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Sun, shade and soil: A case study on how free-field photovoltaic systems alter microclimate and soil

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Abstract

In the context of climate change mitigation efforts, the growing demand for renewable energy is driving the expansion of free-field photovoltaic systems (FFPV), causing significant land-use changes with poorly understood impacts on grassland ecosystems. To investigate the impact of modules on microclimate and soil, TMS-4 sensors were installed in a FFPV in Northern Germany. We defined three areas (= treatment): area directly affected by modules (module), area where modules in a row have been removed (window), and area unaffected by modules (open) with eight sampling positions each. Soil moisture and temperatures were measured at each position to assess the influence of different shading positions within the FFPV. In addition, we analysed soil samples taken with an auger soil sampler at the same positions. We found an increased variability of all parameters in the areas 'module' and 'window' compared to the area 'open' in the rank order: open < window < module. Nitrogen and carbon content as well as temperatures underneath the module and window were reduced; soil moisture was highest underneath the modules. Our results enhance understanding of system-design-driven, position-dependent variations in soil and microclimate within FFPVs.

Keywords: carbon, dual land-use, marginal grassland, nitrogen, photovoltaic, TMS-4 sensors

Introduction

The growing demand for renewable energy sources and the imperative to alleviate climate change impacts, particularly heat stress on flora and fauna, have substantially intensified research in free-field photovoltaic systems (FFPV). In a way the modules also represent anthropogenic structural elements within landscapes, exerting measurable influences on the local microclimate (Armstrong *et al.*, 2016). The present study investigates the influence of varying shading conditions on soil parameters and microclimate within an existing FFPV. Specifically, we compared soil moisture, temperature at three heights, and soil nutrient distribution of two PV-affected areas and one unaffected area.

Materials and methods

The present study was carried out from June to November 2024 in the FFPV 'Solarpark Klein Rheide' in Schleswig-Holstein, Germany. The FFPV was built in 2018. A technical feature of this FFPV is that modules are omitted at regular intervals in each module row to allow for more sunny areas (Fig. 1; window). The grassland vegetation was not sown but grew naturally after the FFPV was built and is mowed once a year. For data analyses, the study period was divided into seasons: summer (June–August) and autumn (September–November). Average air temperature and summed precipitation during summer and autumn, recorded by a weather station at a distance of approximately 7 km from the trial site, were 16.21°C and 231.58 mm and 8.96°C and 213.19 mm, respectively. We defined



Figure 1. GPS positions of each position per area (= treatment) in the Solarpark Klein Rheide.

three treatments: area directly affected by modules (module), area where modules in a row have been removed (window) and area unaffected by modules (open) (Fig. 1). Samples were taken from different positions within each treatment referred to as gap, halfshade, shade and edge—which is following the spatial sequence in the area ‘module’. In May 2024 (after mowing), at each position one TMS-4 sensor (TOMST, Prague, Czech Republic) was installed at a depth of 9 cm measuring soil moisture and temperatures at 15 min intervals at -6 cm, $+2$ cm, and $+15$ cm from the surface. In November 2024, soil was sampled from a depth of 0–10 cm at each position ($n = 10$) using an auger soil sampler. Carbon (C) and nitrogen (N) content were analysed to investigate the effect of shading on soil nutrient distribution. Generalised linear mixed effect models (R package ‘glmmTMB’) with the fixed effects area ($n = 3$), position ($n = 4$) and the interaction of both were calculated for the target variables N, C, soil moisture and temperatures. The sample ID served as random effect. Multiple contrast tests according to Tukey’s HSD test (R package ‘emmeans’) were conducted to analyse the main influencing factors.

Results and discussion

Within the ‘open’ area, measured parameters were similar, whereas in the ‘module’ area significant variability across all measured parameters was detected (Tables 1 and 2). However, the interaction between area and position was significant for all parameters, except for temperature at -6 cm in autumn; in that case only the effect of area was significant. C and N content were lowest in shade of the areas ‘module’ and ‘window’ (Table 1). N content in all areas ranged from 1.03 – 1.49 g (kg DM) $^{-1}$, which is in the range of N contents reported by Blume *et al.* (2016) for Ap-horizons of mineral soils in humid climate. Although the ‘window’ area was not consistently shaded, the lowest C content was found at position ‘shade’ whereas it was highest at its position ‘edge’, which may be explained by a reduced vegetation cover and varying microclimate conditions affecting soil fauna and microbial activity underneath PV modules compared to open areas (Krasner *et al.*, 2025). Grazing sheep may be used to redistribute nutrients in the position ‘shade’ in FFPVs, as modules provide preferred resting sites that increase trampling and defecation. Li *et al.* (2025) found an enhanced diversity of temperature through niche differentiation in a single axis mover FFPV with lowest air temperature at halfshade/edge (combined position in this type of FFPV). In the present study, both air temperatures in the area ‘module’ revealed the lowest values in halfshade, whereas edge revealed the highest values respectively (see Table 2), highlighting the effect of different technical module installations on the microclimate.

Table 1. Estimated means±SE (standard error) of generalised linear mixed effect models for soil moisture, nitrogen (N) and carbon (C).

Area	Position	N (g (kg DM) ⁻¹)	C (g (kg DM) ⁻¹)	Soil moisture (m ³ m ⁻³)	
				Summer	Autumn
Open	Gap	1.46 ± 0.03 ^a	22.2 ± 0.5 ^a	0.24 ± 0.01 ^a	0.27 ± 0.008 ^a
	Halfshade	1.47 ± 0.03 ^a	22.4 ± 0.5 ^a	0.24 ± 0.01 ^a	0.26 ± 0.008 ^a
	Shade	1.45 ± 0.03 ^a	22.1 ± 0.5 ^a	0.22 ± 0.01 ^a	0.26 ± 0.008 ^a
	Edge	1.49 ± 0.03 ^a	22.4 ± 0.5 ^a	0.23 ± 0.01 ^a	0.26 ± 0.008 ^a
Module	Gap	1.29 ± 0.03 ^b	20.1 ± 0.5 ^b	0.23 ± 0.01 ^{ab}	0.27 ± 0.008 ^b
	Halfshade	1.23 ± 0.03 ^b	18.7 ± 0.5 ^b	0.19 ± 0.01 ^a	0.23 ± 0.008 ^a
	Shade	1.03 ± 0.03 ^a	15.4 ± 0.5 ^a	0.26 ± 0.01 ^b	0.29 ± 0.008 ^b
	Edge	1.30 ± 0.03 ^b	19.9 ± 0.5 ^b	0.22 ± 0.01 ^{ab}	0.26 ± 0.008 ^b
Window	Gap	1.26 ± 0.03 ^a	20.2 ± 0.5 ^a	0.22 ± 0.01 ^a	0.28 ± 0.008 ^b
	Halfshade	1.27 ± 0.03 ^a	20.1 ± 0.5 ^a	0.23 ± 0.01 ^a	0.26 ± 0.008 ^{ab}
	Shade	1.26 ± 0.03 ^a	19.3 ± 0.5 ^a	0.19 ± 0.01 ^a	0.24 ± 0.008 ^a
	Edge	1.40 ± 0.03 ^a	22.5 ± 0.5 ^b	0.12 ± 0.02 ^a	0.25 ± 0.001 ^{ab}

Lower case letters indicate significant differences within areas, light grey indicates lower values, while dark grey indicate higher values compared to the area 'open' at the respective positions.

Table 2. Estimated means±SE (standard error) of generalised linear mixed effect models for temperature (Temp) at -6 cm, 2 cm and 15 cm

Area	Position	Temp. (°C) at -6 cm		Temp. (°C) at 2 cm		Temp. (°C) at 15 cm	
		Summer	Autumn	Summer	Autumn	Summer	Autumn
Open	Gap	18.3 ± 0.1 ^a	11.6 ± 0.07 ^c	18.1 ± 0.09 ^a	10.7 ± 0.07 ^a	17.2 ± 0.06 ^a	10.15 ± 0.06 ^a
	Halfshade	18.7 ± 0.1 ^a		18.2 ± 0.09 ^a	10.6 ± 0.07 ^a	17.2 ± 0.06 ^a	10.25 ± 0.06 ^a
	Shade	18.4 ± 0.1 ^a		18.2 ± 0.09 ^a	10.6 ± 0.07 ^a	17.1 ± 0.06 ^a	10.04 ± 0.06 ^a
	Edge	18.6 ± 0.1 ^a		18.2 ± 0.09 ^a	10.5 ± 0.07 ^a	17.2 ± 0.06 ^a	10.12 ± 0.06 ^a
Module	Gap	17.1 ± 0.1 ^b	10.8 ± 0.07 ^a	17.4 ± 0.09 ^c	10.1 ± 0.07 ^a	16.8 ± 0.06 ^c	9.22 ± 0.06 ^a
	Halfshade	15.5 ± 0.1 ^a		15.9 ± 0.09 ^d	10.1 ± 0.07 ^a	16.1 ± 0.06 ^d	9.69 ± 0.06 ^b
	Shade	15.4 ± 0.1 ^a		16.3 ± 0.09 ^b	10.4 ± 0.07 ^b	16.5 ± 0.06 ^b	10.25 ± 0.06 ^c
	Edge	16.8 ± 0.1 ^b		17.7 ± 0.09 ^c	10.8 ± 0.07 ^c	17.2 ± 0.06 ^d	10.29 ± 0.06 ^c
Window	Gap	18.0 ± 0.1 ^b	11.1 ± 0.08 ^b	17.7 ± 0.09 ^b	10.0 ± 0.07 ^a	17.0 ± 0.06 ^c	9.64 ± 0.06 ^a
	Halfshade	16.4 ± 0.1 ^a		16.6 ± 0.09 ^d	10.1 ± 0.07 ^{ab}	16.3 ± 0.06 ^d	9.54 ± 0.06 ^a
	Shade	16.4 ± 0.1 ^a		16.7 ± 0.09 ^d	10.4 ± 0.07 ^c	16.5 ± 0.06 ^b	10.14 ± 0.06 ^b
	Edge	17.5 ± 0.2 ^b		17.6 ± 0.13 ^b	10.3 ± 0.10 ^{bc}	17.0 ± 0.09 ^c	10.14 ± 0.06 ^b

Lower case letters indicate significant differences between areas for temperature at -6 cm in autumn and within areas for all other parameters. Italics indicates lower values, while underlined indicates higher values compared to the area 'open' at the respective positions.

Conclusions

Our findings indicate that PV installations induce position-dependent variations driven by system design parameters such as module size, inter-module gaps, and row spacing. This underlines the need for further scientific investigations into differently equipped FFPVs.

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