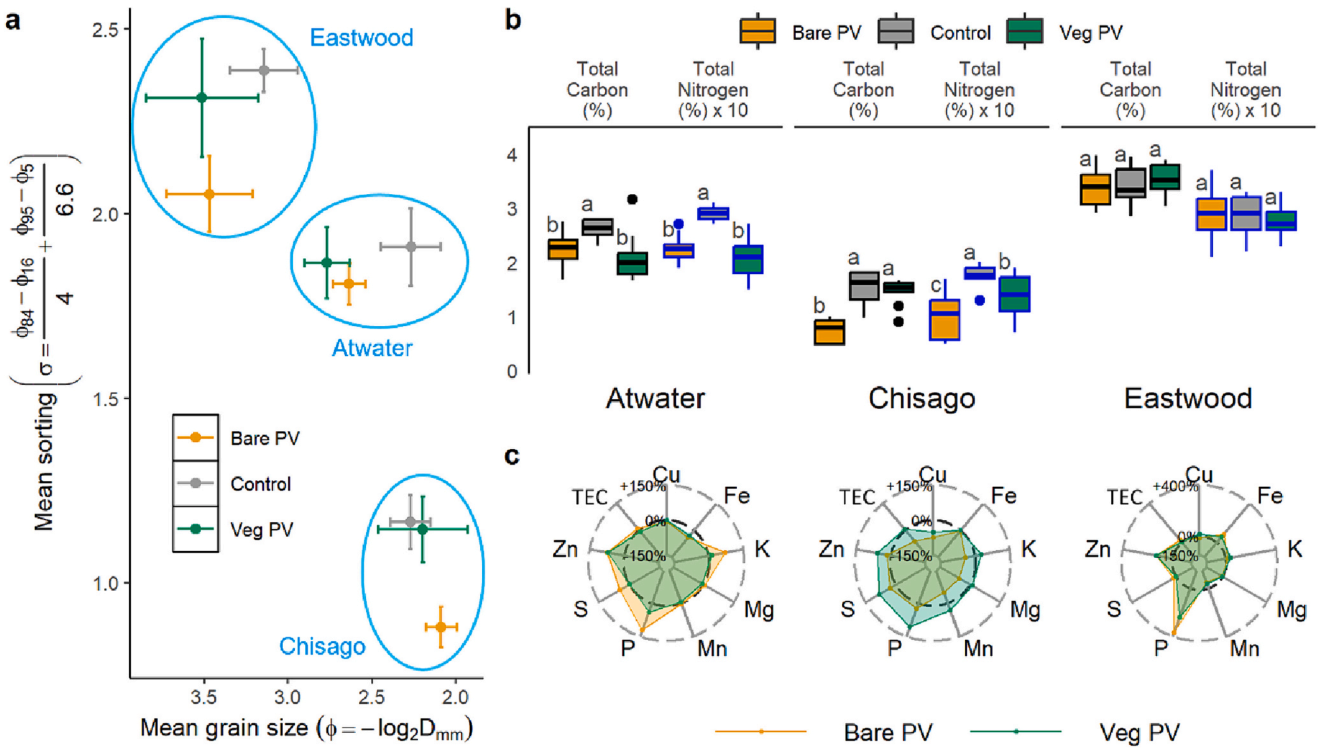

Fig. 4. a. Mean grain size against mean sorting with the whiskers extending to one standard deviation; b. Boxplots of total carbon (% by weight) and total nitrogen (% by weight × 10). The letters next to the boxes show the result of Tukey's honest significance test, and the differing letters represent significant difference among treatments within a facility. The middle notch represents the median, the bottom and the top of the box represent the first and the third quartiles, and the whiskers extend to 1.5 times the interquartile range. The colors represent treatments, and the boxes bordered with black lines show total carbon data while the boxes with blue lines show the total nitrogen data; c. radar plots of the percent difference in soil cations and cation exchange capacity between a corresponding treatment and the control. 0% signifies no deviation from the control. Axis label key: TEC = total exchange capacity; Cu = copper; Fe = iron; K = potassium; Mg = magnesium; Mn = manganese; P = phosphorus; S = sulfur; Zn = zinc. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

over the three years, which is apparent in some of the time series in Fig. 3a but also in the corresponding curves that are wide and multi-modal. This downward drift of the soil moisture measurements was less prominent in the bare PV treatment of all three facilities (Fig. 5a), whose corresponding distribution curves were narrower and more unimodal (Fig. 5b). The distribution of soil moisture varied among the relative positions within each treatment for the bare PV and the veg PV treatments in all three facilities, but the pattern of variation among the relative positions was not consistent across different treatments or facilities. For instance, interspace (IS) and east edge (EE) had higher median soil moisture than did west edge (WE) and below panel (BP) in the bare PV treatment of Atwater and Chisago, but the same was not true in the bare PV treatment in Eastwood nor was it for the veg PV treatment. The only pattern that was consistent in both the bare PV and the veg PV treatments of all three facilities was that the IS had the highest soil moisture.

The daily mean soil temperature was the highest in the control during most of the growing seasons at all three facilities, and it was the lowest in the veg PV treatment at all facilities every growing season (Fig. 6a). As whole, the median soil temperature was the highest in the control and the lowest in the veg PV treatment (Fig. 6b). The difference in average soil temperature between the veg PV and the other two treatments is also the largest in the higher temperatures. Among the relative positions, the IS had the highest median soil temperature, and the BP had the lowest while the those of the WE and the EE's were in the middle.

4. Discussion

Our results indicate that, in this humid temperate climate with these soil types, vegetation under PV arrays without irrigation may not cool the overlying panels or improve their performance to a statistically significant degree. The lack of difference in panel temperature between the bare PV and the veg PV treatments is explained by the similar lack of difference in the air temperature and relative humidity.

The combined influence of PV arrays and vegetation may decrease wind speeds and heterogeneous distribution of soil moisture and temperature in all three facilities, but the treatment responses in soil nutrient, grain size distribution, and hydrology were inconsistent across the facilities and with existing literature. Some of these discrepancies can be explained by the variation in soil characteristics and climate, which imply that the nature and the magnitude of environmental co-benefits of a co-located system are contingent on at least the soil characteristic and the climate. Therefore, site-specific knowledge of the climate and the soil is required to identify which co-benefits can be attained by a potential co-located system and maximize them.

4.1. PV temperature and performance in co-located systems

In humid temperate climates such as this one in Minnesota, vegetating PV arrays may not decrease the operating temperature of the overlying panels or increase their performance to a statistically significant degree. The lack of statistically significant difference in the power output and in the panel temperatures between the bare PV and the veg PV treatments (Fig. 1a, b, and Table 1) was consistent in all three facilities over every growing season at different irradiance levels. This is consistent with observations from a previous study [33], but contrasts with a significant difference in panel temperature observed in an agrivoltaics study in drylands [26].

Higher frequency of rainfall and relative humidity in Minnesota

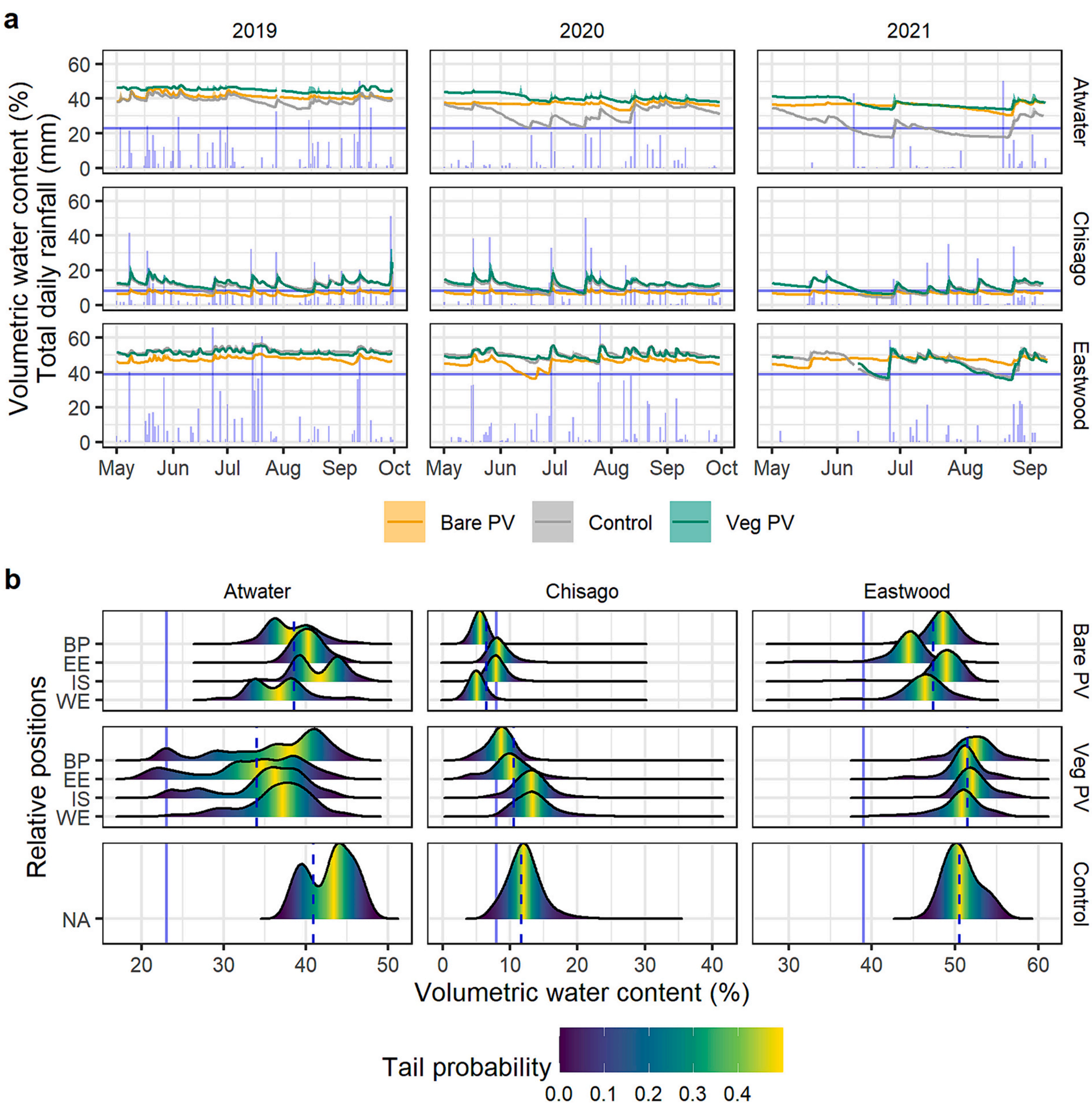

Fig. 5. a. Time series of the daily mean soil moisture (unitless) among the treatments and total daily precipitation (mm), separated by year and facility; the daily mean soil moisture has been averaged across the relative positions; the solid vertical blue line represents soil moisture at field capacity based on the average soil texture at each facility [37]; b. frequency distribution of the soil moisture over all three growing seasons; the curves are separated by the relative positions, and the plotting area is separated by facility, year, and treatment; the colors represent tail probability, and the dashed blue lines represent the median soil moisture across all sensors in the respective treatments. The solid horizontal blue line represents soil moisture at field capacity, as in part a. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

compared to the dryland study may explain this lack of panel temperature difference: generally, a vegetated surface has a longer roughness length than a bare soil surface which leads to increased aerodynamic resistance to water vapor diffusion and decreased potential evapotranspiration [38,39]. On the other hand, because evaporation over a saturated bare soil is limited only by energy availability in the early stage of evaporation, the evaporation rate from a bare soil shortly after rain events is comparable to or higher than the evapotranspiration rate of its vegetated counterpart [39]. Because all three facilities experienced frequent rainfalls over the growing seasons, the evaporation rate in the bare PV treatment was likely comparable to or higher than the evapotranspiration rate of the veg PV for most of the growing seasons. The lack of significant difference in air temperature or relative humidity between the bare PV and the veg PV treatments and the fact that the relative humidity was close to 100% most of the time (Fig. 2) also imply that any additional evapotranspiration in veg PV is unlikely to result in practically significant cooling of the panels that would translate into measurably improved power production. However, if the effects of the climate change were to increase the periods between rainfalls in Minnesota in the future, the prolonged evapotranspiration in the vegetated PV arrays may cause a significant difference in the temperature and the performance of the PV arrays, but irrigation may be required to maintain the cooling effect, which may not be financially practical [33].

4.2. *Soil-specific strategies for restoration*

Slower wind speeds caused by the co-location of PV and vegetation may protect the soil from erosion (Fig. 2), but the original texture of the

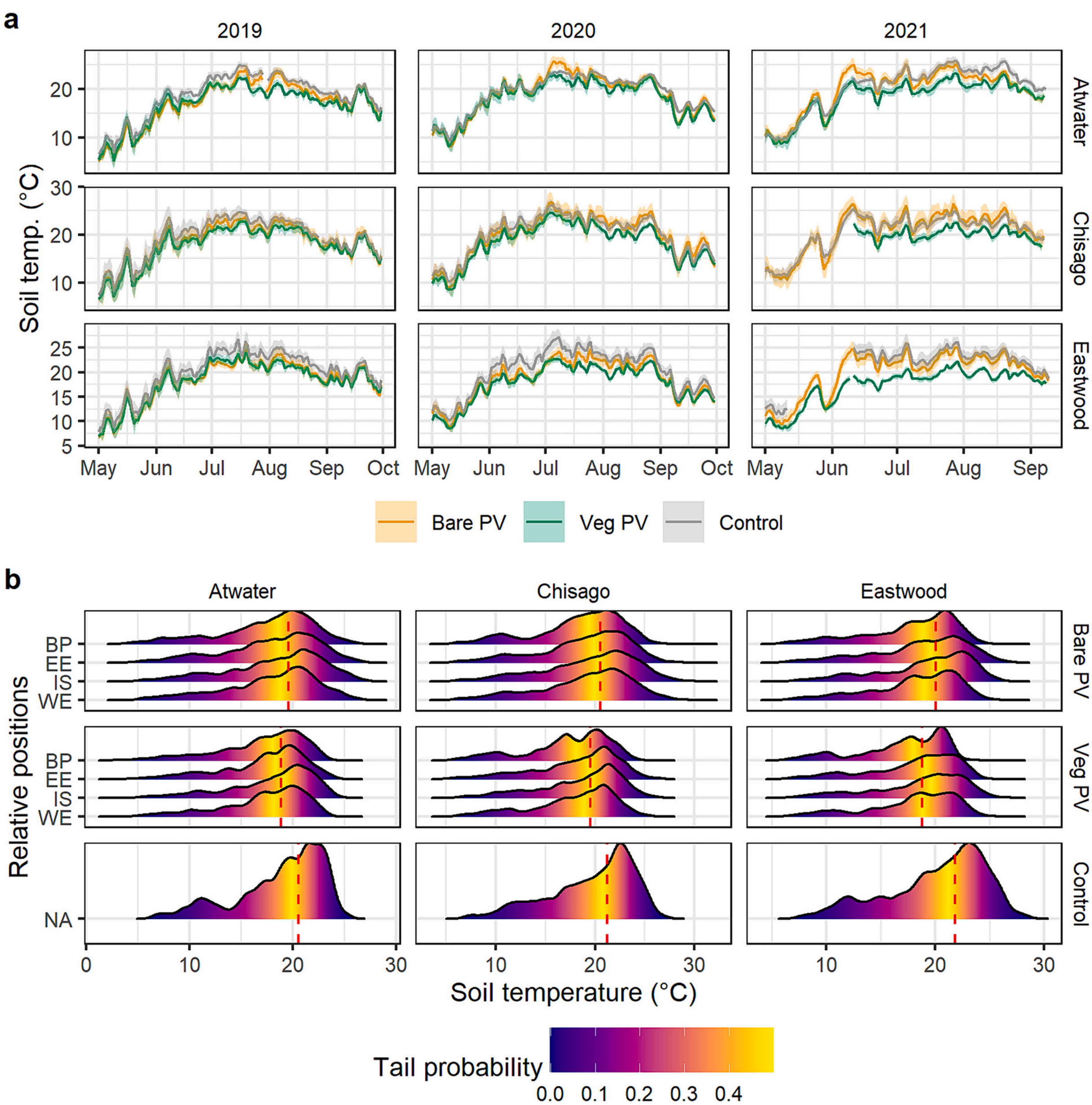

Fig. 6. a. Time series of the daily mean of the soil temperature (°C) among the treatments, separated by year and facility; the daily mean soil temperature has been averaged across the relative positions; b. frequency distributions of the soil temperature measurements over all three growing seasons; the curves are separated by the relative positions, and the plotting area is separated by facility, year, and treatment; the colors represent tail probability, and the dashed red lines represent the median soil temperature across all sensors in the respective treatments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

soil and construction history may have had the strongest influence on the soil nutrient and texture response to the treatments. While minimizing land modification during PV construction is beneficial for all soils, those with higher clay fraction and carbon content may be less susceptible to the change in soil texture and nutrients from land modification than those with lower clay fraction and carbon content.

The consequence of mechanically disturbing the topsoil through stockpiling/replacement or leaving the topsoil exposed through devegetation was more pronounced in soils with less clay content [40]. In the bare PV treatment in Chisago, the stockpiled topsoil of the bare PV had lesser clay and silt fraction in the bare PV treatment than in the veg PV treatment and the control (Fig. S2a), as well as less TC, TN, TEC, Cu, K, Mg, Mn, and OM (Fig. 4b, c & S2a). Since soil organic matter provides structural stability to soil, and clay provides surface for adhesion of organic matter [41,42], loss of either OM or clay fraction may cause the loss of the other and result in a significant drop TEC and anion concentrations. In contrast, the stockpiling and replacing the topsoil in the veg PV treatment in Atwater did not result in a lower TEC than the control (Fig. 4a) despite the loss in OM (Fig. S3). The unexpectedly higher fraction of silt and clay in the removed-then-replaced veg PV treatment compared to both the bare PV treatment and the control may be attributed to the disaggregation of silt and clay from the removal and re-distribution of the topsoil [16]. Increased TEC contributions from the disaggregated clay and silt fractions also explain why the veg PV's TEC was comparable to that of the control despite its comparatively low TC and OM content (Fig. 4c & S3): on top of freeing silt and clay particles, the breakdown of aggregates may expose the previously occluded OM and increase the rate of carbon and nitrogen loss through respiration [43,44]. The breakdown of soil aggregates also correlates with decreased water retention in soils [45], which may be the reason the soil moisture reaches levels lower between rainfalls in the veg PV treatment than those in the control (Fig. 4a). Overall, no consistent pattern in relative abundance of soil ions and TEC emerged, which may be due to the fact that TEC was calculated by totaling the cation concentrations and that the soil ions may have been incorporated in plant biomass when the samples were collected [35].

The lower median average wind speeds and median max wind speeds in the bare PV and the veg PV treatments (Fig. 2) imply that PV arrays may decrease wind speeds, which corroborates the findings of a previous study [25]. Furthermore, the lower mean and max wind speeds in the veg PV treatment compared to that of the bare PV treatment (Fig. 2) implies a compounding wind suppression effect from the co-location of PV arrays and vegetation. In Eastwood, the lower clay fraction in the bare PV treatment (Fig. S2a) in absence of any topsoil stockpiling may indicate loss of clay fraction from the bare PV treatment due to increased exposure of the bare soil. Conversely, the comparatively higher clay fraction in the veg PV treatment alludes to a possibility of unloading of aeolian sediments within the veg PV treatment because of compounding suppression of the wind from the vegetation and PV as well as sufficient mitigation of erosion the vegetation [46,47]. However, aeolian entrainment and saltation mechanisms of clay particles in frequently wet soils in humid climates need to be examined to further quantify the avoided erosion of the clay particles.

The contrasting effects of stockpiling in Chisago and Atwater are in line with previous findings on re-vegetation, which show that the capacity to accumulate carbon is more heavily impacted after a disturbance in coarser soils than in finer soils [13]. While re-vegetating the modified soil with native vegetation can prevent further erosion of the finer soil particle fraction, it may take decades before the soil carbon content returns to the levels seen in prairie grasslands [40,48]. Considering all three facilities were built on prior farmlands that had already been heavily altered from prairie grasslands, re-vegetating PV arrays for the duration of the project may continue increase the soil carbon stock beyond the pre-construction levels and the timeline of this study. While additional soil data are required to separate the effects of soil stockpiling and absence of vegetation, this finding underpins the importance of re-vegetation or preservation of existing vegetation as well as soil during construction. Suggested construction practices that may minimize soil impact such as avoiding land grading or using alternative torque tube designs to accommodate for undulating surfaces with fewer piles [49–51], and the lack of research in the physical viability, insurability, and financial viability of such changes is a research opportunity that may address many environmental concerns about general PV deployment beyond agrivoltaics.

4.3. Agrivoltaic influence on microclimate and hydrology and its implications for cropping geometry and biodiversity

Atwater and Eastwood had higher soil moisture content than Chisago (Fig. 5a) due to relatively higher clay and silt contents in Eastwood and Atwater (Fig. S2a), which may have resulted in high porosity but low hydraulic conductivity [52,53]. For this reason, the soil moisture of the bare PV treatment in Atwater and Eastwood remained higher and fluctuated much less than that of the other two treatments between rainfall events and dry periods. The interannual decrease in the local maxima and minima of soil moisture in the veg PV treatment and the control is likely caused by the decreasing frequency and intensity of rainfall events, but also aligns with decrease in soil moisture due to increased plant uptake that has been observed in other re-vegetation studies [54,55]. In contrast, the water outputs from soil in the bare PV treatment without plant transpiration is downward infiltration and evaporation, but infiltration in Atwater and Eastwood to is limited due to the higher clay content [56], and evaporation rate would fall off quickly compared to the evapotranspiration rate in vegetated counterpart [39,57]. Therefore, the bare PV treatment maintains soil moisture comparable to or higher than that of the veg PV treatment and the control in Atwater and Eastwood even during the long rainfall intervals in 2021 (Fig. 5a).

The difference in the soil moisture and temperature profile among the relative positions in the bare PV and the veg PV treatments show that while PV panels may alter the distribution of both soil moisture and heat, the distribution of soil moisture will be more site-specific than that of soil heat distribution. The contrast in the spatial distribution of the two variables may be a result of the following: First, it is possible that the lateral transfer of heat through the soil is less susceptible to the effects of spatial heterogeneity in the soil than porosity or hydraulic conductivity. Second, the raindrops do not always fall on the soil surface at a right angle because of the wind, allowing the raindrops to reach parts of the soil that lie directly below the PV modules. Therefore, the distribution of soil moisture across the relative positions will vary among the facilities as does the distribution of wind speed and direction (Fig. 3). In contrast, wind does not control solar incidence angles, and the range of solar incidence angles are sufficiently predictable to allow estimation of irradiance without field data [58–60]. Therefore, the direction of soil temperature differences among the relative positions and between the treatments are consistent across the facilities (Fig. 6a and b). When considering the placement of native vegetation or crops in a sun-tracking agrivoltaics system, the soil moisture distribution profile resulting from the wind pattern, soil heterogeneity, and rainfall may introduce more uncertainty than the transverse soil temperature profile given that the facility or the system in question has the mounting height, width (perpendicular to the tracking axis), and the distance between rows that are similar to other facilities or systems in the region. Therefore, considering the historical data of local wind speed and wind direction in addition to the solar resources may be important for understanding water availability for plants in different relative positions of within co-located systems.

The disturbance and the heterogeneity maintained by PV occupation may drive biodiversity under the certain conditions: in prairie grasslands such as those of our study sites, C3 plants are the main drivers of biodiversity but are often shaded and outcompeted by the taller C4 graminoids, which result in community convergence despite the heterogeneity in soil nutrient and moisture [61,62]. However, because C3 forbs can adapt to a wider range of shade conditions than C4 graminoids, persistent shade conditions and potential destabilization of the grass-dominated prairie community from long-term occupation of PV arrays may provide an opportunity for C3 forbs to take advantage of the soil nutrient and moisture heterogeneity and increase the biodiversity [62–66]. In addition to the light requirement, the cooler temperatures and soil moisture levels in the relative locations can be compared with the water requirement of the plant species to select the planting location. The compounding heterogeneity created by the light and moisture conditions in these areas may provide varying niches around PV arrays, and repeated measurements in different climates and soils may be used to model resulting niches during the design stage of a co-located system.

4.4. Implications for climate change resilience

Our soil temperature data indicate that the combination of vegetation and PV arrays may provide compounding thermal protection against the effects of climate change. Global average temperature increase since pre-industrial levels will likely reach 1.5 °C and possibly 2.0 °C even in low anthropogenic radiative climate forcing scenario [67]. As these thresholds are reached, mean temperature in Minnesota may increase by 1.5–2.0 °C, and maximum temperature may increase over 2.0 °C in relation to the 1995–2014 levels [68,69]. While the yield may gradually increase with the warming, both cool- and warm-season plants may experience sharp, non-linear decrease in yield beyond the threshold temperatures of 29–32 °C [70–72]. Furthermore, with the shift in the average soil temperature, the growing season for cool-season plants may be shortened or shifted, causing a phenological mismatch with other organisms that rely on the affected plant species. The soil temperature in every location of veg PV plots were cooler than that of that in the control (Fig. 6b) which suggests that PV arrays buffer the soil temperature response to the increasing air temperature and lengthen the growing season in a future climate where the limiting factor may be extreme heat. Therefore, reduction of soil temperature (Fig. 6b) and insulation from the PV panels may buffer the effects of the climate change and give more time for landowners and organisms to adapt its outcome.

4.5. Future studies

The concentration of soil ions and TEC by extension were not a very reliable measure of soil health. The environmental processes within agrivoltaic system are a relatively new field of study, and there is a critical scarcity of data from varying different climates and soils that limit general conclusions that can be made from the accumulating body of research. While research with data on many variables may be more capable of analyzing complex relationships between different factors, experiments in utility-scale PV facilities are likely constrained by funding, timing, access to the study sites, and bureaucratic but necessary procedures that may influence any of the above. In consideration of these obstacles and the need for abundance of agrivoltaic data around varying environments, future studies may benefit from limiting their scope to a few variables, such as total carbon, nitrogen, soil particle fractions, and OM. Soil particle size distribution is an especially important as it is the key determinant of soils' capacity for retaining OM and TEC by extension [19,73]. Rather than performing a complete suite of tests for soil nutrients and TEC, focusing on soil particle size distribution may allow additional samples and a more statistically robust analysis. In addition to the above, analyzing soil for clay mineralogy may be useful for in calculating the soil's true cation exchange capacity than calculating the TEC by the summing up the cations, whose concentration may vary seasonably [35].

5. Conclusion

In Minnesota and regions with similarly wet growing seasons, co-located vegetation may not generate additional evapotranspiration large enough to result in statistically significant panel cooling or higher PV output, which is corroborated by the lack of difference in panel temperature and power output as well as in air temperature and relative humidity between the vegetated array and its unvegetated counterpart. However, panel cooling and increased PV performance may be possible with irrigation if the effects of climate change were to increase the period between rain events in Minnesota. However, and more importantly, co-locating native vegetation with PV may offer other benefits: compounding microclimatic influence of PV arrays and co-located vegetation may preserve the soil's ability to store nutrients, sequester carbon, and host organisms by providing protection against erosion and the excessive increase in soil temperature due to climate change. These benefits may be magnified in soils with smaller clay fractions which have reduced ability to retain soil carbon and therefore more vulnerable to further loss of the clay particles. Lastly, the shade conditions evidenced by the spatial variation in soil temperature in the PV arrays may act as a persisting disturbance to the dominant grass population in prairie grasslands, increasing the likelihood that shorter plant species may establish, but this has yet to be verified with ecological data. Overall, our study shows that some expected benefits of co-locating native vegetation with PV arrays may vary not only at a regional scale with climate but also at a finer scale with soil texture and near-surface hydrology. Not all the previously reported environmental co-benefits may be achievable in a single co-located system, and case-by-case considerations of the climate, soil properties, and plant communities may help identify which environmental benefits are achievable for a potential development location and maximize them.

CRediT authorship contribution statement

Chong Seok Choi: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jordan Macknick:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **James McCall:** Supervision, Conceptualization, Writing – review & editing. **Rebecca Bertel:** Formal analysis, Funding acquisition, Investigation, Project administration, Writing – review & editing. **Sujith Ravi:** Writing – review & editing, Funding acquisition, Project administration, Supervision.

Declaration of competing interest

The authors declare no competing interests. Any use of trade names is for descriptive purposes only and does not imply endorsement of any format.

Data availability

Both the data and input files necessary to reproduce the graphs is available from the authors upon request.

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Appendix A. Supplementary data

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