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Original Research

Spatial Heterogeneity of Vegetation Communities and Soil Properties in a Desert Solar Photovoltaic Power Station of the Hexi Corridor, Northwestern China

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Abstract

Arid sandy areas have great potential for producing solar power, so many solar photovoltaic (PV) systems have been constructed in desert regions. Hexi corridor, a typical and broadly representative desert ecosystem in northwestern China, is well-known for its abundant sunshine and great numbers of solar PV systems. However, spatial heterogeneity in vegetation and soil properties across different PV panel locations in Hexi Corridor remain unclear to date. To address this gap, we evaluated the spatial heterogeneity of the vegetation community, and soil properties in and near a PV station in a desert region of the Hexi corridor. Measurements were conducted at six locations under and around the panels, and at distances of 200 to 600 m from the panels. Results show that the aboveground biomass (AGB) and three plant diversity indices differed from locations inside and outside the PV station. Soil water contents to a depth of 30 cm were greatest under the panels. Soil organic carbon (SOC) inside the PV station was higher than outside the PV station, and was increased with increasing distance from the panels. On the contrary, total nitrogen (TN) contents inside the PV station was lower than those outside the PV station. The differences in plant diversity indices, SOC, and TN between inside and outside were generally not significant. Our results indicate that solar PV construction on sandy land of the Hexi Corridor impact the spatial distribution of vegetation and soil properties, and the positive effects of PV panels on vegetation and soil may outweigh the negative effects.

Keywords: solar photovoltaic panel, vegetation diversity, soil properties, spatial heterogeneity, desert region

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Introduction

We must limit global warming to 1.5ºC to prevent excessive damage from climate change [1]. Renewable energy, including solar, wind, biomass, hydroelectric power, and geothermal energy, are considered essential alternatives to fossil fuels in efforts to mitigate global warming, an energy crisis, and environmental pollution [2]. Among the renewable energy sources, solar energy is one of the most acceptable and promising energy sources because of its potential adoption in many areas and availability [3]. By using photovoltaic (PV) technology, solar radiation can be converted into sustainable electricity that is then distributed via a region's electrical grid [4-6]. Large-scale PV systems have many environmental benefits and advantages, including the reduction of greenhouse gas emissions [7-8], the reuse of marginal land [7], and a lack of liquid or solid waste products [9], and the PV arrays can even potentially slow winds enough to reduce erosion and dust generation in desertified land [10-11], which helps turn desert green [12]. Consequently, installation of PV power has grown rapidly in recent years [3]. In China, PV installation has also experienced dramatic growth, and China's grid-connected PV systems are now the largest in the world, at a capacity of 204.68 GW in 2019 and 336.20 GW until June 2022 [13]. Furthermore, China's government plans to massively increase PV installation with the goal of reaching 400 GW installed PV capacity in 2030 [13-14].

However, all anthropogenic disturbance of the natural environment may have significant environmental consequences. Therefore, it's necessary to accurately evaluate the impacts of PV installations on local ecosystems to elucidate their ecological impact and provide a framework for ecologically friendly solar energy development. This will be particularly important given how rapidly PV systems are being deployed around the world. For solar PV systems, the environmental impact of large-scale solar PV systems differed between the installation and operation phases [8, 15]. During the installation phase, leveling of the site before installation by using a bulldozer or other heavy equipment destroyed surface vegetation and damaged the soil, including removal topsoil and other actions such as compaction or addition of gravel [16], which made the soil more vulnerable to wind and water erosion, and lower levels of infiltration, especially in fragile ecosystems such as desert land. Besides these, the presence of solar panels changed local land use and is clearly detrimental to the natural landscape [16-17]. However, during operation phrase, PV panels block solar radiation and rainfall [8, 12]. The damaged vegetation slowly recovered, in part because the PV panels reduced wind erosion [13-16]. Field surveys have shown that the PV panels can help maintain high soil moisture levels and relieve heat stress by adjusting the air and ground temperature, which accelerate vegetation recovery progress in arid regions [9, 18-19]. That is, solar panels changed the microclimate affecting plant survival and vegetation development, which finally impact the spatial heterogeneity of vegetation community [20].

In addition to potential shifts of plant, solar PV panels affect the spatial pattern of soil properties [9, 17]. After construction, PV panels changed solar radiation and precipitation. The redistributed rainfall and sunlight that shift with the movement of the sun alter the evaporation, carbon cycling, soil water retention and ecosystem energy balance below the PV panels [21-23]. Wang et al.(2015a) [17] demonstrated that the aboveground biomass inside PV station was relatively higher, which induced a higher soil organic matter inside the station, but the differences of soil organic matter inside and outside station were not significant. Recently, work on the spatial pattern of vegetation and/or soil properties under different land cover types (e.g., forest, grassland, desert shrubland, true desert), climate condition (e.g., evapotranspiration, precipitation), and PV panel installation methods in solar PV systems has been conducted [8]. However, their work was mainly concentrated on three sampling positions: under/below the PV array, in the gap between the PV array and in the control area [9, 17, 24], excluding other positions such as in front of, near the rear of and behind of the PV panels. Then the work of Zhai et al. [25] has examined *Leymus chinensis* community diversity in 6 positions, but still ignoring the different distance outside the station. Thus, there is a lack of available information on whether similar spatial pattern occurs in other ecosystems, such as in China's ecologically fragile Hexi Corridor, which is an important area of arable land in northern China, and provides protection against blowing sand [26].

As a representative area with sufficient solar energy resources, the Hexi Corridor is a potentially important region for solar power generation in China. In 2016, about 19 PV industrial parks had been established in five cities in the Hexi Corridor: Wuwei, Jinchang, Zhangye, Jiuquan, and Jiayuguan. The installed PV capacity was 4.22 GW, which is only behind Qinghai Province, at 5.80 GW [27]. However, the installed PV capacity in Gansu province has now reached 12.49 GW until July 2022 [28]. In addition, nearly all the above-mentioned PV systems have been constructed in desert land in the Hexi Corridor [26]. This is because most of the desert land in the Hexi Corridor has low vegetation cover and strong solar irradiation, and most of the land is unused. These characteristics make it highly suitable for large-scale PV generation systems [10]. Since desert lands in the Hexi Corridor are a fragile ecosystem, the ecological impact of PV systems on the local vegetation, soil, and climate has attracted much attention. Previous studies demonstrated that PV panels can increase the surface roughness, and can thereby weaken the wind in desert regions [2]. Moreover, PV panels can decrease the likelihood of dust storm occurrence by promoting vegetation restoration to protect the soil [2, 10]. Increased vegetation cover can decrease sediment loss by the wind because it reduces the near-surface wind speed and the soil's erodibility, so vegetation both increases the resistance to erosion and increases the capacity for capturing windblown eroded material [29-31]. However, Zhou and Wang (2019) [23] showed that the disturbance created by PV panels had no significant impact on soil nutrient inside and outside the power station, and that vegetation inside the station slowly recovered during operation of the station.

Spatial variations of the vegetation community and soil properties can function as an indicator of ecosystem damage or changes in ecosystem stability. Although there is some understanding of the environmental impacts of PV systems, knowledge of the spatial distribution of vegetation and soil properties in and around PV stations in desert regions is still limited [19, 25]. Thus, the objectives of the present research were (1) to characterize the spatial heterogeneity of vegetation and soil in and around a desert PV power station; (2) to clarify the impact of large-scale PV on vegetation and soil properties in desert land in Hexi Corridor, and (3) to discuss whether the construction of PV systems benefits vegetation and soil recovery.

Material and Methods

Site Description

Our study was conducted in Gulang County, in the eastern part of the Hexi Corridor (37º45′15″N, 103º7′59″E) (Fig. 1a). The climate is a temperate arid continental climate, with annual average precipitation of 200 mm and a mean annual evaporation of 2292 mm, with mean monthly temperatures ranging from -7ºC in January to 19ºC in August. The area has a long sunshine duration, with an annual average of 2628.9 to 2852.3 h of sunlight. The dominant wind direction in Gulang County is from the northwest. The solar power station is located in the northeastern part of Gulang County. Site preparation was conducted in 2013 and the station was connected to the electrical grid in 2014, as a result of the site preparation, all vegetation was removed from the site, leaving a bare sandy surface. Leveling of the site was used before the PV panels were installed. Wire fencing (1.5 m height) was also installed before the station became operational. There is no grazing inside or outside the PV station. The PV panels were fixed polysilicon types (Fig. 1(b, c)) and PV panels all face south. The distance between soil surface and the front of each PV panel is 0.43 to 0.50 m, with a distance between soil surface and the rear of each PV panel is 2.5 m (Fig. 1b), also with a spacing of about 6-7 m between rows of panels.

Experimental Design and Sampling

The research was carried out in September 2017, 3 years after the panels were installed. Sampling sites were distributed inside and outside the PV station (Fig. 2). Inside the PV station, we defined six locations relative to the panels to account for the shading effect of each panel and the redistribution of rainfall: in front of the panel (A), near the front of the panel (B), under the panel (C), near the rear of the panel (D), behind the panel (E), and between two panels (F) (Fig. 3).

At each location, we established a transect that ran parallel to the PV panels. We then sampled using random spacing along each of the six transects, for a total of five 50 cm × 50 cm quadrats in each

a)

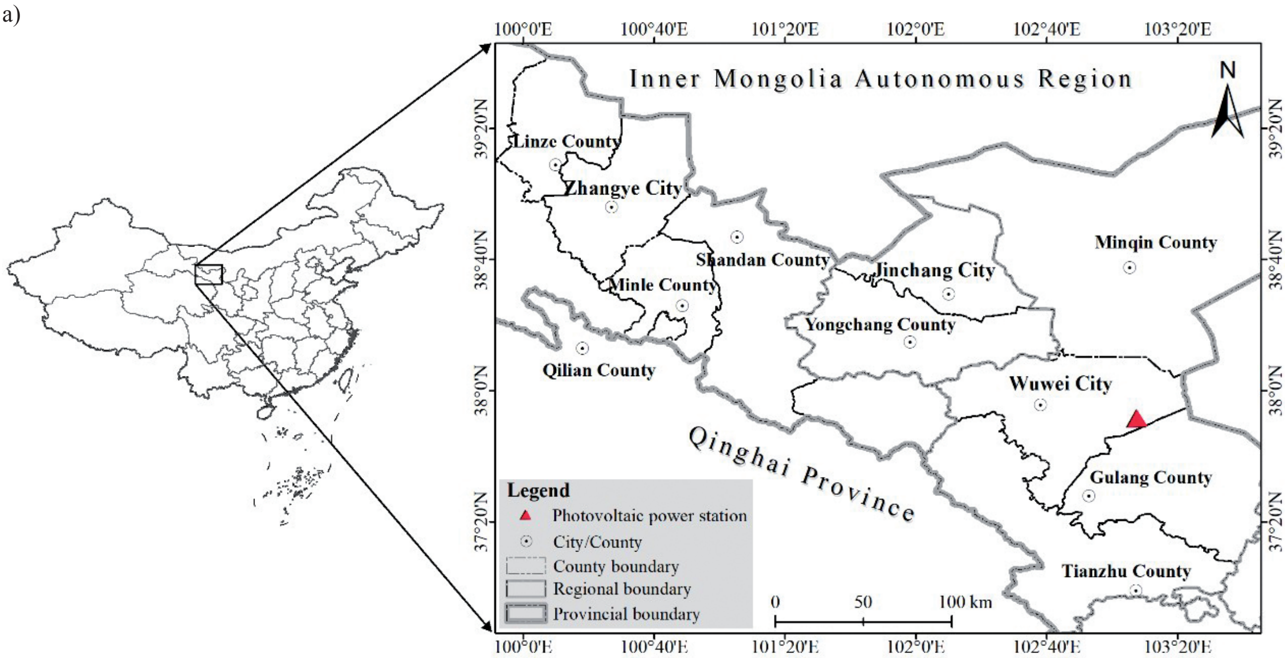

Fig. 1a). The location of the desert solar photovoltaic (PV) power station in the present study.

b)

Fig. 1b). Illustration of the panels at the photovoltaic (PV) station.

c)

Fig. 1c). The area outside the photovoltaic (PV) station.

transect, and a total of 30 quadrats (50 cm × 50 cm) inside the PV station. We also established plots outside the PV station at distances of 200, 400, and 600 m north of the station. At each distance, we established three transects oriented from north to south, and along each transect, we sampled at 10-m intervals, giving a total of five 50 cm × 50 cm quadrats along each transect, and a total of 45 quadrats (50 cm × 50 cm) outside the PV station.

In each quadrat, we recorded the number of plant species, the height of each plant, the number of plants of each species, and the vegetation cover. We then collected the aboveground biomass (AGB) in each quadrat as a single composite sample. We sampled a total of 75 vegetation quadrats in this research. The basic information of plant in each quadrat was used to calculate diversity parameters (Species important values, Species richness index, Shannon-Wiener index and Simpson index) [17].

After collecting the AGB in each quadrat, we randomly collected three soil samples and combined the samples to produce a single composite sample from each quadrat and each soil depth. Soil samples per quadrat at depths of 0 to 10 cm, 10 to 20 cm, and 20 to 30 cm in the soil by excavating a hole (30 cm length × 30 cm width × 30 cm height) using a small shovel. Soils were placed in ziplock plastic bags and transported immediately to the laboratory with ice packs within 1 day. In the laboratory, we immediately divided each field-moist soil sample into two subsamples: one was used for determination of the soil gravimetric water content, and the other was air-dried at room temperature and hand-sieved through a 2-mm mesh to remove stones, visible root material, and plant debris. The air-dried sample was then used for determination of soil pH, the particle

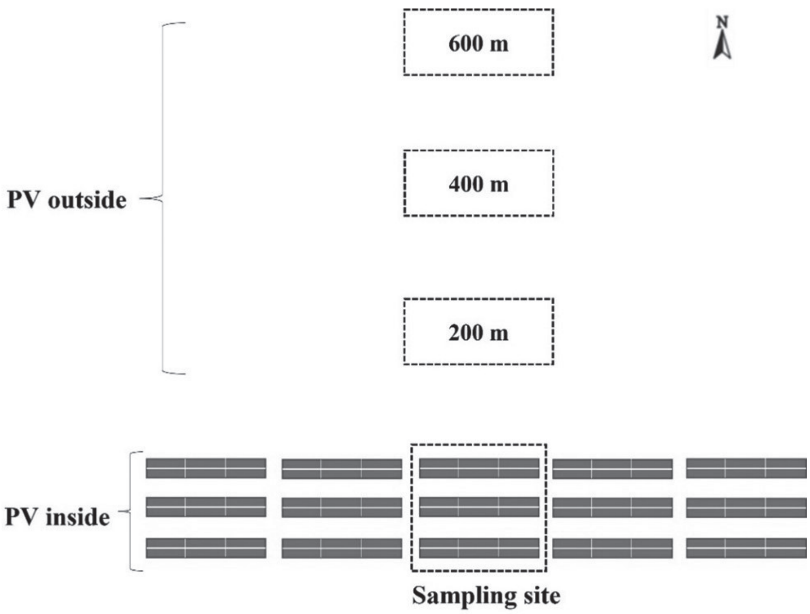

Fig. 2 Distribution of the sampling locations around the photovoltaic (PV) panels inside the station and at 200 to 600 m outside the station.

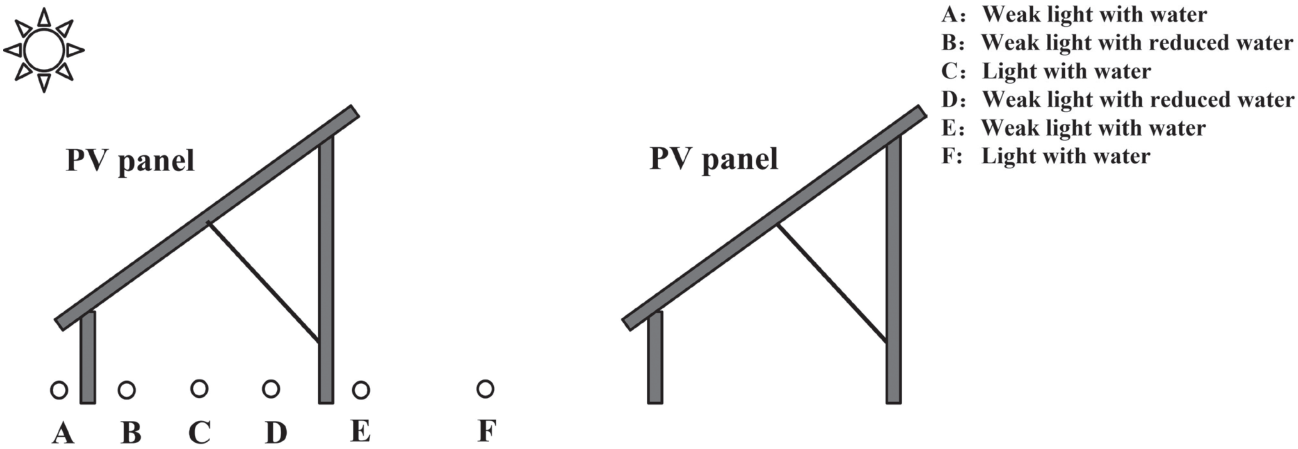

Fig. 3 Locations of the vegetation and soil sampling around the photovoltaic (PV) panels inside the station. Location descriptions: A, in front of the panel; B, near the front of the panel; C, under the panel; D, near the rear of the panel; E, behind the panel; F, between two panels.

size distribution, the soil organic carbon (SOC) content, and the total nitrogen (TN) content.

Laboratory Analysis

The AGB samples were dried at 60ºC in a forced-air oven for 48 h and weighed to the nearest 0.1 g in the laboratory. The soil gravimetric water content was determined by weighing the field-moist sample, then oven-drying it at 105ºC for 24 h. Soil pH was measured using a glass electrode, with a soil/water ratio of 1:2.5(w/v). We determined the soil particle size distribution using a Malvern Mastersizer 2000 Particle Analyzer. The SOC content (% w/w) was determined using the Walkley-Black dichromate oxidation method, and the TN content (% w/w) was determined using the Kjeldahl procedure [32].

Data Analysis

We used one-way ANOVA to identify significant differences in the vegetation community and soil properties among the locations inside and outside the PV station. When the ANOVA result was significant, we used least-significant-difference (LSD) tests to compare pairs of means. All statistical analyses were performed using version 18.0 of the SPSS software (https://www.ibm.com/analytics/spss-statistics-software). We used Pearson's correlation coefficient (r) to quantify the relationships among the measured vegetation and soil properties.

Results and Discussion

Spatial Heterogeneity of Vegetation Composition

We found 3 families, 7 genera, and 7 species in the plant community inside and outside the desert PV station (Table 1), and four species from four genera in the *Amaranthaceae* family accounted for 57.1% in all species. The species important value was lowest in front of the panel and life forms at the station were dominated by annual herbs (71.4% of the species). The five most important species were *Agriophyllum squarrosum, Bassia dasyphylla, Corispermum hyssopifolium, Salsola collina,* and *Taraxacum mongolicum*. *Agriophyllum squarrosum* and *Bassia dasyphylla* were found both inside and outside the PV station, whereas the other three species were mostly found inside the PV station.

Spatial Heterogeneity of Vegetation Diversity

Vegetation community is a critical biotic component in sand dune habitats because it has both direct and indirect impacts on the stability and resilience of dunes [33-34]. The aboveground biomass (AGB) in front of the panel was significantly higher ($P<0.05$) than that at other locations inside the station, but not significantly different from the values outside the station (Table 2). Similarly, differences in the Species richness index, Shannon-wiener index and Simpson index also did not differ significantly among the sample locations (Table 2, $P>0.05$), and were higher inside the PV station. Moreover, the vegetation community compositions outside PV station were in the order of 200 m>400 m >600 m (Table 2). Our finding suggests that the construction of PV panels in desert land resulted in spatial variations of herbaceous community diversity, which is in accordance with the other studies in solar PV system. The rain harvesting and shading by the PV panels can slow wind and water erosion, which promote vegetation restoration and plant diversity inside the PV station [9, 25]. By using a microclimate model, Li et al. (2018) [19] reported that the PV panels of large-scale solar farms in the Sahara Desert reduced the surface albedo, creating a beneficial

Table 1. Vegetation characteristics in the desert photovoltaic (PV) station.

Families	Species	Life form	Species important value								
			Inside PV						Outside PV		
			A	B	C	D	E	F	200 m	400 m	600 m
Amaranthaceae	*Agriophyllum squarrosum*	Annual herb	0.13	—	0.26	—	—	0.22	0.47	0.54	0.69
	Bassia dasyphylla	Annual herb	0.31	—	0.65	—	0.52	—	0.35	0.31	0.24
	Corispermum hyssopifolium	Annual herb	0.47	—	—	—	0.19	0.28	—	—	—
	Salsola collina	Annual herb	—	—	—	—	—	0.39	—	—	—
Asteraceae	*Taraxacum mongolicum*	Perennial herb	—	—	—	—	0.16	—	—	—	—
	Echinops gmelini	Annual herb	—	—	—	—	—	—	0.20	—	—
Verbenaceae	*Verbena officinalis*	Perennial herb	—	—	—	—	—	—	—	0.41	—

"—"represents not found. Location descriptions: A, in front of the panel; B, near the front of the panel; C, under the panel; D, near the rear of the panel; E, behind the panel; F, between two panels. 200, 400, and 600 m represent distances outside the station.

albedo-precipitation-vegetation feedback, leading to increasing temperature and precipitation that increased the vegetation cover.

We also found the number of plants, Shannon-Wiener index, and Simpson's index under the panel were lower than those in front of the panel and behind the panel, although the differences between positions were not significant (Table 2, $P>0.05$). This contradicts the results reported by Zhai et al. (2018) [25] in Inner Mongolia *Leymus chinensis* communities, but in consistent with the results at south edge of Mu Us desert [17]. This discrepancy may be explained by different precipitation amount, land types and PV installation details. Zhai et al (2018) [25] reported that the precipitation in Inner Mongolia PV station was 282.4 mm, whereas in our study is only 200 mm. The land type in Inner Mongolia was *Leymus chinensis* community, whereas the land type in this study was sandy land. Further, the smaller vegetation community under the panels may have resulted from a combination of the PV panel's slope (39º) and height (43 to 50 cm) in the present study. The PV panel slope and height reported by Zhai et al. (2018) [25] were 30º and 138 cm, respectively. The lower PV panel height, higher PV slope and lower precipitation in our study would gather more rain near in front of the PV panels, but prevent rain from reaching the surface below the panels, and the lower water availability would decrease the vegetation diversity under the panels. The significant negative correlations between SWC and number of plants also proved this (Fig. 7). Further, the

Table 2. Vegetation community diversity in the desert photovoltaic (PV) station.

Locations		Variables				
		Number of plants	AGB (g·m^{2})	Species richness index	Shannon-Wiener index	Simpson index
Inside PV station	A	64	50.64±3.94a	2.00±0.58a	0.55±0.29a	0.36±0.18a
	B	0	0	0	0	0
	C	10	3.81±3.35b	1.33±0.33a	0.22±0.22a	0.16±0.16a
	D	0	0	0	0	0
	E	135	18.04±7.08ab	2.00±0.01a	0.34±0.15a	0.21±0.11a
	F	6	8.03±5.02b	2.00±0.58a	0.55±0.29a	0.36±0.18a
Outside PV station	200 m	27	43.92±11.19 b	2.00±0.58a	0.55±0.29a	0.36±0.18a
	400 m	11	46.20±2.54ab	1.67±0.33a	0.36±0.19a	0.24±0.13a
	600 m	9	24.29±5.67ab	1.33±0.33a	0.17±0.17a	0.11±0.11a

AGB: aboveground biomass. Values are mean±standard error. Values within a column followed by the same letter did not differ significantly (ANOVA followed by LSD test, $P>0.05$). The locations are listed in the method section.

Table 3. Soil texture in the desert photovoltaic (PV) station.

Locations		Sand (%)			Silt (%)			Clay (%)		
		0-10 cm	10-20 cm	20-30 cm	0-10 cm	10-20 m	20-30 cm	0-10 cm	10-20 cm	20-30 cm
Inside PV station	A	91.9±0.8a	90.4±0.8b	91.1±0.1ab	5.9±0.6a	7.2±0.5a	6.5±1.7ab	2.2±0.2a	2.4±0.4a	2.5±0.4ab
	B	92.6±1.1a	92.8±0.2ab	92.5±2.2ab	5.3±0.8a	5.2±0.1ab	5.6±1.7ab	2.0±0.4a	2.0±0.1a	1.9±0.4ab
	C	93.1±1.4a	92.8±0.8ab	93.0±1.7ab	4.9±1.1a	5.2±0.7ab	5.0±1.4ab	2.0±0.3a	2.0±0.1a	2.0±0.3ab
	D	93.6±0.9a	94.2±1.3ab	93.6±1.5ab	4.6±0.7a	4.0±1.0b	4.5±1.2ab	1.8±0.2a	1.8±0.3a	1.9±0.3ab
	E	94.2±2.2a	94.3±0.4a	93.7±0.2ab	4.2±1.7a	4.0±0.3b	4.5±0.2ab	1.6±0.5a	1.7±0.1a	1.8±0.0ab
	F	93.0±0.8a	92.5±0.7ab	92.8±0.7ab	5.1±0.6a	5.5±0.6ab	5.2±0.5ab	1.9±0.2a	2.1±0.1a	2.0±0.1ab
Outside PV station	200 m	92.2±2.0a	91.6±1.3ab	92.0±1.8ab	5.7±1.5a	6.0±0.9ab	5.8±1.4ab	2.1±0.5a	2.4±0.4a	2.2±0.4ab
	400 m	93.2±2.0a	94. 9±0.2a	94.0±0.3a	4.9±1.5a	3.6±0.1b	4.3±0.3b	1.8±0.5a	1.5±0.1a	1.7±0.1b
	600 m	92.4±0.1a	94.2±0.7ab	90.1±2.7b	5.7±0.2a	4.1±0.6b	7.3±2.1a	1.9±0.1a	1.7±0.2a	2.6±0.6a

Values are mean±standard error. Values within a column followed by the same letter did not differ significantly (ANOVA followed by LSD test, $P>0.05$). The locations are listed in the method section.

spatial pattern of vegetation diversity between locations inside and outside the PV station was not significant (Table 2), demonstrating that the vegetation community in our study may be able to recover over time after the disruption created by the establishment of the station ends. In any event, the current values suggest relatively rapid recovery of the vegetation to levels comparable to those outside the station; as a result, installation of the station appears to have had little or no long-term effect on the vegetation community.

Spatial Heterogeneity of Soil Texture and pH

All soils had a dominant sandy texture with a low clay content (Table 3). The mean sand contents to a depth of 30 cm were 91.1% in front of the panel, 92.6% near the front of the panel, 93.0% under the panel, 93.8% near the rear of the panel, 94.1% behind the panel, 92.8% between two panels, 92.0% at 200 m, 94.1% at 400 m, and 92.2% at 600 m. At a depth of 10 to 20 cm, the sand content was significantly higher behind the panel and at 400 m from the station, and the silt content was significantly lower near the rear of the panel and behind the panel than at all other locations except 400 and 600 m from the station. The corresponding mean clay contents ranged from 1.5% to 2.4% and did not differ significantly between sample locations in 0-20 cm depth (Table 3). Very few of the differences were significant. Interestingly, sand content in 0-10 cm depth inside the PV station was highest behind the panel and lowest in front of the panel, but the silt and clay contents in 0-10 cm depth showed an opposite pattern (Table 3). After investigating the airflow in Ulan Buh desert, Zhao (2016) [35] indicated that PV panels reduced near-surface wind speed. The wind speed at 10 cm height in front of the panels decreased by 36.65% compared to that outside the station, which is beneficial for soil silt and clay content accumulated in front of the panels when the wind blows from behind of the panels and between two panels.

Spatial variations in soil pH were differed from different positions (Fig. 4(a-c)). The pH ranged from 8.15 to 8.74, and at a depth of 10 to 20 cm was significantly lower near the front of the panel and at 400 and 600 m from the station; at a depth of 20 to 30 cm, it was significantly lower near the rear of the panel and at 400 and 600 m from the station ($P<0.05$).

Spatial Heterogeneity of Soil Water Content

In the present study, the average SWC at a depth of 0-30 cm depth inside the PV station was higher than those outside the station (Fig. 5(a-c)). Similar results have been reported by Liu et al. (2018) [9] in desert regions and Choi et al. (2020) [36] in grassland. The relatively higher SWC inside the PV station could be due to shading and wind sheltering by the PV array, as these has been found to decrease actual evapotranspiration by 10-40% [37]. The change in soil water content in sand dunes is mainly affected by the interaction between precipitation and evaporation. This interaction is governed by two key processes: (1) the balance between infiltration of water under gravitational energy and evaporation caused by the difference in water potential between the soil and the atmosphere, and (2) thermo-osmosis (movement of water against a potential gradient) and condensation of vapor controlled by heat conduction and heat diffusion processes [38]. Installation of PV panels changed the heat and rainfall distribution, which impact spatial heterogeneity of soil water content.

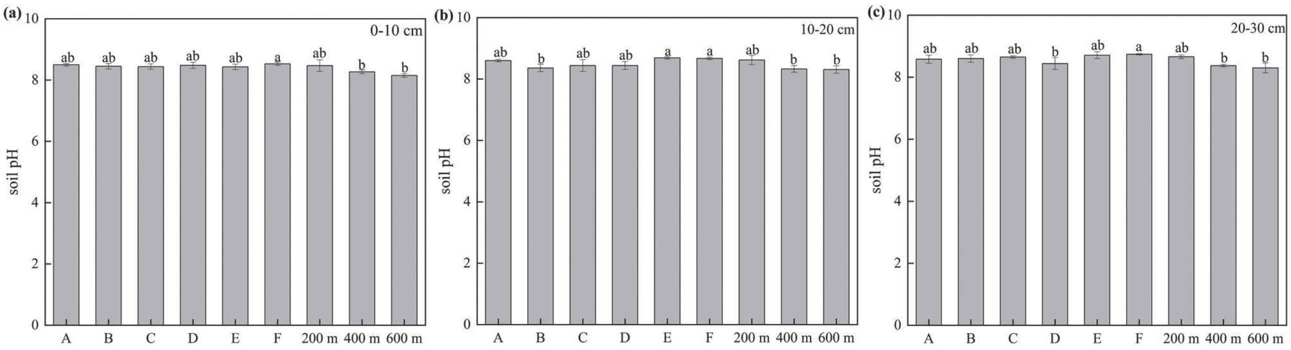

Fig. 4. Variations of the soil pH at the desert photovoltaic (PV) station. Bars indicate mean, error bars indicate standard error. Values of a parameter followed by the same letter did not differ significantly (ANOVA followed by LSD test, $P>0.05$). The locations are listed in the method section.

The soil water content (SWC) to a depth of 30 cm (Fig. 5) was significantly ($P<0.05$) higher under the panel than at most other locations, with the following exceptions: at a depth of 0 to 10 cm, SWC at 600 m from the station was not significantly different from that under the panel; at depths of 10 to 20 cm and 20 to 30 cm, SWC in front of the panel was still lower than that under the panel, but did not differ significantly. Liu et al. (2019) [9] found that solar panels directly intercepted part of the precipitation, which would be prevented from reaching the soil under the panels. The higher SWC under the panels, at a location where rainfall would be prevented from directly reaching the soil, is more difficult to explain. However, it's plausible that this can be explained by the combination of shading under the panels (which reduces solar heating of the soil that would increase evaporation of soil water) with reduced wind speed (a force that removes evaporated water from the soil). In contrast, locations near the front of the panel, near the rear of the panel, and behind the panel cannot gather sufficient rainfall and would be exposed to more sunlight, thereby increasing evaporation and decreasing SWC.

Moreover, SWC increased with increasing depth at all locations except 600 m from the station (Fig. 5). This is likely because water that infiltrates below the near-surface soil layer is less exposed to solar radiation and wind because of PV panels, and is therefore slower to evaporate. Additionally, our investigation occurred in September, when the air temperature was dropping quickly, vegetation growth was slowing, and precipitation was decreasing, but soil evaporation was still actively occurring. The precipitation is lower than evaporation during this period, which made SWC to a depth of 10 cm lower than that deeper in the soil. Additionally, SWC outside the PV station in 10-30 cm depth decreased with increasing distance, indicating a spatial heterogeneity outside the PV station.

Spatial Heterogeneity of Soil Organic Carbon, Total Nitrogen and C:N Ratio

We found the locations inside the PV station tended to have a higher soil organic carbon (SOC) content than outside PV station, but few of these differences were significant (Fig. 6(a-c)). This spatial heterogeneity has been reported by several research in solar PV systems [17, 23]. Wang et al. (2015a) [17] found that soil organic matter in the soil shaded by solar panels was higher than in surrounding locations, and they attributed this to a greater aboveground biomass inside the PV station, which provided more plant litter and more dead roots to the soils, thereby increasing the soil organic matter content. Similarly, our results also found the AGB in front of the panels was higher than that outside PV station (Table 2). The PV panels provide shelter from the wind and rain, which means more plant leaves and roots can remain inside the station (i.e., they are not carried away from the site by wind or water), thereby improving soil organic carbon content inside the PV station.

At a depth of 0 to 10 cm, SOC was significantly higher near the rear of the panel, behind the panel, and between two panels than it was at 200 m from the station (Fig. 6(a), $P<0.05$), and was highest behind the panel to a depth of 20 cm (Fig. 6(a, b)). This may result from the greater species number at this location (Table 2). According to Zhang et al. (2017) [39], the quality and quantity of plant litter and roots combined with soil organisms and microorganisms affect the accumulation and turnover of soil organic carbon. The SWC was highest under the panel (Fig. 5), but the SOC content under the panel was not highest and was even lower than that behind the panel (Fig. 6(a-c)). Although soils under the panel can receive limited rainfall through gaps between the PV panels, this soil receives only weak light during most of the day, which is not beneficial for plant growth; as a result, little vegetation became established under the panels (Table 2). Thus, the limited plant input of litter to the

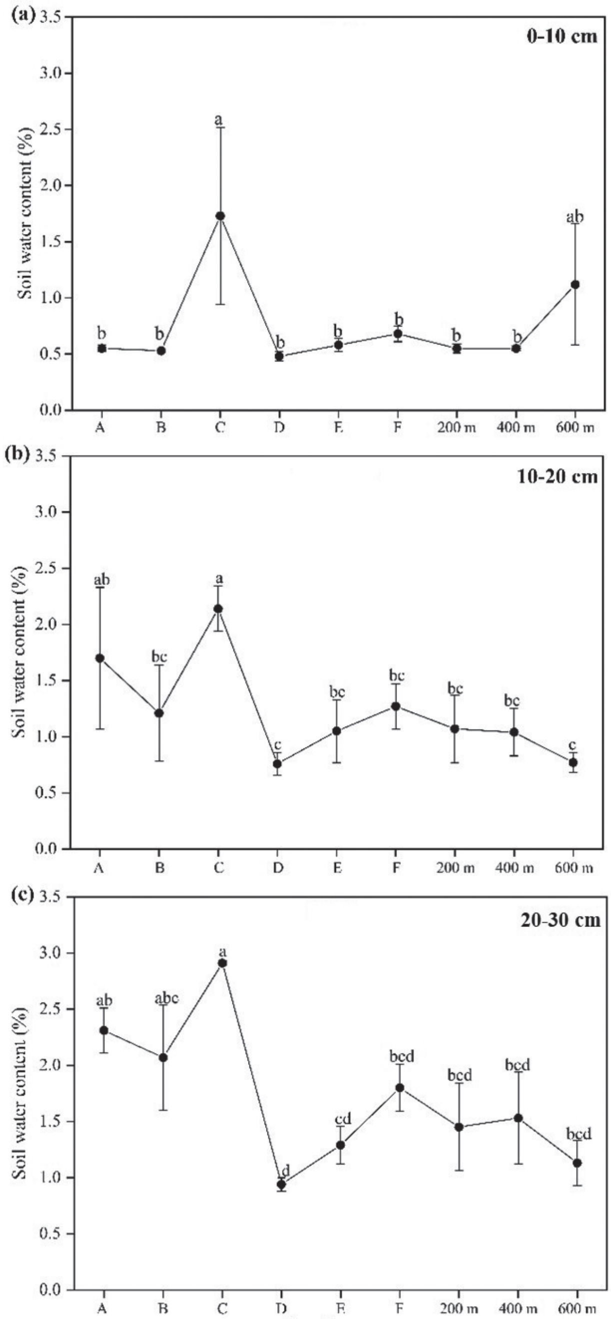

Fig. 5. Variations of the soil water content (%, w/w) at the desert photovoltaic (PV) station. Values of a parameter followed by the same letter did not differ significantly (ANOVA followed by LSD test, $P > 0.05$). The locations are listed in the method section.

soil resulted in a lower SOC content under the panel. Besides these, the SOC content outside the PV station increased with increasing distance from the panels except for 10-20 cm depth, but this trend was not significant (Fig. 6(a-c)), indicating that the disturbance created by establishing the station was concentrated inside the station.

On the contrary, the total nitrogen (TN) contents at inside PV station were lower than at outside PV station (Fig. 6(d-f)). The TN content did not differ significantly among locations, with the exception that at a depth of 20 to 30 cm, TN contents near the rear of the panel, behind the panel, and between two panels were significantly lower than the value at 200 m from the station (Fig. 6(d-f)). The community of soil nitrogen-fixing microbes may differ from locations. Moreover, soil TN content inside the PV station was highest in front of the panel in 0-10 cm depth, this may result from the higher aboveground biomass in this location (Table 2). Previous studies indicated that the input of SOC depends on the return of organic residues and on the humification coefficient for organic residues, whereas the input of TN depends on the return of plant residues to the soil and on biological nitrogen fixation [40]. Our research also found the soil TN content in 0-30 cm depth ranged from 0.009 to 0.038% (Fig. 6(d-f)), which was greatly lower than the results reported by Wei et al. (2022) [41] in edge of Ulan Buh desert (0.05 to 0.06 g kg^{-1} in 0-100 cm depth in different succession stage). According to Aerts (2000) [42], plant growth and litter decomposition was nitrogen limited, especially in arid region. Poor precipitation, redistributed soil water content and micro-habitat in this research combined to restrict plant growth under PV array, resulting in low soil nitrogen accumulation, which is more obvious inside the PV station.

Generally, the C:N ratio was recognized as the essential factor that impacts the equilibrium of C and N cycling, which is determined by the activity of plant absorption and microorganisms [43]. The C:N ratio at inside PV station was higher than that at outside PV station, but did not differ significantly between locations in 0-20 cm depth (Fig. 6(g-i)). The spatial distribution of C:N ratio were as follows: at depths of 0 to 10 cm, the ratio was higher near the front of the panel and under the panel, (Fig. 6g) at depths of 20 to 30 cm, the ratio was significantly higher near the rear of the panel than under the panel and in front of the panel. Further, the C:N ratio at outside PV station increased with increasing distance. The C:N ratio inside PV station ranged from 1.73 to 18.29, whereas the C:N ratio outside PV station ranged from 0.86 to 2.63 (Fig. 6(g-i)), demonstrating that the soil microbial decomposition capacity may higher at outside PV station than inside.

Relationships Among the Species Richness and Soil Factors

Pearson's correlation analysis indicated that the soil water content (SWC to a depth of 30 cm) was significantly positively associated with sand content, but significantly negatively correlated with number of plants, AGB and biodiversity values (the species-richness index, Shannon-Wiener index, and Simpson index) (Fig. 7, $P<0.05$). The biodiversity values were significantly positively correlated with each other. This indicates that soil water content was one of the main driving factors for plant distribution in PV station.

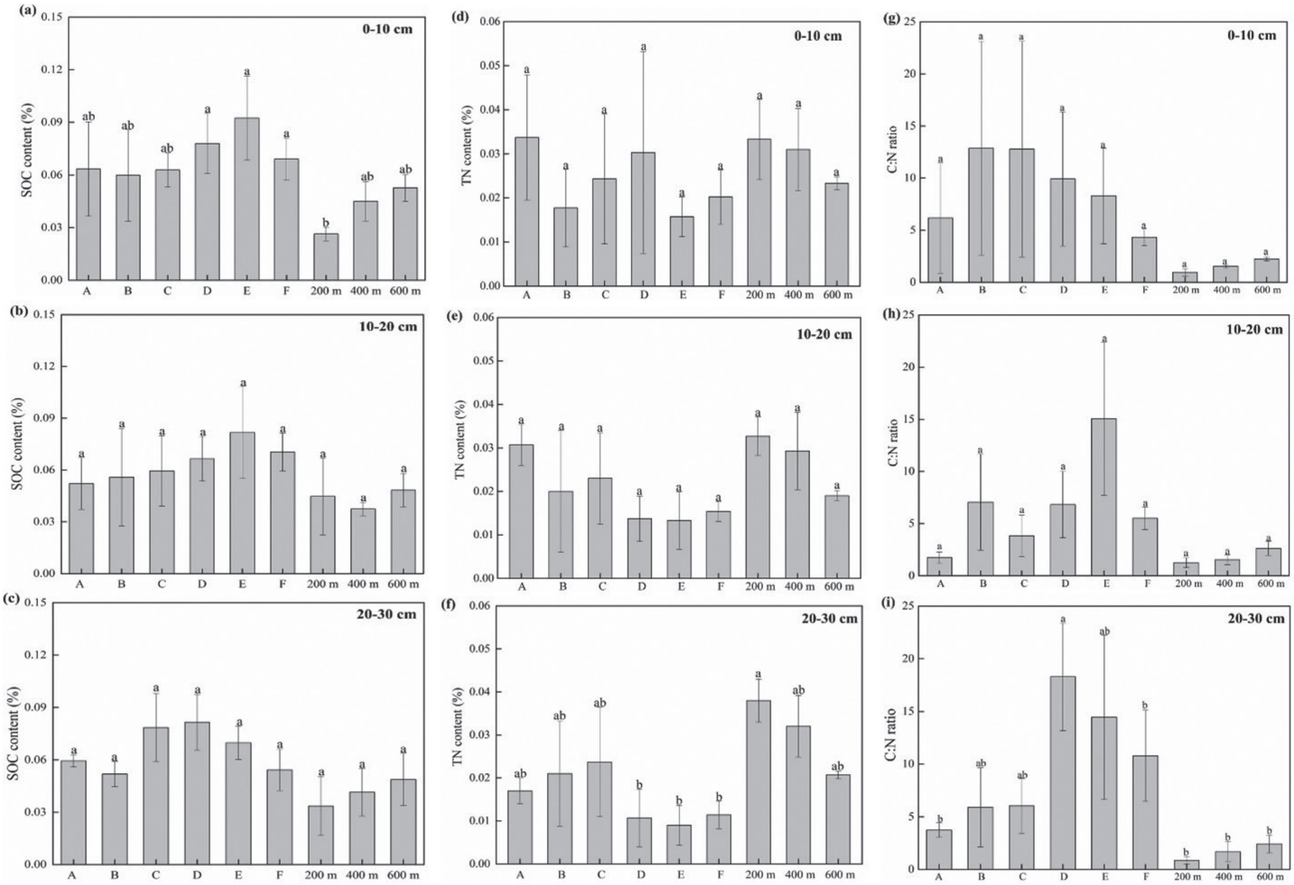

Fig. 6. Variations of the soil organic carbon (SOC) content (a, b, c), the soil total nitrogen (TN) content (d, e, f), and the soil C:N ratio (g,h,i) at the desert photovoltaic (PV) station. Bars indicate mean, error bars indicate standard error. Values of a parameter followed by the same letter did not differ significantly (ANOVA followed by LSD test, P>0.05). The locations are listed in the method section.

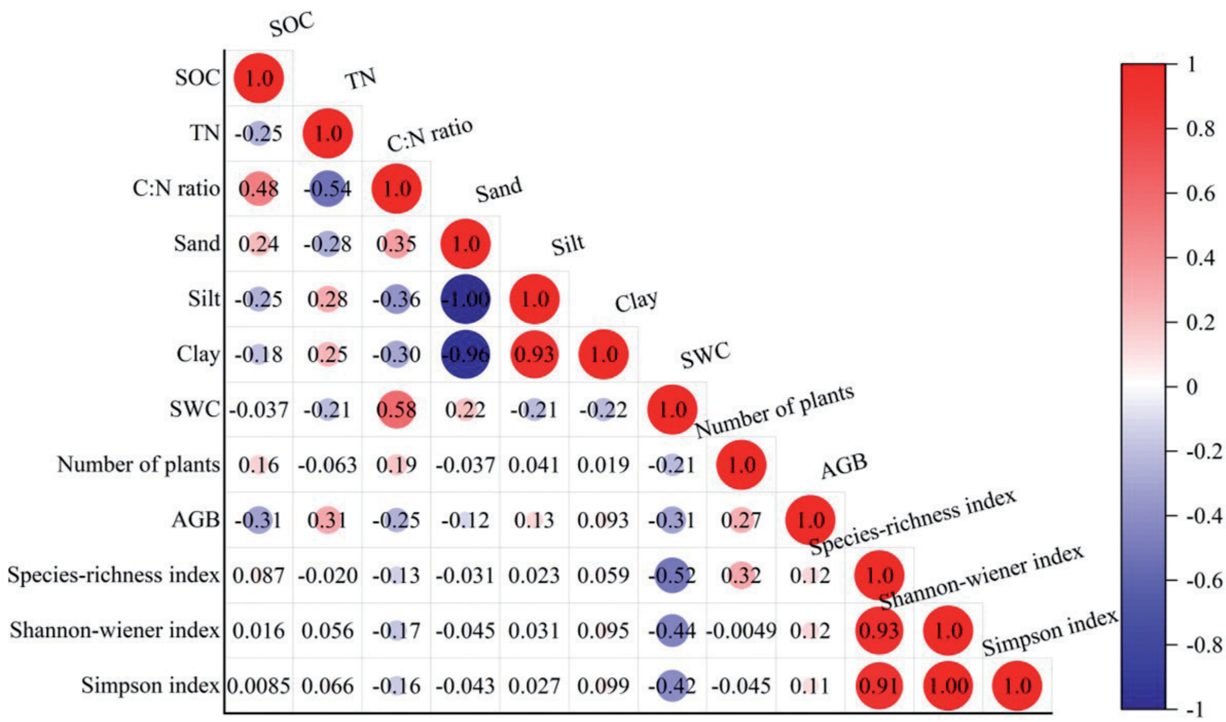

Fig. 7. Pearson's correlation coefficient (r) values for the relationships among the soil and vegetation indices at the desert photovoltaic (PV) station. AGB, aboveground biomass; SWC, soil water content; SOC, soil organic carbon; TN, soil total nitrogen.

The C:N ratio was significant positively correlated with SOC, but significant negatively associated with TN content (Fig. 7, $P<0.05$). This is in accordance with the results reported by previous findings [44-45], demonstrating that the spatial heterogeneity of soil C:N ratio in this study was affected by soil SOC and TN, and soil N had a great influence on the C:N ratio distribution because of higher *r*-value (Fig. 7). The spatial distribution of soil C:N ratio in the surface soil depth was easily disturbed by some factors (e.g. climate, plant life form, soil microorganism), which impact the correlation between SOC and TN and the C:N ratio. Moreover, a significant negative correlation was observed between SOC and TN content (Fig. 7, $P<0.05$).

In addition, a significant positive correlation was found between SOC and sand content, but a significant negative relationship was found between SOC and clay content (Fig. 7, $P<0.05$). The soil clay content in 0-30 cm depth in this study ranged from 1.54 to 2.56%, which is much lower than sand content. Thus, soil sand content, rather than clay content, is the main reason that affect the spatial heterogeneity of SOC in the desert solar PV station.

Our results found that the PV panels influenced the spatial heterogeneity of vegetation properties and SOC and TN. However, neither the species diversity nor the SOC and TN contents showed significant differences between inside and outside PV station, excluding SOC in 0-10 cm depth, which is in accordance with the results reported by Armstrong et al. (2016) [24] in England Westmill solar park. This may be because too little time (less than 4 years) had passed between establishment of the PV station and our field survey, but may also indicate rapid recovery of both the soil and vegetation within only 3 years after establishment of the station. Du et al.(2021) [46] found that the soil moisture and biological characteristics can reached the level before the subsidence, but soil organic matter content was still lower than that in the un-subsidence area after 10 years restoration in natural revegetation areas at the semi-arid coal mining subsidence areas. This indicates that natural ecological restoration may need more times after a serious disturbance, especially for soil nutrients in arid region.

The investigation we proposed provides an accurate prediction how vegetation and soil properties alter with solar PV panels installation in arid sandy land. Our finding confirms the results of previous research that solar PV panels altered microclimate (e.g., sunlight, precipitation, and evaporation) and thus changed the spatial heterogeneity of vegetation and soil factors inside and outside the PV station in desert area [4, 8-10]. Besides these, the installation method of PV panels, sampling position, and distance of the PV panels also impact the variations of plant and soil. The results of our research can serve as a reference for future studies on the ecological impact of solar PV station in desert region. However, the exact cause for other environmental changes, such as the potential risk of affecting biodiversity in sandy ecosystems by the construction of PV station has attracted much attention but are not covered in the present research due to limited data [47]. Thus, to better understand ecological impacts of solar PV system, future research should strive to explore the mechanisms of ecological indicators spatial heterogeneity at different spatial scales and recovery stages.

Conclusions

Our study clearly demonstrates that the spatial heterogeneity of number of plants, species diversity, aboveground biomass, soil water content, SOC and TN contents inside solar PV station can be altered by PV panels, and the extent of these changes vary across different locations. We also found the PV panel had some beneficial effects on plant species composition, diversity patterns, and soil properties, since there were few significant differences between the index values inside and outside the station, suggesting that after 4 years of operation, the vegetation community and soils inside the PV station was showing strong signs of recovery to pre-disturbance levels, especially behind the panels and between two panels. Where the panels increased SWC and decreased evaporation, growing conditions were more favorable, and the vegetation community improved. There were few significant effects on soil nutrients, although the SOC and TN contents may have increased slightly inside the station. Based on these findings, it appears that the damage caused by establishment of the PV station may be healing, although it will be necessary to return in a few years to confirm this hypothesis.

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Conflict of Interest

The authors declare no conflict of interest.

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