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Environmental Impacts of Pastoral-Integrated Photovoltaic Power Plant in an Alpine Meadow on the Eastern Tibetan Plateau

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Abstract: Rising global energy demand and the transition toward low-carbon energy sources have driven a rapid expansion of ground-mounted solar parks worldwide. This expansion constitutes a substantial land use change with largely unexplored implications for the ecosystems they occupy, particularly in the ecologically fragile and sensitive region of the Tibetan Plateau (TP). To assess the impacts of a typical photovoltaic (PV) power station on the alpine meadow ecosystem, this study conducted year-round observations of local microclimate and soil hydrothermal regimes within and adjacent to a pastoral-integrated PV plant on the eastern TP. The results show that PV installations significantly increase annual net radiation while reducing albedo and wind speeds. The influence of PV panels on air temperature is highly asymmetrical, with daytime heating, nighttime cooling, summer heating, and winter cooling. The PV arrays introduce notable spatial heterogeneity in soil hydrothermal regimes, show a cold-moist pattern in the array gaps and a cold-dry distribution beneath the panels. Such changes extend the frozen period and reduces soil moisture depletion rates. Our findings suggest that PV arrays could, in fact, enhance ecosystem resilience to climate warming; however, further research is needed to assess their impacts on hydrological processes, carbon balance, and biodiversity.

Keywords: Photovoltaic power plant, Alpine meadow, Microclimate, Soil hydrothermal dynamics, Field observations

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1. Introduction

Photovoltaic (PV) power generation is a critical solution for addressing the global energy crisis, mitigating climate change, and reducing environmental pollution (Kan et al., 2021; Prăvălie et al., 2019). In recent decades, significant strides in the solar energy industry have been driven by the global transition from carbon-intensive fossil fuels to renewable energy and the rapid decline in solar PV costs (Wei et al., 2024). As the global leader in the photovoltaic industry, China has maintained its dominant position in PV power generation, with cumulative installed capacity accounting for approximately one-third of the global total (Birol, 2022). In line with its carbon peaking and carbon neutrality goals, China is expected to continue rapidly expanding PV power generation nationwide.

Despite the clear advantages of PV power plants in clean energy production, their widespread deployment significantly alters local land surface properties and climate (Armstrong et al., 2016; Wei et al., 2024). These changes result primarily from the combined effects of surface roughness, the dark surfaces of PV panels, their energy output, and heat released during power generation (Broadbent et al., 2019; Taha, 2013; Xu et al., 2024; Yang et al., 2017). However, the environmental impacts of PV systems exhibit considerable regional variability, with studies reporting inconsistent trends and magnitudes of change depending on the local climate, ecosystem type, and PV array configuration.

For instance, PV arrays significantly influence albedo, a critical land surface parameter that directly influences the surface energy balance and climate dynamics (Wei et al., 2024). Numerical simulations often assume a simplified albedo value of 0.1 for PV arrays (Li et al., 2018; Lu et al., 2021), remote sensing and in-situ measurements typically report higher values, though with notable inconsistencies between the two methods (Chang et al., 2018; Li et al., 2022c; Wei et al., 2024; Xu et al., 2024; Yang et al., 2017). Similarly, PV plants influence near-surface air temperatures, most field studies indicate that PV panels increase daytime air temperatures due to heat released during electricity generation, a phenomenon similar to the urban heat island effect

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(Armstrong et al., 2016; Broadbent et al., 2019; Fthenakis and Yu, 2013; Yang et al., 2017; Zheng et al., 2023). For example, Yang et al. (2017) showed that PV panels in desert areas can increase both daytime and nighttime 2m air temperatures by approximately 0.7°C and 0.1°C, respectively, due to the heat released during power generation and the heat retention effect near the ground. In arid regions of California, Barron-Gafford et al. (2016) found that PV panels raised summer 2.5m air temperatures by more than 3°C compared to nearby wildlands. However, Keiko et al. (2009) conducted research on large-scale PV power plants in desert regions and found that PV modules had a self-cooling mechanism at night, with temperatures 2–4°C lower than the surrounding atmospheric temperature when sunlight ceased. These significant variations in the environmental impacts of solar farms may be attributed to differences in their characteristics, such as type, spatial scale, capacity, installation methods, and background environmental conditions (Xu et al., 2024). These discrepancies highlight the need for observational studies to better understand the impacts of PV arrays across diverse climate zones and surface types.

The Tibetan Plateau (TP), known as the "Third Pole," is one of the most ecologically fragile regions on earth, playing a crucial role in global climate regulation. Its complex soil freeze-thaw dynamics, important water conservation functions, and substantial carbon release potential make it highly sensitive to environmental disturbances (Chen et al., 2016; Yao et al., 2022). Additionally, the TP's long daylight hours, high solar radiation intensity, low temperatures and vast areas create ideal natural conditions for the development of PV industries (Li et al., 2022a; Tang et al., 2013; Wang and Qiu, 2009). In recent years, PV power plants have proliferated across the TP (Lyu et al., 2024), yet their impacts on microclimate and soil hydrothermal conditions, particularly in alpine meadows, remain underexplored. While extensive research exists on PV-induced microclimatic changes in deserts, a critical gap remains in understanding their effects on alpine ecosystems, which are both ecologically fragile and climate-sensitive. To address this gap, this study investigates the effects of a pastoral-integrated PV power plant on the microclimate and soil hydrothermal conditions of an alpine meadow on the eastern TP. Field observations were conducted at two neighboring sites within the

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Dongneng PV solar park to monitor key variables, including air temperature, humidity, radiation balance, and soil hydrothermal conditions. The primary aim of this research is to evaluate and quantify the environmental impacts of PV plant deployment in this unique ecosystem, providing valuable insights into the environmental consequences of large-scale PV power generation. This work seeks to contribute to a deeper understanding of the environmental effects of renewable energy and offer insights for sustainable development as PV energy continues to expand.

2. Method

2.1 Site description

The Dongneng PV power plant (34°3′19.5″N, 101°53′17.6″E) is situated in Maqu, Gansu Province, on the eastern Tibetan Plateau at an altitude of 3440 m (Figure 01a). The region's climate is classified as a sub-frigid humid zone based on China's climate regionalization (Zheng et al., 2010). The nearest meteorological station, located approximately 15 km from the study site, recorded a mean annual precipitation of 607 mm and an average air temperature of 1.84 °C from 1971 to 2020. The study area features alpine meadow vegetation dominated by Stipa aliena, Potentilla anserine, and Scirpus pumilus, with average vegetation heights of 0.3 m in summer and 0.1 m in winter. The PV power plant, located on flat terrain, was constructed in September 2021 and became operational in August 2022. It has a capacity of 50 MW and utilizes bifacial photovoltaic panels (LONGi Green Energy Technology Co., Ltd.) with a photoelectric conversion efficiency of 21.1%. The arrays are south-facing, spaced 8 m apart, and fixed at an inclination angle of 36°. The panels are mounted 1.7 m and 4.4 m above the ground at their lower and upper edges, respectively.

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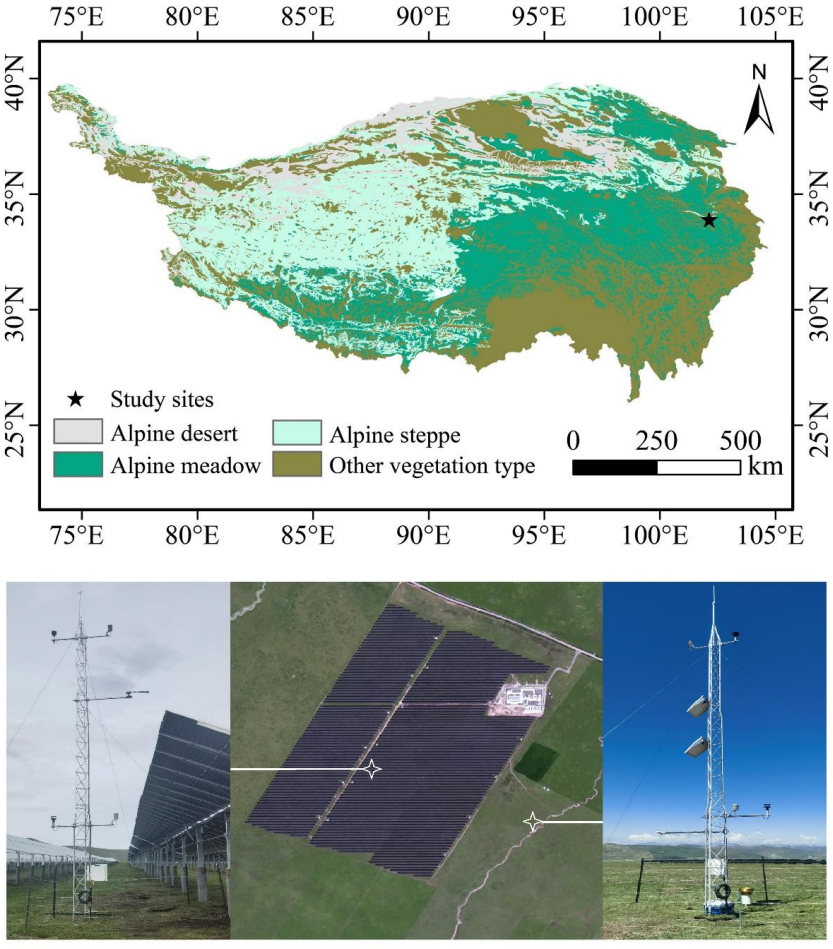

Figure 01 Map and photographs showing (a) location of Dongneng solar power plant in Tibetan Plateau, (b) © Google map of Dongneng solar power plant and surrounding area, (c) PV measurement site, and (c) reference site.

2.2 Measurements

This study deployed two 10-m towers (Fig. 01b): one within the PV array (PV site, Fig. 01c) and another reference site (RF site, Figure 01d) in an unmodified alpine meadow, approximately 180 m east of the PV farm. The RF site served as a baseline for comparing environmental conditions in areas impacted by the PV farm. Air temperature and humidity were recorded using HC2A-S3 sensors (Rotronic Instrument Corp., Switzerland) at 2.5 m and 10 m heights on both towers. Wind speed and direction were

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measured with WindSonic4 sensors (Gill Instruments, UK) at the same heights to evaluate the PV array's effect on local airflow patterns. Four-component radiation measurements (CNR-4, Kipp and Zonen, Netherlands) were taken at 2 m for the RF site and at 7 m for the PV site to assess the differences in radiation balance above the PV array and over the natural meadow. Soil temperature (CS109, Campbell Scientific, Inc., USA) and moisture (CS616, Campbell Scientific, Inc., USA) were measured at depths of 5 cm and 10 cm. At the PV site, sensors were installed beneath the PV panels and in the inter-row gaps to assess the hydrothermal effects of shading. All sensors were set to a sampling frequency of 1 Hz, with data averaged every 10 minutes by the CR1000 data loggers (Campbell Scientific, Inc., USA). Data were collected continuously over a one-year period, from June 2023 to May 2023, to capture seasonal variations in microclimate and soil hydrothermal conditions.

To ensure data quality, the study applied the following quality control measures: (1) the short-wave radiation at night was set to zero according to the solar altitude angle；(2) removed downward shortwave radiation exceeding the solar constant (1361 W/m²) during the daytime；(3) used the MAD method (Mauder et al., 2013) for outlier detection in temperature and humidity data. If three consecutive outliers were present, they were not considered as actual anomalies.

3. Results and discussion

3.1 The effect of PV arrays on wind regimes

During the observation period, the PV site experienced prevailing winds predominantly from the west and southeast (Figure 02). The structured layout of the PV panels redirected airflow primarily toward the east and west, contrasting with the more variable wind directions observed at the RF site. At a height of 2.5 m, beneath the upper edge of the PV panels, west and east winds accounted for 48% of total airflow in summer and 57% in winter, compared to 38% and 43% at the RF site.

The presence of PV panels increased surface roughness, enhancing frictional drag and obstructing near-surface wind flow. Consequently, wind speeds at a height of 2.5 m

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decreased by 39.1% in spring, 36.0% in summer, 33.6% in fall, and 36.2% in winter. The reduction was most pronounced for southeast winds, exceeding 70%, while the impact on west winds was relatively minor, with wind speed reductions of approximately 30%.

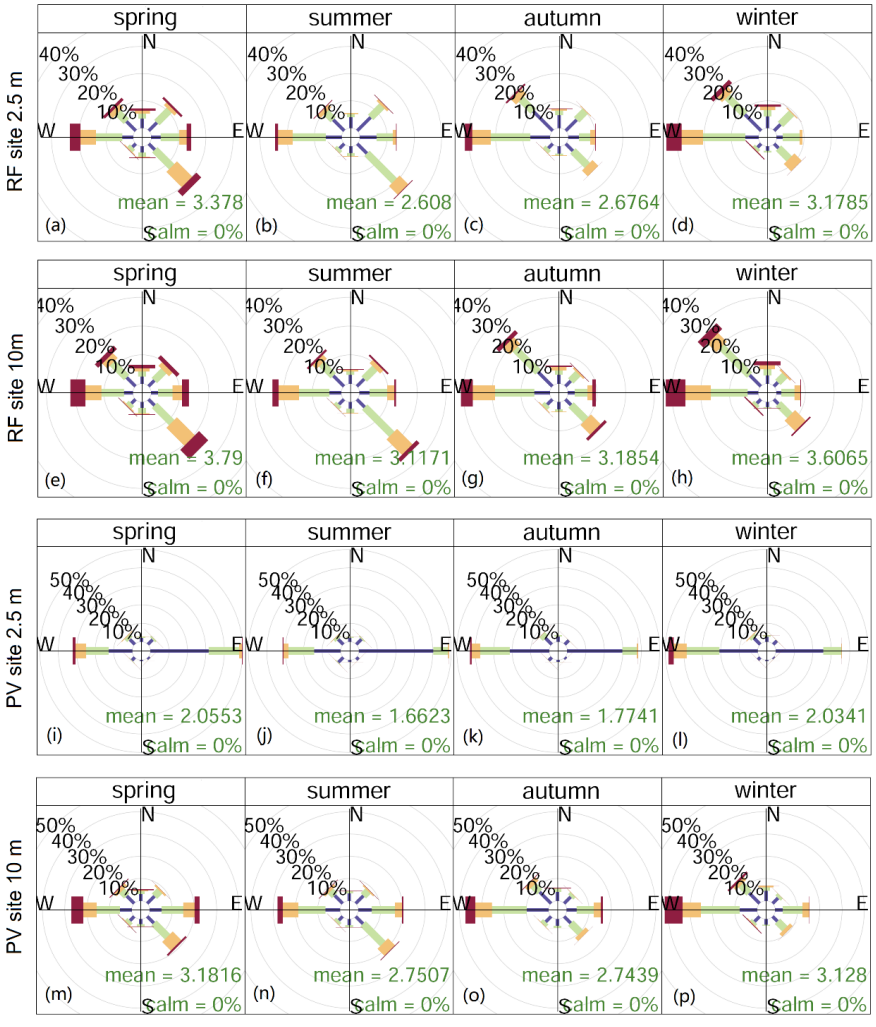

Figure 02 The wind roses at two comparative sites.

At 10 m, above the top edge of the PV panels, the directional redistribution of airflow by the panels remained consistent. West and east winds accounted for 48% of the total in summer and 56% in winter, compared to 36% and 40% at the RF site. However, the obstructive effect of the PV panels on wind speed was less pronounced at this height,

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with reductions of 15.8% in spring, 11.9% in summer, 14.1% in fall, and 13.3% in winter. North winds experienced the largest reductions (approximately 40%), while west winds were minimally affected, with reductions of around 7%.

These findings reveal a pronounced directional dependence of the PV panels' influence on wind regimes, consistent with previous studies (Jiang et al., 2021; Li et al., 2022b). However, variations in the magnitude of effects can be attributed to differences in PV field layouts and background climatic conditions.

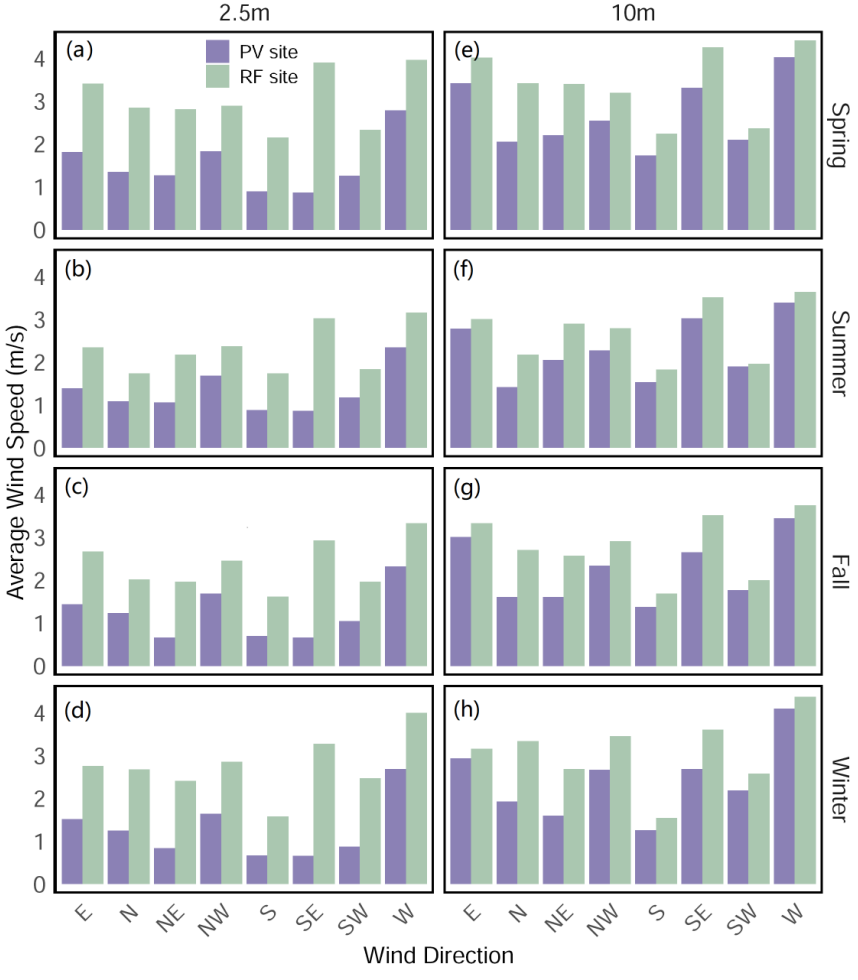

Figure 03 Seasonal variations in average wind speed by direction at 2.5 m and 10 m heights for PV and RF sites.

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3.2. The effect of PV panels on surface radiation components

As shown in Figure 04 and Table 01, downward shortwave radiation (DR) and downward longwave radiation (DLR) measured above the PV panels were comparable to those observed over the natural meadow. However, upward shortwave radiation (UR) was significantly reduced above the PV panels due to their strong solar absorption, particularly in the peak values of the seasonal average diurnal variations. The peak UR values were approximately 38% lower in summer and 50% lower in winter at the PV site. The daily total UR at the PV site was lower than at the RF site by 36.7% in spring, 36.8% in summer, 43.2% in fall, and 47.8% in winter (Table 01).

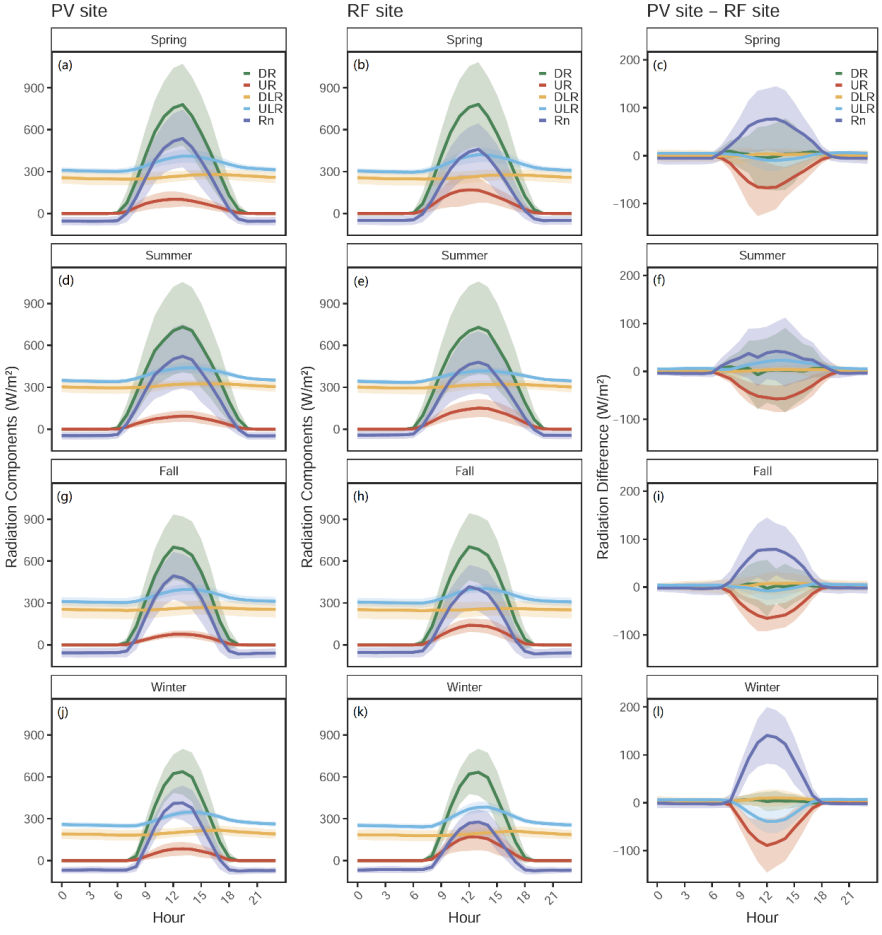

Figure 04 Seasonal averaged diurnal variations in radiation components and their differences between PV and RF sites.

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Table 01 Averaged daily total radiation (MJ) components for PV and RF sites.

		PV site	RF site	Relative change
DR	Spring	20.48	20.33	0.7
	Summer	20.99	20.82	0.8
	Fall	16.94	16.83	0.6
	Winter	14.12	14.00	0.9
	Annual	18.13	17.99	0.8
UR	Spring	2.93	4.63	-36.7
	Summer	2.85	4.51	-36.8
	Fall	2.04	3.59	-43.2
	Winter	2.04	3.90	-47.8
	Annual	2.46	4.16	-40.8
DLR	Spring	22.54	22.46	0.4
	Summer	26.77	26.59	0.7
	Fall	22.15	21.95	0.9
	Winter	15.94	15.81	0.8
	Annual	21.85	21.70	0.7
ULR	Spring	29.52	29.41	0.4
	Summer	32.12	31.90	0.7
	Fall	29.04	28.88	0.6
	Winter	24.48	24.85	-1.5
	Annual	28.79	28.76	0.1
Rn	Spring	10.56	8.75	20.7
	Summer	12.79	11.00	16.3
	Fall	8.01	6.31	26.8
	Winter	3.55	1.05	238.1
	Annual	8.73	6.78	28.8

The daily albedo at the PV site was 0.184 in spring, 0.159 in summer, 0.161 in fall, and 0.228 in winter. Compared to the RF site, the PV array reduced the albedo by 29.9%, 33.6%, 33.4%, and 30.1%, respectively. At an annual scale, installation of a PV field led to a 31.56% decrease in surface albedo compared to the alpine meadow. As summarized in Table 02, the reduction in albedo of this alpine meadow is slightly lower than the average findings over desert areas at annual and seasonal scales (Broadbent et al., 2019; Li et al., 2022c; Stern et al., 2023; Yang et al., 2017; Ying et al., 2023), but much higher than that observed over barren areas (Chang et al., 2018) and water body (Ying et al., 2023). The reduction in this study aligns with the finding that the higher the albedo of the background surface, the more pronounced the relative change in

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surface albedo over the PV farm (Xu et al., 2024).

For upward longwave radiation (ULR), although the daily cumulative values between the two sites are relatively similar (Table 01), their differences vary between day and night as well as across seasons. During nighttime, ULR at the PV site is consistently slightly higher than that at the RF site across all seasons, with an average increase of approximately 5.0 Wm^{-2}. However, during the daytime, seasonal variations showed contrasting patterns. In spring, fall, and winter, the PV site recorded lower ULR than the RF site. The daytime greatest negative deviation being most pronounced in winter (-39.0 W m^{-2}), followed by spring (-10.1 Wm^{-2}) and autumn (-8.0 Wm^{-2}).

PV plant effects on ULR, which vary between daytime and nighttime as well as across different seasons, have also been observed in previous studies (Broadbent et al., 2019; Chang et al., 2018; Jiang et al., 2021; Li et al., 2022b; Yang et al., 2017). The underlying reasons for these variations are primarily attributed to three interrelated factors: (1) the lower emissivity of PV modules (~0.83) (Broadbent et al., 2019) compared to natural surface (0.95–1) (Campbell and Norman, 1998), which reduce ULR; 2) the cavity effect (Broadbent et al., 2019), where semi-enclosed spaces beneath PV modules cause repeated radiative exchanges, enhancing ULR; and 3) differences in land surface temperature (LST), which influences ULR patterns depending on the season and time of day(Chang et al., 2018; Yang et al., 2017). Wang et al. (2024b) reported that the PV site exhibited higher land surface temperatures (LST) during nighttime and the warm-season daytime, but lower LST during the daytime in the cold season. This result suggest that during both nighttime and warm-season daytime, the elevated LST at the PV site exerts a positive influence on ULR, while the reduced LST at the PV site during the cold-season daytime has a negative effect, diminishing ULR.

In this study, we infer that the higher ULR observed at the PV site during both nighttime and summer daytime is primarily due to the combined positive effects of the cavity effect and the higher LST, which outweigh the negative effect of the PV modules' lower emissivity. Conversely, the lower ULR at the PV site compared to the reference site during the daytime in spring, autumn, and winter likely results from the dominant negative effects of lower LST and the PV modules' lower emissivity, which surpass the

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positive effect of the cavity effect.

The net radiation (Rn) differences between the PV and RF sites also showed clear seasonal dependencies. The PV site exhibited higher Rn across all seasons, with peak diurnal variations exceeding the RF site by 76.8 Wm^{-2} in spring, 42.0 Wm^{-2} in summer, 78.8 Wm^{-2} in fall, and 140.6 Wm^{-2} in winter. The relative difference in Rn between two sites also showed that the influence of PV panels on Rn was most pronounced in winter (Table 01), corresponds to the result that the largest relative difference in albedo during this season. Consistent with previous studies (Broadbent et al., 2019; Chang et al., 2018; Jiang et al., 2021; Li et al., 2022b; Li et al., 2022c), PV modules can significantly amplify land surface energy availability. The relative difference in Rn between our two sites showed that the influence of PV panels on Rn was most pronounced in winter (Table 01), not only due to the largest relative difference in albedo during this season but also as a result of manual adjustments to the tilt angle of PV panels and snow clearing on their surfaces.

Table 02 Comparison of in-situ albedo observations across different PV power plant.

Latitude (°)	Longitude (°)	Land cover	In-situ albedo observations			Source
			Background	Absolute change	Relative change	
36.136N	100.588E	Barren	0.17^{Summer}	-0.01	-6.3%	Chang et al. (2018)
36.136N	100.588E	Barren	0.19^{Winter}	0.02	11%	Chang et al. (2018)
36.503N	95.233E	Desert	0.26^{Annual}	-0.07	-27%	Yang et al. (2017)
44.410N	87.660E	Desert	0.23^{Summer}	-0.09	-39.1%	Li et al. (2022c)
44.410 N	87.660E	Desert	0.22^{Summer}	-0.08	-36.4%	Ying et al. (2023)
29.965N	35.059E	Desert	0.38^{Annual}	-0.21	-55.2%	Stern et al.

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						(2023)
32.555N	111.284°W	Desert	0.31 October to June	-0.11	-35.5%	Broadbent et al. (2019)
32.303N	119.793E	Water body	0.101 annual	-0.019	-18.8%	Li et al. (2022b)
34.055N	101.888E	Alpine meadow	0.184 Spring	-0.079	-29.9%	This study
34.055N	101.888E	Alpine meadow	0.159 Summer	-0.081	-33.6%	This study
34.055N	101.888E	Alpine meadow	0.161 Fall	-0.081	-33.4%	This study
34.055N	101.888E	Alpine meadow	0.228 Winter	-0.098	-30.1%	This study
34.055N	101.888E	Alpine meadow	0.258 annual	-0.085	-31.6%	This study

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3.3 The effect of PV arrays on air temperature and humidity

The PV panels significantly influenced air temperature (Ta) at both 2.5 m and 10 m heights, with diurnal and seasonal variations observed between the PV site and RF site (Figure 05). At 2.5 m, the PV site exhibited an average annual Ta increase of 0.08°C compared to the RF site. This increase was more pronounced at 10 m, with an annual mean difference of 0.17°C.

The influence of PV panels on Ta demonstrated a distinct diurnal asymmetry. During the daytime, the PV site consistently shows a warm bias relative to the RF site due to heat released from PV panels. The maximum warm bias ranges from 0.65°C (winter) to 1.60°C (summer) at 2.5 m, and from 0.46°C (winter) to 0.70°C (summer) at 10 m. These values are consistent with previous studies in desert or barren areas, which reported local increases in daytime air temperature ranging from 0.1°C to 1.9°C (Broadbent et al., 2019; Fthenakis and Yu, 2013; Jiang et al., 2021; Yang et al., 2017).

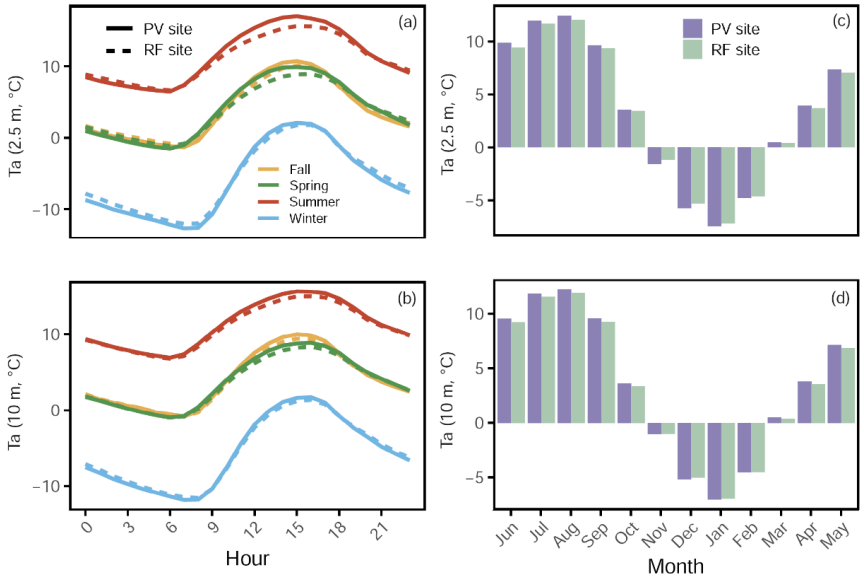

Figure 05 Diurnal and monthly variations of air temperature (Ta) at different heights (2.5 m and 10 m) for PV and RF sites.

During the nighttime, the PV site exhibits a cold bias relative to the RF site. At 2.5 m, the maximum cold bias ranges from -0.46°C in summer to -0.89°C in winter, while at

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10 m, it varies between -0.01°C in summer and -0.46°C in winter. The cooling effect of PV farms is primarily attributed to two key mechanisms (Barron-Gafford et al., 2016; Broadbent et al., 2019; Yang et al., 2017): (1) the shielding effect of PV panels, which minimizes heat accumulation in the soil and enhances nocturnal radiative cooling of the ground surface; and (2) the reduction in PV panel temperatures below ambient air temperature at night, further contributing to the cooling of near-surface air. Interestingly, a small number of studies have reported that PV plants also exhibit a nocturnal warming effect. For instance, Barron-Gafford et al. (2016) observed a significant nocturnal heating effect of 3–4°C at a height of 2.5 m in a utility-scale PV array in southern Arizona. This may be attributed to the presence of impervious surfaces near the PV array, as well as the smaller and less continuous scale of the PV array (Broadbent et al., 2019).

The dynamics of monthly Ta suggest that PV panels also exhibit asymmetrical effects on near-surface air temperature between warm and cold seasons (Figure 05c, d). From March to October, the PV site generally experiences higher Ta than the RF site. However, from November to February, the PV site sees lower Ta compared to the RF site. This seasonal reversal may be attributed to the enhanced cooling effect and reduced warming effect of PV panels during the colder months with lower solar input.

The warming effect of PV arrays on Ta in this alpine meadow region is much weaker than that observed in low-altitude areas (Barron-Gafford et al., 2016; Fthenakis and Yu, 2013; Jiang et al., 2021; Li et al., 2022b; Yang et al., 2017). This phenomenon can be attributed not only to differences in PV array characteristics but, more importantly, to the lower background temperature in this region. Higher daily temperatures are known to enhance the warming effect of PV panels (Broadbent et al., 2019; Jiang et al., 2021). Specific humidity (q) was also influenced by the PV panels. It was consistently higher than at the RF site (Figure 06). This increase was most significant during summer daytime, when q at the PV site was up to 4% higher at a height of 2.5 m. This can be attributed to reduced wind speeds and lower evapotranspiration beneath the PV panels, which retain more moisture in the immediate environment. At 10 m, however, the differences in q between the two sites were less pronounced due to the reduced

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influence of near-surface shading.

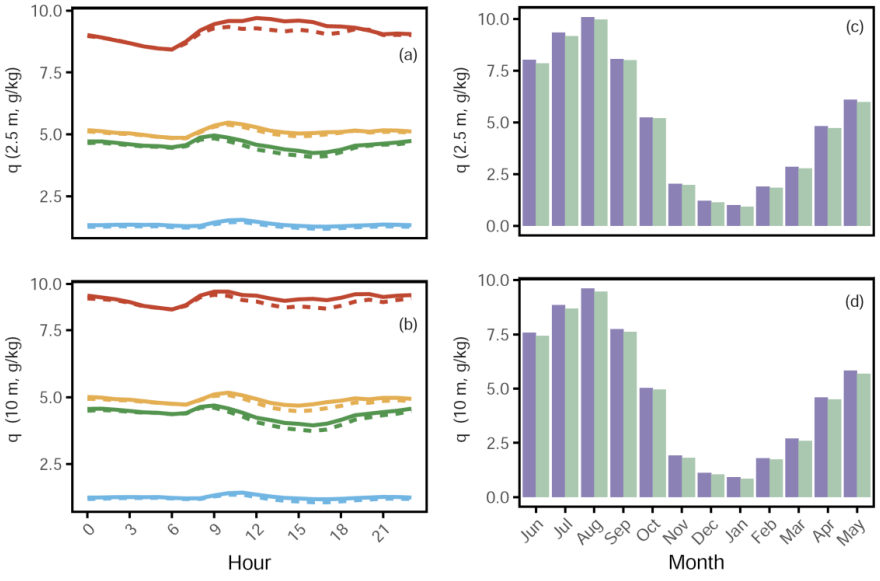

Figure 06 Diurnal and monthly variations of air specific humidity (q) at different heights (2.5 m and 10 m) for PV and RF sites.

The vapor pressure deficit (VPD) exhibits diurnal and seasonal patterns (Figure 07) similar to those of Ta (Figure 05). The daytime maximum positive bias ranges from 0.03 kPa (winter) to 0.16 kPa (summer) at 2.5 m, and from 0.01 kPa (winter) to 0.05 kPa (summer) at 10 m. The nighttime maximum negative bias occurs in spring, with a value less than 0.03 kPa. On a seasonal scale, the difference in VPD between the two sites reaches its peak in summer, with the average VPD at 2.5 m and 10 m at the PV site being approximately 10.8% and 4.1% higher than at the RF site, respectively. Annually, VPD at the PV site is slightly higher than at the RF site, with differences of about 5% at 2.5 m and 1% at 10 m.

The discrepancy between VPD and q suggests that variations in VPD are primarily driven by temperature changes rather than differences in specific humidity in this alpine region. This indicates that, despite the higher q at the PV site, the warming effect of PV panels during the daytime elevates the air's evaporative demand, potentially exacerbating water loss from vegetation and soil. However, the relatively higher soil moisture observed at the PV site may help offset this effect by sustaining local

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evaporation and transpiration rates.

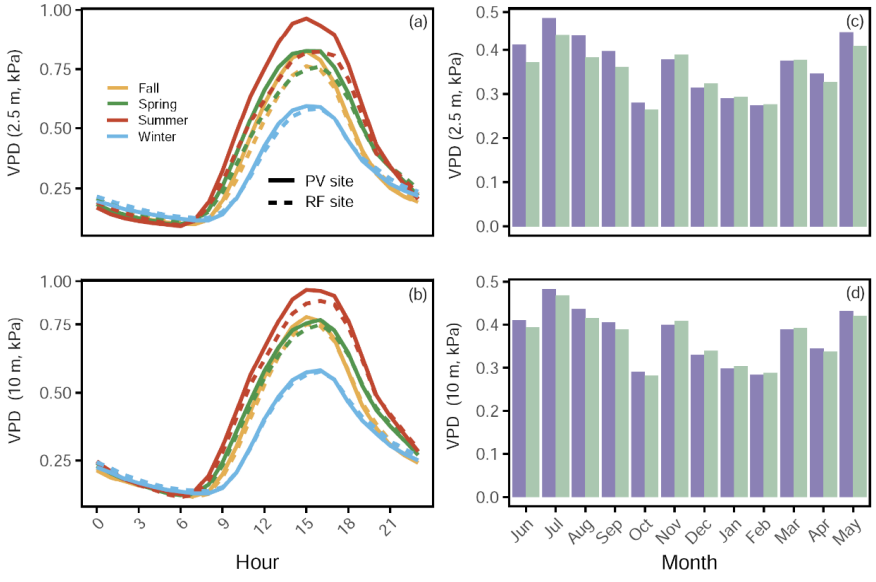

Figure 07 Diurnal and monthly variations of vapor pressure deficit (VPD) at different heights (2.5 m and 10 m) for PV and RF sites.

3.4. The effect of PV arrays on soil temperature and soil moisture

The presence of PV arrays significantly influences the thermal properties of the soil. The shading effect of PV panels results in consistently lower soil temperatures (Ts) beneath the panels and in the gaps between rows throughout the year. Soil beneath the panels begin to freeze (daily Ts below 0°C for three consecutive days) 27 days earlier and thaw 20 days later compared to the RF site. In the gaps between rows, freezing begins 20 days earlier and thawing is delayed by 31 days. At a 10 cm depth, similar trends are observed, with freezing starting 28 days earlier and thawing delayed by 31 days beneath the panels, and in the gaps, freezing occurs 26 days earlier with a 28-day delay in thawing.

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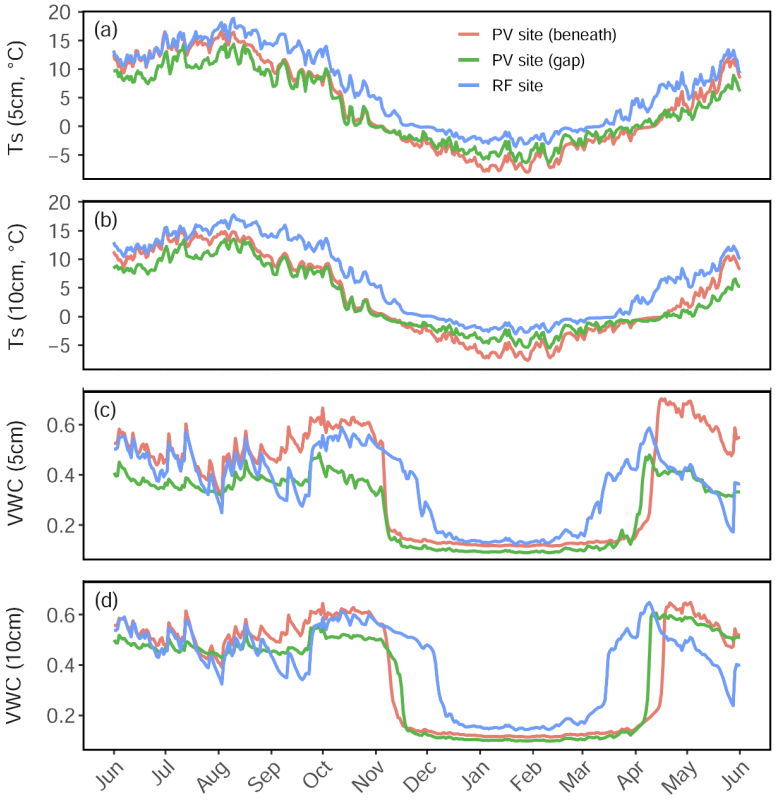

Figure 08 Seasonal dynamics of daily average soil temperature (Ts) and volumetric water content (VWC) at 5 cm and 10 cm depths.

During spring, summer, and fall, Ts at both depths are highest at the RF site, followed by the gaps between the rows, and lowest beneath the panels (Table 03). The differences in Ts between the locations are most pronounced in the fall, with the RF site showing that Ts is 3.89°C higher than in the gaps and 4.23°C higher than beneath the panels at a depth of 5 cm. This result aligns with previous studies that have documented significant cooling effects in PV fields due to shading, which lowers the soil temperature relative to surrounding areas (Armstrong et al., 2016; Choi et al., 2024; Wu et al., 2022; Yue et al., 2021; Zheng et al., 2023).

During winter, the Ts pattern shifts to RF site > beneath the panels > in the gaps between the rows (Table 03). Specifically, at a 5 cm depth, the average Ts at the RF site is approximately 2.33°C higher than beneath the panels and 3.83°C higher than in the

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gaps. At 10 cm depth, the temperature difference is approximately 1.89°C higher at the RF site compared to beneath the panels, and 3.65°C higher compared to the gaps. The slightly higher Ts beneath the PV panels compared to the gaps may be attributed to the insulation effect of the panels and their thermal radiation properties. PV panels reduce direct exposure to cold air, limiting heat loss from the soil. Additionally, the panels absorb solar radiation and transfer some of the heat to the soil beneath, helping to maintain relatively higher temperatures. In contrast, the soil in the gaps between the rows is more exposed to cold air, leading to greater temperature fluctuations and lower overall temperatures. (Yue et al., 2021) also reported that the soil beneath the PV panels maintains warmer soil conditions in winter due to the insulation and heat transfer provided by the PV panels.

Table 03 Average soil temperature (°C) at 5 cm and 10 cm depths for PV and RF sites.

	Annual	Spring	Summer	Fall	Winter
RF site (5cm)	6.50	5.29	14.64	7.73	-1.67
PV site (gap, 5cm)	3.53	2.24	13.50	3.89	-5.50
PV site (beneath, 5cm)	2.97	1.65	10.73	3.50	-4.00
RF site (10cm)	6.37	4.66	14.37	7.95	-1.49
PV site (gap, 10cm)	3.27	1.53	12.61	4.08	-5.14
PV site (beneath, 10cm)	2.79	0.48	10.42	3.59	-3.34

Soil volumetric water content (VWC) also exhibits significant seasonal variations across different locations (Figure 08). In spring and autumn, soil moisture at the RF site remains consistently higher compared to the other two locations (Table 04). This is primarily due to earlier soil thawing in spring and delayed freezing in autumn at the RF site. In summer, average SWC in gaps between the PV rows is higher than that at the RF site by about 9% at both depths (Table 04). This difference can be mainly attributed to two main factors: (1) the inclined structure of the PV panels channels precipitation toward the gaps between the rows, significantly enhancing water recharge in this area;

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(2) the lower wind speed and reduced soil temperature within gaps between the rows, caused by shading from the PV panels, effectively suppress evaporation and maintain higher soil moisture levels. This result align with Choi et al. (2024), who reported that the interspace of PV arrays had the highest soil moisture (25 cm) regardless of whether the PV was bare or vegetated across three utility-scale PV facilities in Minnesota, USA.

Table 4 Average soil moisture at 5 cm and 10 cm depths for PV and RF sites.

	Annual	Spring	Summer	Fall	Winter
RF site (5cm)	0.36	0.38	0.44	0.46	0.15
PV site (gap, 5cm)	0.37	0.41	0.48	0.45	0.12
PV site (beneath, 5cm)	0.27	0.29	0.37	0.32	0.10
RF site (10cm)	0.40	0.44	0.47	0.51	0.18
PV site (gap, 10cm)	0.37	0.36	0.51	0.48	0.12
PV site (beneath, 10cm)	0.35	0.38	0.47	0.43	0.10

Conversely, the summer average SWC beneath the PV panels is the lowest among the three locations (Table 04) due to precipitation interception by the panels, which limits direct water input to the underlying soil. Interestingly, at 10 cm depth, the summer average SWC shows no significant difference between the beneath-PV and RF sites. However, at 5 cm depth, the SWC beneath PV is approximately 16% lower than at the RF site. This suggests that subsurface soil layers under PV panels may benefit from lateral water redistribution and upward soil moisture migration driven by capillary action and vegetation root water uptake (Jury and Horton, 2004), partially offsetting the reduced surface recharge. Different form the result of Yue et al. (2021), who reported significantly higher SWC at depths of 10–40 cm beneath PV panels compared to non-PV areas during the rainy season, with the moisture difference decreasing with depth. Choi et al. (2024) observed inconsistent effects across facilities: the median SWC beneath PV panels was lower than the reference site in two facilities but higher in one. This highlights that, even under similar climatic conditions, variations in PV system

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structure, soil properties, and management practices can lead to inconsistent SWC patterns beneath PV panels.

Due to the seasonal variability of precipitation, seven consecutive 6-day periods without rainfall occurred in this alpine meadow when the soil was in a thawed state. Therefore, the linear decrease slopes of daily SWC at different locations inside and outside the PV field were compared. The Figure 09 shows that the decrease rates of soil moisture at the RF site at 5 cm and 10 cm depths are significantly higher than those at PV sites, approximately 1.3 times and 3.5 times the rate of decrease between the PV rows and beneath PV, respectively. This result further indicates that the presence of the PV field effectively inhibits soil moisture loss.

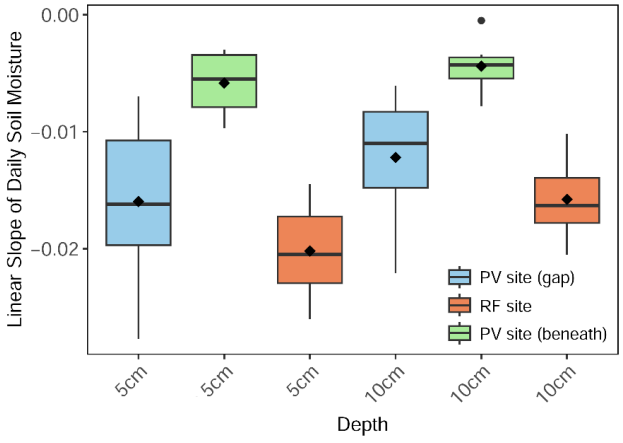

Figure 09 Linear decrease slopes of daily SWC (5cm and 10cm) at different locations for PV and RF sites during dry periods.

4. Conclusions and Implications

Pastoral-integrated PV power plant, a form of agrivoltaism, offer an innovative solution to the increasing demand for sustainable pastoralism and renewable energy. As solar PV energy development continues to expand, concerns about its potential impacts on the ecological environment, particularly in fragile and sensitive regions such as the Tibetan Plateau, are gaining prominence.

This study investigates the effects of PV arrays on the local meteorological conditions and soil hydrothermal dynamics in a high-altitude alpine meadow on the eastern Tibetan

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Plateau. The findings reveal that the installation of PV panels increases annual mean net radiation by 28.9%, while reducing albedo and 2.5 m wind speed by 31.6% and 36.2%, respectively. Despite the slight warming effect on annual mean air temperature (Ta), the impact of PV panels is highly asymmetric: daytime heating, nighttime cooling, summer warming, and winter cooling. During summer daytime, Ta, q, and VPD at the PV site are 11.1%, 4%, and 22.2% higher, respectively, than at the RF site. The PV field introduces substantial spatial heterogeneity in soil hydrothermal properties. Beneath the panels, the soil exhibits a cold-moist characteristic, while the gaps between PV rows display a cold-dry distribution. Lower soil temperatures extend the frozen period within the PV field by nearly 50 days compared to the RF site. Furthermore, the rate of soil moisture loss during non-freezing periods is significantly reduced, with depletion rates beneath the panels and in the gaps being up to 3.5 and 1.3 times lower, respectively, compared to the RF site.

These results suggest that PV arrays provide thermal buffering effects, which are crucial for mitigating the impacts of climate warming on the Tibetan Plateau. Climate projections indicate that global temperatures will likely surpass the 1.5 °C threshold, with regional warming on the Tibetan Plateau expected to exceed the global average due to elevation-dependent warming (You et al., 2020). Such rapid warming has already impacted soil freeze-thaw cycles, hydrological systems, carbon dynamics, and vegetation succession (Armstrong et al., 2014; Chen et al., 2022; Luo et al., 2020; Ma et al., 2022; Yang et al., 2014; Zhao et al., 2021). By buffering soil temperature fluctuations and extending the frozen period, PV arrays can mitigate permafrost degradation and associated greenhouse gas emissions. Moreover, reduced soil moisture depletion during dry periods creates favorable conditions for vegetation growth and photosynthesis. However, the shortened growing season may reduce vegetation carbon absorption, potentially offsetting some of these benefits.

The study area, a critical water source region for the upper Yellow River, plays a vital role in regional hydrology. Enhanced soil moisture promotes deep percolation, which strengthens groundwater recharge and supports water conservation. However, changes in freeze-thaw dynamics, such as advanced freezing and delayed thawing, could alter

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the spatial and temporal distribution of runoff. This is particularly evident in the release patterns of meltwater and frozen soil water, potentially disrupting downstream water availability. Although the current observational equipment in this study does not provide quantitative evapotranspiration (ET) results, an analysis based on the established relationship between ET and meteorological factors (Allen et al., 1998) indicates that PV arrays exert a dual impact on ET. On one hand, PV systems elevate Ta and VPD, which enhances atmospheric demand for water vapor, thereby intensifying ET. On the other hand, the shading effect of PV panels reduces the Rn reaching the soil surface, and the structural design of the arrays significantly decreases wind speed. These two factors collectively suppress ET. Therefore, subsequent research should utilize eddy covariance systems, along with lysimeters, to quantitatively assess the impact of PV fields on ET.

From a biodiversity perspective, the introduction of microenvironmental heterogeneity through shading and moisture redistribution by PV arrays may influence vegetation dynamics. The reduced Ts and longer frozen conditions may limit the dominance of tall, light-demanding grasses, creating niches for shade-tolerant C3 plants (Wang et al., 2024a). This shift could counteract vegetation homogenization trends, promoting species diversity in alpine grasslands. However, the shortened growing season poses challenges for species with growth cycles tied to freeze-thaw dynamics, potentially reducing their adaptive capacity. PV arrays may act as both stabilizing and destabilizing forces for plant communities, necessitating further study on their long-term ecological impacts.

These broader-scale implications suggest that PV arrays offer a pathway to improve alpine meadow ecosystem resilience in a warming climate. Future research should incorporate multi-year observations and numerical models to evaluate the long-term effects of PV arrays on regional climate, hydrological processes, and ecological functions, including biodiversity and carbon sequestration, under varying climatic conditions.

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Code/Data availability

The data and code supporting the findings of this study are available upon request to the corresponding author, Shaoying Wang (wangshaoying@lzb.ac.cn).

Author contribution

Conceptualization: SW and XM; methodology: SW, PY and QL; funding acquisition: SW, XM, ZL and ZL; data curation and visualization: SW, LS, and WN; field measurement: SW, WN; All authors actively contributed to the discussions and to the writing of the final version of the paper.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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