



Moss-biocrusts strongly decrease soil surface albedo, altering land-surface energy balance in a dryland ecosystem

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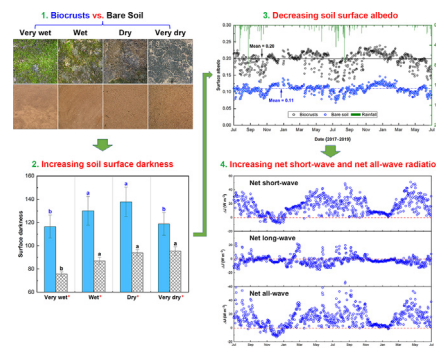
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HIGHLIGHTS

- Biocrusts increased surface soil darkness (44%), roughness (90%), and moisture (22%).
- Surface albedo of biocrust covered soil (0.11) was about half that of bare soil (0.20).
- Decreased albedo of biocrust stems from increased darkness, roughness, and moisture.
- Biocrusts increased soil temperature when dry, but decreased soil temperature when wet.
- Biocrusts may have positive effects on global climate change by decreasing albedo.

GRAPHICAL ABSTRACT



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ABSTRACT

Land surface albedo measures the degree to which the sun's radiation is absorbed or reflected, and thus can be highly influential in global climate trends, local weather phenomena, and biological processes. As an extensive living cover in drylands, biocrusts cover substantial land surface but their potential influences on surface albedo and energy balance are underdocumented, and its temporal dynamic is virtually unknown. We continuously measured the surface albedo, land-surface energy balance, temperature and moisture of moss-biocrust covered soil and bare soil for two years, and measured the surface color and roughness of the two land cover types. Our results showed that the surface albedo of the biocrusts was 43.4% lower than that of the bare soil, due to the increased darkness (43.7%) and roughness (90.4%) together with increased moisture (20.7%) of the biocrust layer. Through time, the albedo of the biocrusts were negatively and linearly related with surface soil temperature or moisture, which resulted in lower albedo in summer and higher albedo in other seasons. As a result of decreased albedo, biocrusts decreased outgoing short-wave radiation by 44.8% in comparison to the bare soil, and consequently they increased net short-wave radiation by 11.4% and net all-wave solar radiation by 22.9%. However, the increased energy absorption by the biocrusts did not consistently increase soil temperature; instead, soil temperature increased by up to 9.3 °C under dry conditions but decreased by as much as 11.4 °C under wet conditions, resulting in a net cooling. This indicates that the temperature regimes of the biocrust-covered soil were not determined only by albedo, but also by modification of soil thermal properties by biocrusts. Because biocrusts

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are highly responsive to land use, it appears that altered albedo and energy balance may be one of the ways in which human activity can impact climate and weather.

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1. Introduction

Soil surface albedo is the fraction of the incident solar radiation that is reflected from the soil surface (Sugathan et al., 2014). As it defines the rate of the absorbed portion of the incident solar radiation, surface albedo plays a critical role in the energy balance of the earth's surface and thus affects the trend of regional and global climate change. Soil surface albedo is a complex feature, which varies diurnally and seasonally with changing sun angle (Zheng et al., 2017), and is also largely affected by soil surface characteristics, especially surface color, roughness, and moisture. For example, surface albedo is negatively related to the soil darkness (Post et al., 2000), soil roughness (Matthias et al., 2000; Cierniewski et al., 2013), and soil moisture (Oguntunde et al., 2006; Sugathan et al., 2014). Generally, soil surface albedo controls the amount of heat absorbed by the soil and regulates land-surface energy balance, which further affects soil water and heat processes and finally determines soil temperature and moisture dynamics (Lagos et al., 2013; Haghighi et al., 2018). Soil surface albedo is capable of providing substantial useful information about the entire soil system, and is integral to the long-term and large-scale observation and modeling of land-surface energy balance (Betts, 2009; Burakowski et al., 2018), evapotranspiration and water resource sustainability (Yang et al., 2010; Tian et al., 2013), meteorological forecasting (Wang and Davidson, 2007; Boussetta et al., 2015), climate change and global warming (Betts, 2000; Zeng and Yoon, 2009). This is especially so in drylands with sparse vegetation and exposed soil surfaces.

Drylands, situated in the sub-humid, semiarid and arid climate regions, cover 41% of the earth's land surface, provide 44% of all cultivated land and support 50% of the world's livestock (Mortimore et al., 2009). However, dryland degradation has become one of our most important global environmental problems, due to climate change and intensive human land use activities (Sivakumar, 2007; D'Odorico et al., 2013). Specifically, vascular vegetation covers only about 5% of the surface as a result of scarce but concentrated precipitation, intensive evapotranspiration, and a long history of severe soil loss in some regions such as the northern Chinese Loess Plateau (Wang et al., 2008) and transition zones around the Sahara desert (Hein and De Ridder, 2006). Therefore, the large interspaces between the sparse vascular plants in drylands are exposed and vulnerable to land degradation, inclusive of soil erosion. Fortunately, these interspaces are variably covered by biocrusts, with some areas attaining nearly complete coverage. Due to their wide distribution, biocrusts have been regarded as an essential part of land cover in dryland ecosystems (Maestre et al., 2016; Bowker et al., 2018). Importantly, it has been reported that the biota inhabiting these biocrusts are a strong influence on surface albedo in drylands (Rodríguez-Caballero et al., 2018).

Biocrusts are surface soil layer, a few millimeters or centimeters deep, engineered by symbiotic communities (composed of cyanobacteria, mosses, lichens, green algae, fungi, and bacteria) and closely bound soil particles (Belnap et al., 2016; Bowker et al., 2018). They are ecosystem engineers in dryland ecosystems and play a major role in various soil processes and functions, such as decreasing soil erodibility and erosion (Bu et al., 2015; Gao et al., 2017), regulating hydrology and soil moisture (Xiao et al., 2010; Xiao et al., 2019b), affecting the fixation and efflux of atmospheric carbon (Su et al., 2013) and nitrogen (Heindel et al., 2018), and shaping the development of vascular plant communities (Havrilla et al., 2019). As a widespread living land-surface cover, biocrusts are capable of greatly changing soil surface color, roughness, and moisture (Rutherford et al., 2017). It is generally expected that biocrusts are able to decrease surface albedo due to

their dark color in contrast to uncrusted soil, and therefore that they can increase solar radiation absorption and subsequently increase soil temperature in drylands (Qin et al., 2002; Zhang et al., 2014). Taking the Israel-Egypt borders as an example, it was found that satellite images of the Israeli side were much darker in contrast to the Egyptian side (Otterman, 1974; Otterman et al., 1975), mostly due to the trampling of biocrusts on the Egyptian side by Bedouin-tended herds which was a prohibited practice on the Israeli side (Karnieli and Tsoar, 1995; Meir and Tsoar, 1996). It was speculated that the bright soil color resulted in increased surface albedo and colder temperatures, which possibly caused decreased precipitation and thus further decrease in vegetation cover and further cooling (Otterman et al., 1975; Ashkenazy and Shilo, 2018). However, such assumptions and connections has not been fully tested over time owing to the lack of year-round measurements of the surface albedo and energy balance for both biocrust-covered and uncrusted bare soils. Due to the utmost importance of surface albedo in determining soil temperature for many ecological processes (Couradeau et al., 2016), it is key to fully and temporally quantify the biocrust effect on surface albedo and its connection with soil temperature. Furthermore, because biocrusts are sensitive to land use change, the outcome of their loss or gain is important for understanding anthropogenic impacts on dryland ecosystems.

In our previous studies, we have found that biocrusts strongly influence soil temperature regimes in dryland ecosystems (Xiao et al., 2013; Xiao et al., 2016), and these influences were partly attributed to the soil thermal properties regulated by the biocrust layer (Xiao et al., 2019a). However, the specific mechanisms underlying soil warming remain unknown. In this study, we hypothesized that biocrust would decrease soil surface albedo because of their modification of surface soil color, roughness, and moisture, and subsequently they would considerably alter land-surface energy balance and soil temperature regimes in dryland ecosystem. Based on these hypotheses, we continuously measured the surface albedo, energy balance, and soil temperature (0–30 cm) of moss-dominated biocrust covered soil and bare soil in two years on the northern Loess Plateau of China. The objectives of our study were: (1) to investigate the year-round biocrust effects on surface albedo and land-surface energy balance and their seasonal variation in semi-arid drylands; (2) to clarify the mechanisms of biocrust effects on surface albedo through changing surface soil color, roughness, and moisture; and (3) to analyze the connections between biocrust effects on soil temperature and their alteration of surface albedo and surface energy balance. Our study will elucidate the ways in which biocrusts alter the thermal environment of the soil, and more broadly provide a better understanding of the potential effects of dryland land use on climate and weather.

2. Materials and methods

2.1. Study area

The study area is located in the Liudaogou watershed (38°46'–38°51' N, 110°21'–110°23' E; 1081–1274 m in altitude and 6.9 km² in area) on the northern Loess Plateau of China (Fig. 1A). The average annual precipitation and free-water evaporation are 409 mm (~80% occurring in summer) and 1337 mm, respectively. The average annual temperature is 8.4 °C, with a mean monthly temperature of −9.7 °C in winter and 23.7 °C in summer. Thus, the climate in the study area is characterized as a representative semiarid climate. The area was previously affected by severe soil loss with erosion rates of up to 20,000 t km^{−2} year^{−1} because of the serious degradation of natural

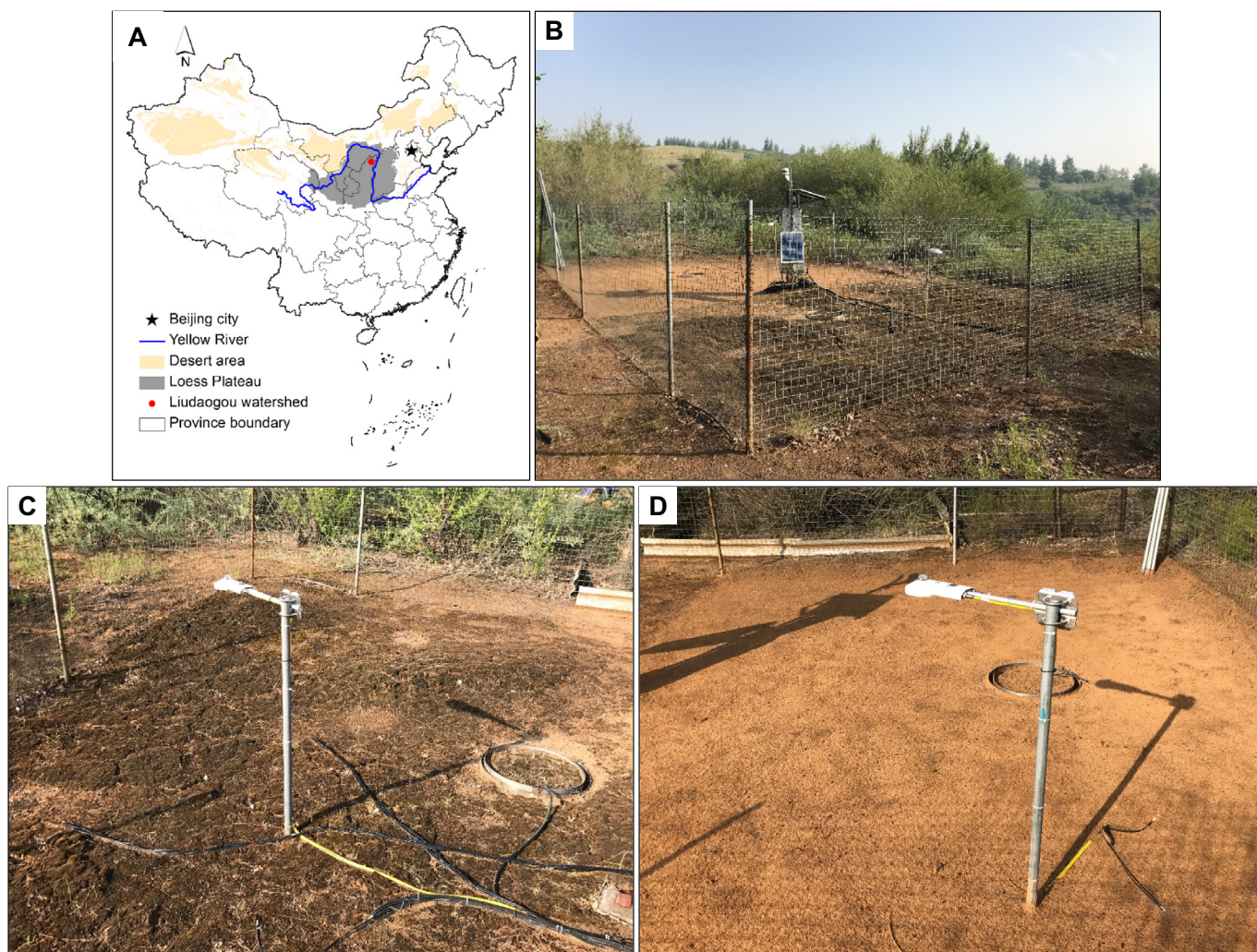


Fig. 1. Location of the study area (Liudaogou watershed; A) on the Northern Chinese Loess Plateau and the paired measurement plots (B) of biocrusts (C) and bare soil (D) with a CNR4 net radiometer.

vegetation (Cai, 2001). Apart from intensive water erosion, it is noteworthy that wind erosion is also severe in this area as strong wind is very common in the winter and spring (with wind speed of 1.05 m s^{-1} on average and up to 4.69 m s^{-1} at 2.0 m aboveground from September to April in 2017–2019). Subsequently, the “Grain for Green” project was implemented in the past decades to recover vegetation, and a great deal of native shrubs were artificially planted to conserve soil (Cao et al., 2009). Subsequently, biocrusts dominated by mosses spontaneously developed on the stabilized soil surfaces, presently attaining a mean coverage of ~30% and sometimes >90% (Xiao et al., 2010).

In our study, a sparse shrubland, composed of *Artemisia ordosica* Krasch. and *Caragana korshinskii* Kom., with nearly complete moss-biocrust covering was selected for monitoring. The aeolian sandy soil in the study area is classified as an entisol in USDA soil taxonomy, and as an arenosol in the FAO soil classification, and its texture was generally loamy sand (USDA).

2.2. Experimental design and measurement

2.2.1. Experimental design

Two factors were considered: soil surface cover (two levels: the biocrust covered soil and uncrusted bare soil) and time (covering 730 days across two years). We selected three pairs of plots ($5 \times 5 \text{ m}$;

see Fig. 1B), each pair consisting of a biocrust plot (Fig. 1C) and a bare soil plot (Fig. 1D), within ~1–2 m of each other. The three pairs were about 50–100 m apart, and their surface albedo, land-surface energy balance, temperature and moisture were continuously measured for two years. The characteristics of biocrusts and the surface soil properties of the two land cover types were also analyzed.

Generally, the biocrusts (about 30-year-old and >95% of moss cover) were located more closely to shrubs and naturally developed on fixed aeolian sand, while the bare soil was located further away from shrubs and thus had suffered wind and water erosion. The bare soil surfaces were regularly disturbed with repeated trampling to keep them bare if obvious recovery of biocrusts was observed. Plots did not contain any shrubs, and were not overlapped by any shrubs. All plots were located at very similar landscape positions, south-oriented and had <5% slope.

2.2.2. Measurements of surface albedo, land-surface energy balance, temperature and moisture

Our measurements included the following three modules for each plot. (1) The solar radiation at 1.0 m aboveground, including incoming short-wave and long-wave radiation and outgoing short-wave and long-wave radiation, was measured by the CNR4 net radiometer (Kipp & Zonen B.V. in The Netherlands; see Fig. 1C–D). (2) The soil temperature and moisture at 2, 6, 10, 20, 30 cm depths were measured with the 5TE (METER Group, Inc. in USA) sensors. (3) The air temperature

at 2.0 m aboveground was measured by a HMP155 (Vaisala in Finland) probe. (4) The rainfall was monitored with the TE525MM (Campbell Scientific, Inc. in USA) automatic recording rain-gauge.

All above probes were connected to a CR3000 micrologger (Campbell Scientific, Inc. in USA) and powered by a solar cell (see Fig. 1B–D), and maintained on site in the same locations for two years from July 1, 2017 to June 30, 2019. All parameters were measured every 10 s and stored in 10-minute and daily tables, respectively.

2.2.3. Measurements of biocrust characteristics and surface soil properties

The surface roughness of the biocrusts and bare soil plots were measured once by the chain method (Jester and Klik, 2005), and the photos of the plots were taken using a digital RGB camera under four different degrees of hydration for analysis of surface greenness and darkness. The degrees of hydration were defined as follow based soil water holding abilities of the two treatments: biocrusts under very wet (soil moisture $(\theta) \geq 0.18 \text{ cm}^3 \text{ cm}^{-3}$), wet ($0.12 \text{ cm}^3 \text{ cm}^{-3} \leq \theta < 0.18 \text{ cm}^3 \text{ cm}^{-3}$), dry ($0.08 \text{ cm}^3 \text{ cm}^{-3} \leq \theta < 0.12 \text{ cm}^3 \text{ cm}^{-3}$), and very dry ($\theta < 0.08 \text{ cm}^3 \text{ cm}^{-3}$) conditions; bare soil under very wet ($\theta \geq 0.13 \text{ cm}^3 \text{ cm}^{-3}$), wet ($0.10 \text{ cm}^3 \text{ cm}^{-3} \leq \theta < 0.13 \text{ cm}^3 \text{ cm}^{-3}$), dry ($0.07 \text{ cm}^3 \text{ cm}^{-3} \leq \theta < 0.10 \text{ cm}^3 \text{ cm}^{-3}$), and very dry ($\theta < 0.07 \text{ cm}^3 \text{ cm}^{-3}$) conditions.

In addition to the in-situ measurements, the upper 2 cm of biocrust covered soil and bare soil were sampled once on August of 2018 (approximately the middle of our experimental period) using $10 \times 10 \times 2 \text{ cm}$ Petri dish at each plot. The biocrust characteristics and surface soil properties were measured based on these single-time-point samples because we assumed that these values were nearly stable during the two-year period. This assumption was made mostly on the basis that our biocrusts were at a stable stage dominated by mosses (30-year-old) in contrast to the initial stages, which is completely or partly dominated by cyanobacteria or lichens. In fact, we sampled and measured the biomass of these biocrusts each year in the past 10 years, and the results demonstrate that their biomasses were quite stable.

The biocrust characteristics and surface soil properties of the samples were measured as follows in the laboratory. (1) The biocrust layer (biological components and their closely attached soil particles) was carefully separated from the underlying soil of each biocrust sample; subsequently, the thickness of the biocrust layer was measured with a digital caliper at 10–15 points. (2) The bulk density of the samples was measured using the immersion method (Roth, 1997) for the biocrust layer and using the core method for the bare soil; the different methods were used owing to the irregular shape and uneven depth of the biocrust layer, which was not conducive to coring. (3) Three quadrats (2 cm square) per biocrust sample were chosen, and used to simply calculate moss density from the total number of moss gametophytes in these quadrats. (4) The moss species were identified according to morphological traits with the help of a hand lens plus a closer look under the microscope if necessary. (5) The moss plants were separated from soil with water (through a 2-mm screen) and dried at 65°C for 24 h for the measurement of moss biomass. (6) As another indicator of biocrust biomass and photosynthetic capacity, the chlorophyll content of the samples was measured by grinding and extracting the chlorophyll itself from the mosses using acetone before calculating the chlorophyll concentration by measuring absorption at 663 nm and 645 nm through a UV-Vis spectrophotometer (DR 5000, Hach Company in USA). (7) The particle-size distribution of the samples was determined through the pipette method after removal of carbonates, organic matter, and soluble salts (Carter and Gregorich, 2006). (8) The organic matter content of the soil was determined with the oil bath- $\text{K}_2\text{Cr}_2\text{O}_7$ titration method (oxidization with dichromate in presence of H_2SO_4 , heated at 180°C for 5 min) (Li et al., 2010). (9) The saturated water content and field capacity was measured by the oven drying method after the saturation (24 h) and saturation-free drainage ($24\text{--}24 \text{ h}$) of the samples, respectively (Carter and Gregorich, 2006).

2.3. Data analysis

The greenness (G) and darkness (D) were used together to quantify the surface color of the biocrusts and bare soil. Based on the RGB photos taken from the plots, the surface greenness of the biocrusts and bare soil was calculated through Eq. (1), where R_{DN} , G_{DN} , and B_{DN} denotes the mean digital number (DN) for red, green, and blue color channel, respectively (Richardson et al., 2009). Similarly, the surface brightness (B) of the photo was obtained through calculating the sum of $R + G + B$ for all pixels divided by 3 then by the total number of pixels as presented in Eq. (2), where $R_{\text{DN}-i}$, $G_{\text{DN}-i}$, and $B_{\text{DN}-i}$ indicates the R_{DN} , G_{DN} , and B_{DN} of the i th pixel from 1 to n , respectively, and n is the total number of pixels in the photo. After that, the surface brightness was directly transformed to darkness through Eq. (3).

$$G_{\text{CC}} = G_{\text{DN}} / (R_{\text{DN}} + G_{\text{DN}} + B_{\text{DN}}) \quad (1)$$

$$B = \left(\sum_{i=1}^n R_{\text{DN}-i} + G_{\text{DN}-i} + B_{\text{DN}-i} \right) / (3 \times n) \quad (2)$$

$$D = 255 - B \quad (3)$$

Moreover, according to the measured incoming short-wave radiation (J_{si}) and long-wave radiation (J_{li}) and outgoing short-wave radiation (J_{so}) and long-wave radiation (J_{lo}), we calculated the net short-wave radiation (J_{sn}), net long-wave radiation (J_{ln}), and net all-wave radiation (J_{n}) for each treatment at daily scale through Eqs. (4)–(6), respectively.

$$J_{\text{sn}} = J_{\text{si}} - J_{\text{so}} \quad (4)$$

$$J_{\text{ln}} = J_{\text{li}} - J_{\text{lo}} \quad (5)$$

$$J_{\text{n}} = J_{\text{sn}} + J_{\text{ln}} \quad (6)$$

We also calculated surface albedo (α) based on Eq. (7) and the ratio (R) of incoming to outgoing solar radiation based on Eq. (8).

$$\alpha = J_{\text{so}} / J_{\text{si}} \quad (7)$$

$$R = (J_{\text{so}} + J_{\text{lo}}) / (J_{\text{si}} + J_{\text{li}}) \quad (8)$$

The absolute and relative (%) differences (biocrusts – bare soil) in the measured parameters between the biocrusts and bare soil were used to describe the biocrust effects on soil properties, surface albedo, solar radiation, and soil temperature and moisture at different depths. Here the accumulated daily mean soil temperature (AT) was also calculated through Eq. (9) to further analyze the differences in soil temperature between the two treatments. In Eq. (9), T_i is the daily mean soil temperature of the i th day, where $i = 1\text{--}n$, and $n = 365$ or 730 . The variations of the measured parameters were also investigated through comparing their average or total amount in different months and seasons (spring, summer, fall, and winter), as well as under different moisture conditions (very wet, wet, dry, and very dry).

$$AT = \sum_{i=1}^n T_i \quad (9)$$

Owing to our repetitive measurements of the most parameters over 730 days (24 months), the repeated measures ANOVA (two-way: crust and time) was performed to evaluate the statistical differences between the biocrusts and bare soil at a 0.05 level of probability in IBM SPSS Statistics 25, after the test of homogeneity of variance and Mauchly's test of sphericity. The differences in surface color, roughness, and other fundamental soil properties between the two treatments were also statistically evaluated at a 0.05 level of probability by the paired-samples

t-test after normality and equality of variance tests. The variation in surface color and albedo under different soil moisture conditions were statistically tested by the one-way ANOVA, followed by Duncan's multiple range test. The best fit regression (mostly linear and polynomial) was conducted to demonstrate the relationships between the surface albedo and soil moisture or soil temperature, as well as the diurnal change trends of surface albedo of the two treatments.

3. Results

3.1. Characteristics of biocrusts and their effects on surface soil properties

As listed in Table 1, our biocrusts were dominated by the mosses *Bryum arcticum* (R. Brown) B.S.G. and *Didymodon vinealis* (Brid.) Zander. These biocrusts were generally 95.2% in cover, 13.7 mm in thickness, 41.5 gametophytes cm^{-2} in moss population density, and 0.21 g cm^{-2} in moss biomass. As compared with the bare soil, the biocrusts had 38.0% higher content of clay and 54.1% higher content of silt but 5.9% lower content of sand (Table 1). The biocrusts also decreased surface soil bulk density by 31.4% in comparison to the bare soil, and subsequently they increased saturated water content by 19.7% and field capacity by 15.5% (Table 1). Also, the surface roughness of the biocrusts was 90.4% higher than that of the bare soil in Table 1.

Moreover, the biocrusts averaged 29.5% higher content of organic matter and 83.3% higher content of chlorophyll than the bare soil, which resulted in distinguishing surface colors between the biocrust covered and bare soils (see Fig. 2). As shown in the subfigures C–F of Fig. 2, the biocrust surface was generally green under wet and very wet conditions but mostly black under dry and very dry conditions; while the bare soil surface was always a light (high value) yellow-red in color (Fig. 2G–J). As indicated in Fig. 2A, the biocrusts averaged 21.7% higher greenness in contrast to the bare soil when the mosses were wet after rainfall, but when they became dry the biocrusts and bare soil had similar greenness. Additionally, the darkness of the biocrust surface averaged 51.7% higher than the bare soil, although it strongly varied within different soil moisture conditions (Fig. 2B). As given in Table 1 and Fig. 2, these differences in the soil properties between the biocrusts (biocrust layer) and bare soil were all statistically significant ($t \geq 2.86$, $P \leq 0.013$).

3.2. Biocrust effects on solar radiation and radiation balance

The biocrusts and bare soil generally had very similar (insignificant; $F \leq 0.01$, $P \geq 0.93$) incoming short-wave radiation and incoming and outgoing long-wave radiation (Fig. 3), but the biocrusts had much lower outgoing short-wave radiation (significant; $F = 182.0$, $P < 0.001$) as compared with the bare soil. These differences in solar radiation between the two treatments can be clearly seen in Figs. 4 and S1–S2, which showed that the curves of outgoing short-wave radiation of the two treatments were distant from each other (Figs. 4B and S1B), but the curves of incoming short-wave radiation (Figs. 4A and S1A) and incoming (Figs. 4C and S1C) and outgoing long-wave radiation (Figs. 4D and S1D) were almost indistinguishable between the two treatments. As a result, the net long-wave radiation (Figs. 5B and S2B) was barely affected by the biocrusts in contrast to the bare soil, but the net short-wave radiation (Fig. 5A) and subsequently the net all-wave solar radiation (Fig. 5C) was strongly increased by the biocrusts.

The detailed daily mean solar radiation and radiation balance of the two treatments over the two years were listed in Tables S1–S2, respectively. In Table S1, the differences in outgoing short-wave, net short-wave, and net all-wave solar radiations between the two treatments were significant ($F \geq 6.86$, $P \leq 0.059$), while the differences in other types of solar radiation between the two treatments were non-significant ($F \leq 0.62$, $P \geq 0.48$). According to the *P* values listed in Table S1, we can easily locate the major differences between the two treatments on the outgoing short-wave radiation (19.2 vs. 34.8 W m^{-2}), net

short-wave radiation (153.1 vs. 137.4 W m^{-2}), and net radiation (73.6 vs. 59.9 W m^{-2}). These differences amounted to as much as $-11,239.4$, $11,461.1$, and 9981.3 W m^{-2} across the two years for the outgoing short-wave radiation, net short-wave radiation, and net radiation, respectively (Table S2), accounting for 44.9%, 11.4%, and 22.8% of that solar radiation of the bare soil, respectively. As indicated by the ratios of outgoing to incoming solar radiation in Fig. S2D, the biocrusts decreased the ratio by 2.8% (0.86 vs. 0.89) in contrast to the bare soil across the two years.

The differences in outgoing short-wave radiation (Fig. 4B), net short-wave radiation (Fig. 5A), and net all-wave solar radiation (Fig. 5C) between the biocrusts and bare soil varied strongly among different months, which generally increased from early winter (December) to mid-summer (July) and decreased from late summer (August) to late fall (November). As listed in Table 2, we always observed a decrease in outgoing short-wave radiation and an increase in net short-wave radiation for the biocrusts in contrast to the bare soil across the four seasons, but the magnitude of decrease and increase depended on season. The relative differences between the biocrust and bare soils ranged from 17.0% (summer) to 32.5% (winter) for the net solar radiation across the four seasons, and the biocrust effect on solar radiation was seasonally-dependent in the order of winter > spring > fall > summer (Table 2).

3.3. Biocrust effects on soil surface albedo and its seasonal variation

As shown in Fig. 6, the daily mean surface albedo of the biocrusts ranged from 0.07–0.61 ($CV = 0.05$), while that of the bare soil ranged from 0.13–0.73 ($CV = 0.05$). Across the two years, the biocrusts averaged 43.4% (0.11 vs. 0.20; $F = 167.99$, $P < 0.001$) lower daily surface albedo than the bare soil. Moreover, the surface albedo of both treatments fluctuated greatly within different months (Fig. 6), apparently mostly determined by the surface soil temperature (originally solar radiation) and moisture (originally rainfall). Specifically, we found that the biocrusts and bare soil had a similar variation pattern of daily mean surface albedo, which decreased from January to July and then increased from July to December (Figs. 6–7). Despite this, the surface albedo of the biocrusts was consistently lower than that of the bare soil in every month or season (Fig. 7). Moreover, the surface albedo of the two treatments varied substantially during the period of June–October but changed only slightly during the other periods, according to a comparison of coefficients of variation between the two periods (biocrusts = 0.11 vs. 0.07; bare soil = 0.13 vs. 0.07) and standard errors presented in Fig. 7. The results of repeated measures ANOVA in Table 3 showed that the effects of the two factors, including crust (biocrusts or bare soil) and time (12 months), on soil surface albedo were statistically significant ($F \geq 28.87$, $P \leq 0.002$). These two factors also had strong ($F = 5.78$, $P = 0.055$) interaction effect (crust $\times$ time) on soil surface albedo as listed in Table 3.

We further divided the surface albedo of the two treatments into four levels based on degrees of hydration. As shown in Fig. 8, the albedo of the biocrusts (Fig. 8A) were 0.09, 0.095, 0.101, and 0.11 under very wet, wet, dry, and very dry conditions, respectively, while that of the bare soil (Fig. 8B) were 0.15, 0.16, 0.19, and 0.21 under the four moisture conditions, respectively. From Fig. S3A, we can further see that the surface albedo of the two treatments linearly decreased with increasing soil moisture ($R^2 \geq 0.57$, $n = 652$), but the biocrusts had a much gentler (69.8%) slope as compared with the bare soil, indicating that the difference in the surface albedo between the two treatments also decreased with increasing soil moisture. In other words, in contrast to the bare soil, the presence of the biocrust layer decreased surface albedo more when the biocrust layer was dry, and conversely it decreased surface albedo less when the biocrust layer was wet (Fig. S3A). Similarly, negative linear relationships were also observed between the surface albedo and the surface soil temperature in Fig. S3B. In addition, the diurnal changes of surface albedo of the biocrusts and bare soil were

Table 1
Fundamental characteristics of biocrusts and bare soil in the study plots.

Measurements	Biocrusts	Bare soil	Absolute difference ^c	Relative difference (%) ^c	t	p ^d
Biocrust cover (%)	95.2 ± 3.1	–	–	–	–	–
Biocrust thickness (mm) ^a	13.7 ± 0.8	–	–	–	–	–
Dominant moss species	<i>Bryum argenteum</i> Hedw., <i>Didymodon vinealis</i> (Brid.) Zander					
Moss biomass (g cm ^{−2})	0.21 ± 0.02	–	–	–	–	–
Moss density (gametophyte cm ^{−2})	41.5 ± 8.2	–	–	–	–	–
Chlorophyll content (mg g ^{−1})	0.18 ± 0.04	0.03 ± 0.01	0.15 ± 0.01	83.3 ± 0.3	5.59	<0.001
Percentage of clay (<2 μm) (%) ^b	4.3 ± 0.1	2.6 ± 0.1	1.7 ± 0.1	38.0 ± 2.0	15.32	<0.001
Percentage of silt (2–50 μm) (%) ^b	6.4 ± 0.4	2.5 ± 0.1	3.9 ± 0.4	54.1 ± 2.9	9.87	<0.001
Percentage of sand (50–2000 μm) (%) ^b	89.3 ± 0.5	95.0 ± 0.1	−5.6 ± 0.5	−5.9 ± 0.5	−11.82	<0.001
Surface roughness	7.93 ± 0.25	0.67 ± 0.03	7.26 ± 0.26	90.4 ± 0.7	28.42	<0.001
Bulk density (g cm ^{−3})	1.08 ± 0.02	1.58 ± 0.01	−0.50 ± 0.02	−31.4 ± 1.2	−26.41	<0.001
Saturated water content (g g ^{−1})	0.27 ± 0.01	0.21 ± 0.01	0.05 ± 0.01	19.7 ± 1.0	4.77	<0.001
Field capacity (g g ^{−1})	0.15 ± 0.01	0.13 ± 0.01	0.03 ± 0.01	15.5 ± 2.2	2.86	0.013
Organic matter content (g kg ^{−1})	8.29 ± 0.41	5.55 ± 0.18	2.74 ± 0.26	29.5 ± 1.6	10.68	<0.001

^a Biocrust thickness includes biocrust layer and the adherent soil.
^b Classification of soil particle size is based on the soil texture classification system of the United States Department of Agriculture.
^c Absolute difference = biocrusts – bare soil; Relative difference = (biocrusts – bare soil) / bare soil × 100%.
^d Two-tailed P values.

generally U-shaped both under wet (Fig. S4A) and dry (Fig. S4B) conditions, except for a few outliers approaching sunset. Despite the nearly identical shape of these curves, the surface albedo of the biocrusts in Fig. S4 was always lower than that of the bare soil.

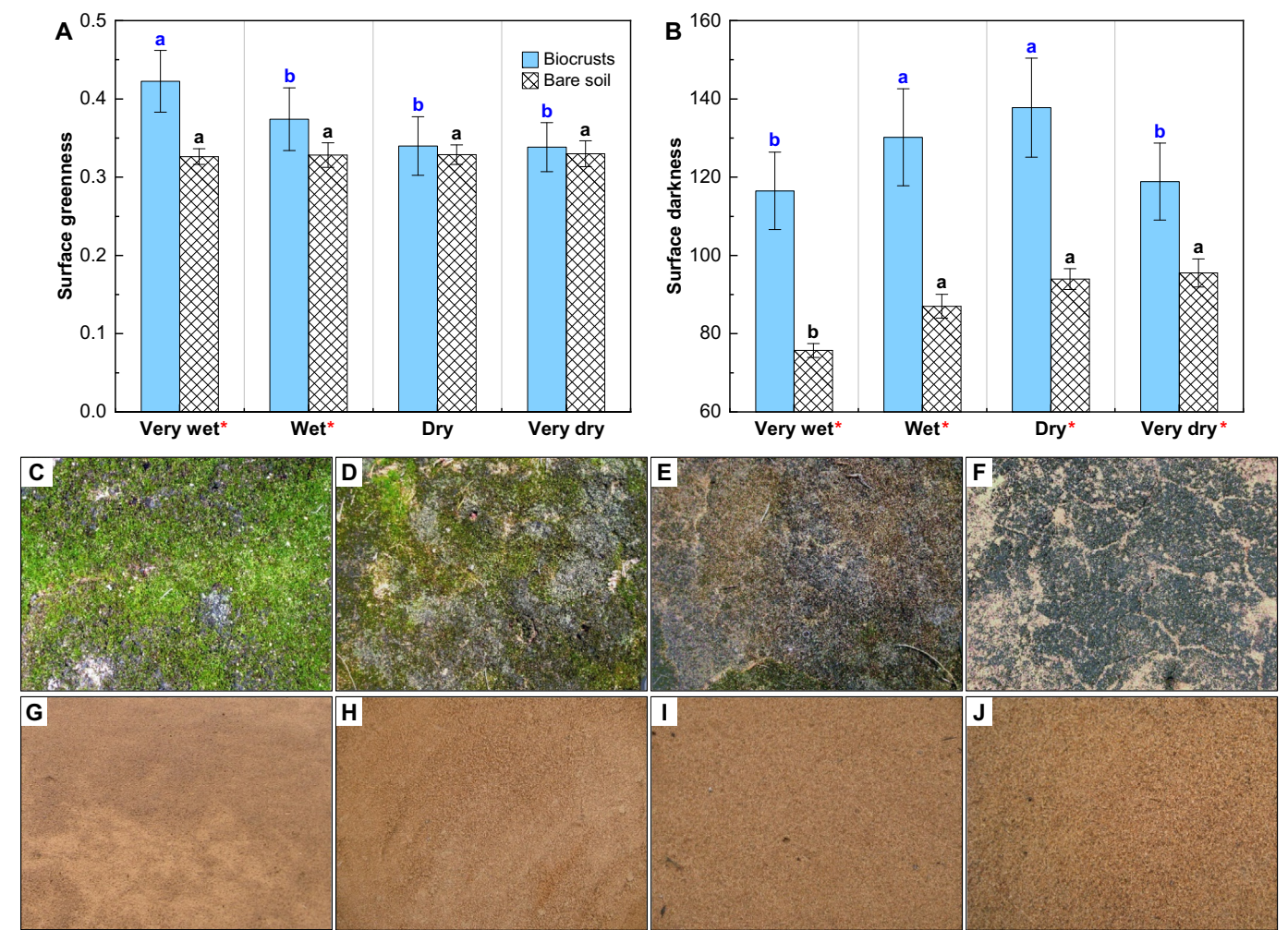


Fig. 2. Surface greenness and darkness of biocrusts (A) and bare soil (B) under different soil moisture conditions: (C) Biocrusts under a very wet condition; (D) biocrusts under a wet condition; (E) biocrusts under a dry condition; (F) biocrusts under a very dry condition; (G) bare soil under a very wet condition; (H) bare soil under a wet condition; (I) bare soil under a dry condition; (J) bare soil under a very dry condition. Vertical bars on plots indicate standard deviations. The asterisk (*) indicates that the difference between the biocrusts and bare soil is significant at a 0.05 level of probability, and the different letters presented in each soil treatment indicate significant differences among different soil moisture conditions at a 0.05 level of probability.

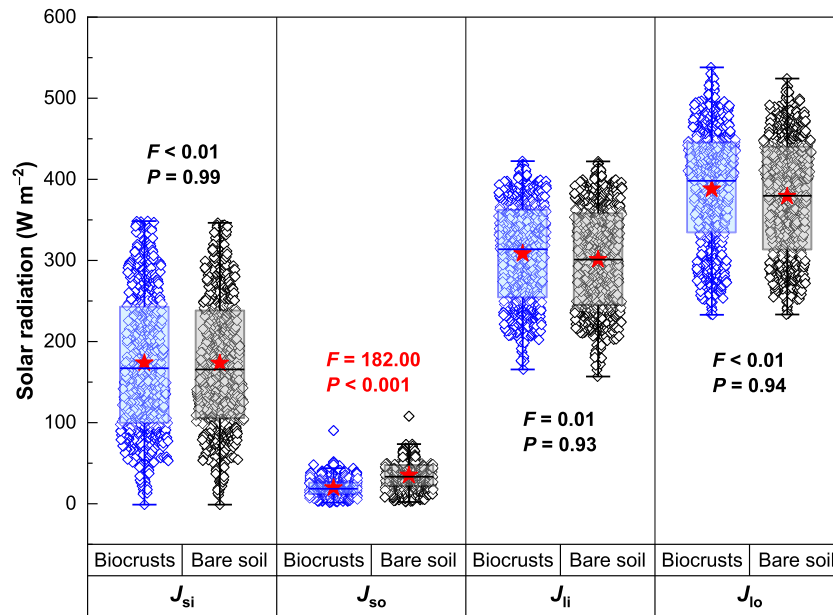


Fig. 3. Daily mean solar radiation of biocrusts and bare soil over two years, including incoming short-wave (J_{si}) and long-wave far infrared (J_{li}) radiation and surface-reflected short-wave (J_{so}) and outgoing long-wave (J_{lo}) radiation. The hanging bars, upper fence, lower fence, line, and red star on plots indicate whiskers (scores outside the middle 50%), upper quartile (75% of the scores fall below the upper quartile), lower quartile (25% of the scores fall below the upper quartile), median (the mid-point of the data), and arithmetic mean, respectively.

3.4. Biocrust effects on soil temperature and moisture dynamics

In comparison to the bare soil, the biocrust covered soil mostly had higher temperature under dry conditions but generally had lower temperature under wet conditions (Figs. 9 and S5). According to the annual average temperature of the two years listed in Table S3, the soil temperature of the biocrusts averaged 0.3–1.0 °C lower ($F \leq 6.41$, $P \geq 0.064$) than that of the bare soil, dependent on depth. The accumulated daily mean temperature data also supports a cooling effect of biocrusts on soils ranging from 2.3–7.9% (Table S4). These results obtained in Tables S3–S4 implied that the biocrust layer generated the strongest impacts on soil temperature at 10 cm depth (also see Fig. 9D), and the magnitude of the effect at other soil depths followed the sequence 20 cm (Fig. 9E) > 30 cm (Fig. 9F) > 6 cm (Fig. 9C) > 2 cm (Fig. 9B).

Furthermore, the magnitude of biocrust effects on soil temperature was highly variable under different soil moisture and temperature conditions associated with different months, as shown in Figs. 9 and S5. In the four seasons listed in Table 4, the difference in the accumulated daily mean temperature between the biocrusts and bare soil averaged 3.0% (summer)–10.0% (fall) at 0–30 cm depths in the four seasons. In spite of this, we should notice that the overall effects of biocrusts on soil temperature included both temperature decreases and increases (Fig. 9), but the increases were more than counterbalanced by the decreases, resulting in an average temperature decrease. Actually, the biocrusts decreased daily mean soil temperature by up to 4.0–6.0 °C in wet conditions, dependent on depth, while they increased daily mean soil temperature by up to 1.2–2.1 °C in dry conditions, dependent on depth (Figs. 9 and S5). These effects were much stronger if the 10-minute mean temperature were further considered, where the soil temperature was decreased by up to 11.4, 9.0, 7.7, 5.6, and 4.7 °C in wet conditions and increased by up to 9.3, 3.4, 2.3, 1.3, and 1.5 °C in dry conditions at the five depths, respectively.

The results in Figs. S6–S7 showed that the biocrusts consistently had higher content of soil water at 2–10 cm depths (Figs. S6B–D and S7B–D) but simultaneously had lower content of soil water at 20–30 cm depths (Figs. S6E–F and S7E–F). Across the two years, the daily mean soil

moisture of the biocrusts was increased on average by 0.012 (20.7% higher), 0.027 (45.8% higher), and 0.049 (86.0% higher) $\text{cm}^3 \text{cm}^{-3}$ in comparison to the bare soil at 2, 6, and 10 cm depths (significant; $F \geq 7.58$, $P \leq 0.05$), respectively (Table 5). As compared with the bare soil, the biocrusts decreased the daily mean soil moisture on average by 0.024 and 0.053 $\text{cm}^3 \text{cm}^{-3}$ at 20 and 30 cm depths ($F \geq 64.72$, $P \leq 0.001$), respectively, accounting for 32.4% and 55.8% of that of the bare soil at 20–10 cm depths, respectively (Table 5).

4. Discussion

4.1. Effects of biocrusts on soil surface albedo and solar radiation

In our study, we found that the presence of biocrusts nearly halved the surface albedo from 0.20 to 0.11, on average across two years. According to the approximate ranges of albedo of natural surfaces (Lal, 2017), the surface albedo of the bare soil in our study is equal to the lower range of the albedo of “sand” (0.2–0.4), which is a reasonably accurate description of the soils in our study (see Fig. 2G–J). In contrast to bare soil, the surface albedo of biocrusts in our study fell into the albedo range of “dark-colored soil surfaces” (0.1–0.2) or about equal to that of “grassland” (0.1) (Lal, 2017), showing that our biocrusts exerted an impact comparable in magnitude to a shift in parent material or the influence of vascular vegetation.

Our biocrusts had a lower surface albedo compared to other studies of biocrust albedo, possibly due to the major differences in the cover and composition of the biocrusts studied, the properties of the underlying soil, the environmental conditions, and timing and duration of measurements. For example, Rutherford et al. (2017) reported that the surface albedo of biocrusts was as high as ~0.22 on the Colorado Plateau of USA, but their biocrusts had ~25% of moss cover while our moss biocrusts were 95% in cover. They also found that the surface albedo of their biocrusts reached up to ~0.34 when the biocrust community was experimentally shifted from moss-lichen to cyanobacteria through climate change simulations (Rutherford et al., 2017), while our biocrust community was always dominated by mosses. Furthermore,

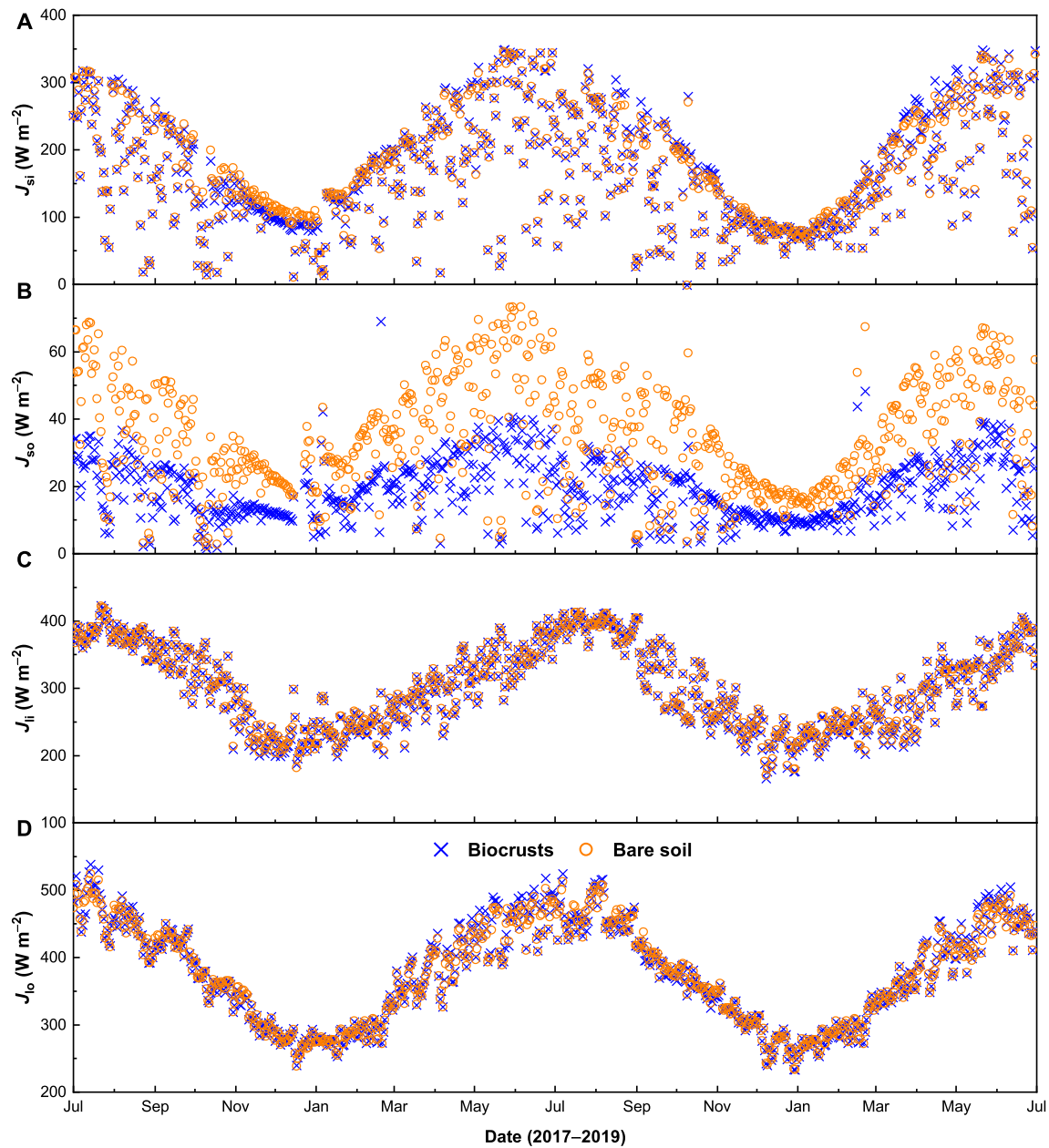


Fig. 4. Changes of daily mean solar radiation of biocrusts and bare soil over two years. (A) Incoming short-wave radiation (J_{si}); (B) outgoing short-wave radiation (J_{so}); (C) incoming long-wave radiation (J_{li}); (D) outgoing long-wave radiation (J_{lo}).

Rutherford et al. (2017) measured the surface albedo of biocrusts in 8 days under limited environmental conditions, while we continuously observed the surface albedo of biocrusts across two years under a variety of environmental conditions likely to induce different albedos. In addition to Rutherford et al. (2017), various other studies have used either models or empirical measurement to arrive at biocrust albedos ranging from 0.17–0.33 in Israel and elsewhere in China (Qin et al., 2002; Kidron and Tal, 2012; Zhang et al., 2014). In contrast to these studies, the much lower surface albedo of our biocrusts may have been caused by the higher cover of mosses (almost no cyanobacteria or lichens), the longer duration of measurements perhaps spanning previously under-sampled low albedo periods, or a wetter climate (and therefore wetter soils) owing to the relatively abundant annual precipitation (409 mm).

The degree to which our biocrusts lowered albedo relative to bare soil surfaces (43.4%) was reasonably comparable to other studies,

though this value varies from place to place. For example, Belnap (1995) compared the trampled biocrust surface to untrampled biocrust surface and found that there was up to a 50% increase in reflectance from 0.25 to 0.50 μm of wavelength on the Colorado Plateau of USA. Similarly, a few studies also report that the albedo of biocrusts is lower than surfaces without biocrust by 15.0% at the Tengger Desert in northern China (Zhang et al., 2014), by 28.3% in the sand dunes along the Israel-Egypt border (Qin et al., 2002), by ~38.7% in Negev Desert of Israel, and approximately by 54.5% in the Błędów Desert (Caputa, 2016). Although the magnitude of the biocrust-induced albedo change varies globally, the sign has thus far been consistently reported as negative, i.e. a decrease in albedo.

More interestingly, biocrust effects on surface albedo vary within different wavelengths of sunlight. Different wavelengths of sunlight are not equally reflected, which gives rise to a variable color of surfaces

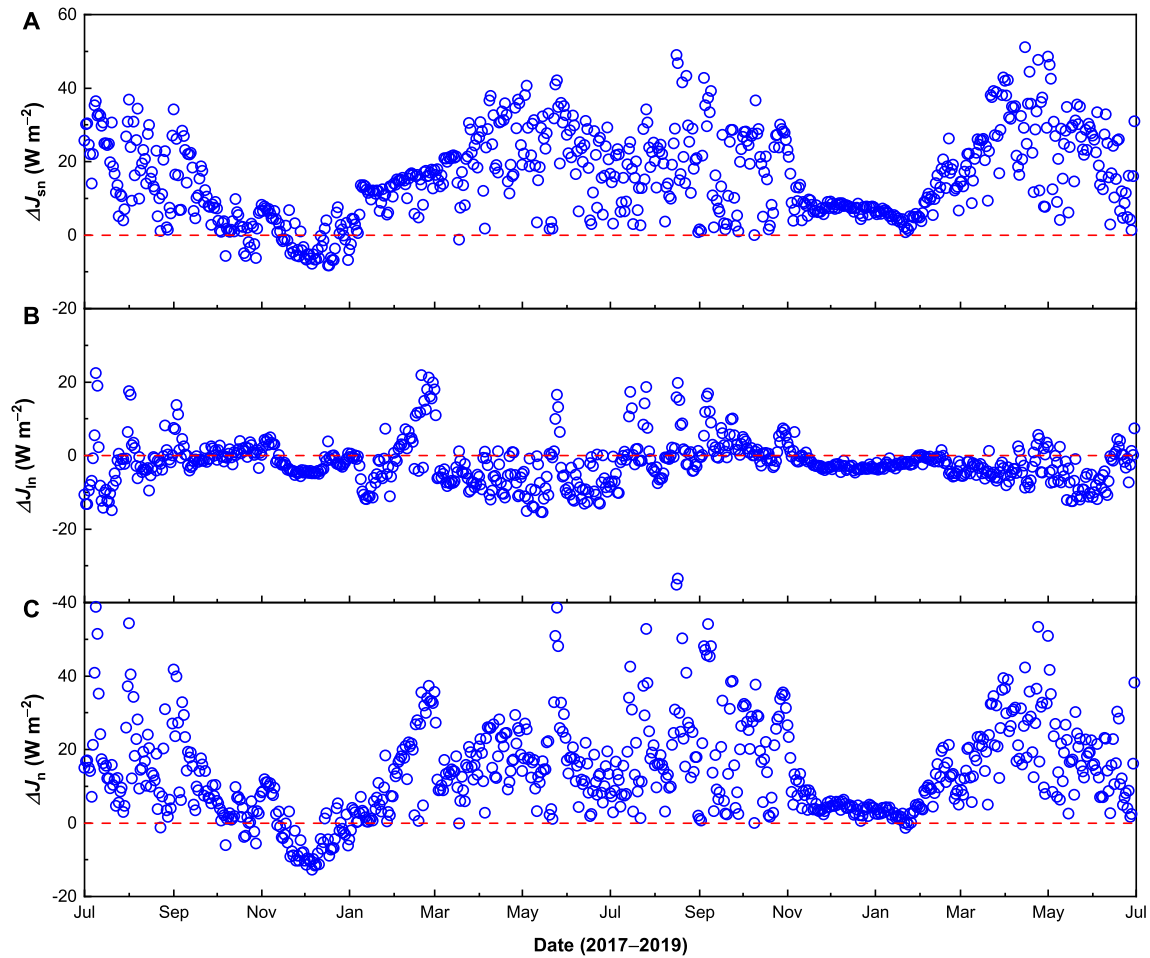


Fig. 5. Differences (Δ , Δ = biocrusts – bare soil) in net solar radiation between biocrusts and bare soil over two years. (A) Differences in net short-wave radiation (ΔJ_{sn}); (B) differences in net long-wave radiation (ΔJ_{ln}); (C) differences in net solar radiation (ΔJ_n) including both short-wave and long-wave radiation.

and differences in reflectance of certain wavelengths due to differences in physical or chemical characteristics of the soil surface. Confirming this principle, Rodríguez-Caballero et al. (2015b) reported that: cyanobacterial biocrusts showed low reflectance, increasing from the blue region to longer wavelengths with an absorption maximum at 500 nm and another one at 680 nm; chlorolichen and moss biocrusts showed a signature spectra similar to cyanobacteria, but were characterized by lower and higher reflectance, respectively; bare soil spectra had higher reflectance in the red and near infrared part of the spectrum and a deeper absorption around 500 nm. Such features may be used to

identify biocrust cover and type and estimate biocrust biomass and biological activity.

4.2. Mechanisms of biocrust effects on soil surface albedo and its seasonal variation

In our study, we attribute the decreasing effects of biocrusts on soil surface albedo to biocrust-mediated increases in soil surface darkness (Fig. 2B), roughness (Table 1), and moisture (Figs. S6B and S7B). Further, we propose that the relative influence of these factors follows

Table 2

Seasonal (spring, summer, fall, and winter) amount of solar radiation of biocrusts and bare soil over two years.

Solar radiation ^a	Spring (March–May)			Summer (June–August)			Fall (September–November)			Winter (December–February)		
	Biocrusts	Bare soil	ΔJ in % ^b	Biocrusts	Bare soil	ΔJ in % ^b	Biocrusts	Bare soil	ΔJ in % ^b	Biocrusts	Bare soil	ΔJ in % ^b
J_{si} ($W m^{-2}$)	41,430.3	40,594.3	2.1	41,122.2	41,004.4	0.3	24,831.5	25,275.4	−1.8	18,295.3	18,756.0	−2.5
J_{so} ($W m^{-2}$)	4427.4	8183.9	−45.9	4185.7	7623.9	−45.1	2630.6	5040.1	−47.8	2606.6	4295.8	−39.3
J_{li} ($W m^{-2}$)	55,048.0	55,203.3	−0.3	69,621.7	69,533.0	0.1	53,228.0	53,470.2	−0.5	41,913.0	42,350.1	−1.0
J_{lo} ($W m^{-2}$)	73,772.8	73,013.3	1.0	85,213.5	84,673.0	0.6	65,674.2	66,071.5	−0.6	50,823.9	50,844.4	0.0
J_{sn} ($W m^{-2}$)	36,993.2	32,406.0	14.2	36,936.5	33,380.5	10.7	22,205.0	20,240.0	9.7	15,463.8	14,155.9	9.2
J_{ln} ($W m^{-2}$)	−18,773.7	−17,896.0	4.9	−15,591.8	−15,140.0	3.0	−12,355.8	−12,511.3	−1.2	−11,199.4	−10,938.6	2.4
J_n ($W m^{-2}$)	18,219.5	14,510.0	25.6	21,344.7	18,240.5	17.0	9849.2	7728.7	27.4	4264.4	3217.3	32.5

^a J_{si} = incoming short-wave radiation; J_{so} = outgoing short-wave radiation; J_{li} = incoming long-wave radiation; J_{lo} = outgoing long-wave radiation; J_{sn} = net short-wave radiation; J_{ln} = net long-wave radiation; J_n = net all-wave radiation.

^b ΔJ in % = $(J_{biocrusts} - J_{ck}) / J_{ck} \times 100\%$. $J_{biocrusts}$ = solar radiation of biocrusts; J_{ck} = solar radiation of bare soil.

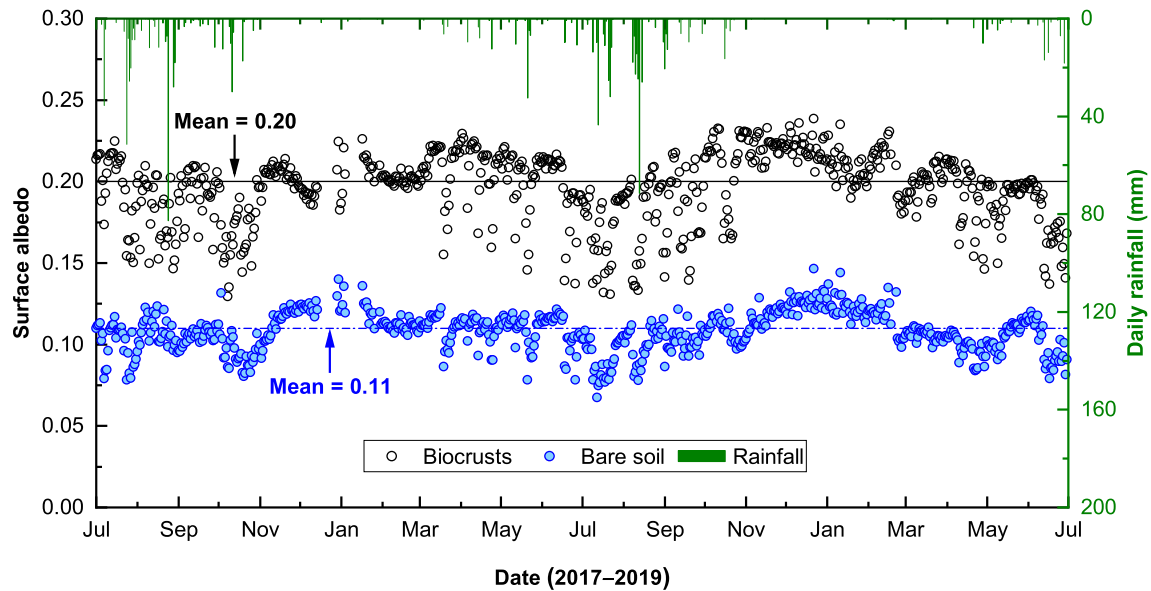


Fig. 6. Changes of daily mean surface albedo of biocrusts and bare soil over two years.

the order of darkness > roughness > moisture, similarly to uncrusted soil (Lal, 2017) and also the cyanobacterially-dominated biocrusts studied by Rutherford et al. (2017).

First, surface albedo is generally decreased with increasing darkness of soil, which may reflect the soil organic matter content and many other important soil physical and chemical characteristics (Lal, 2017). In our study, the moss plants made the surface color of the biocrust covered soil much darker than the bare soil, especially in dry conditions (Fig. 2E–F). We might expect even more darkness if the biocrust community was dominated by dark-pigmented cyanobacteria or dark-colored lichens rather than mosses (Rutherford et al., 2017), because their pigments can decrease albedo more and remain dark in both dry and wet states, while mosses are lighter when dry and instantly shift to green after absorbing water. Some lichens are light-colored, and thus might hypothetically have a very different effect on albedo.

Secondly, increased surface roughness of the biocrusts contributed significantly to decreased surface albedo, because rough surfaces induce

lower albedo values, especially when sun angle is low and the shading effect lowers the reflection (Lal, 2017). In our study, the surface roughness of the biocrusts was not only directly increased by the presence of moss plants, but also possibly by many other indirect aspects, such as surface cracks and micro-topography, caused by nonuniform swelling and shrinkage behavior of the biocrust layer in freeze-thaw and dry-wet cycles (Rodríguez-Caballero et al., 2015a), and the pinnacled surface morphology, caused by the uneven protection of biocrusts against erosion (Williams et al., 2012). These effects appear to overwhelm roughness differences caused by different soil textural classes; one might expect fine-textured soils to increase surface albedo due to relatively smooth surface (Lal, 2017). However, our biocrusts had higher content of clay and silt relative to sand, yet still were much rougher than bare soil, suggesting that the texture is less important than the effects of the biocrust covering it.

Finally, the increase in soil moisture content would ordinarily increase the portion of the incident solar radiation absorbed by the soil

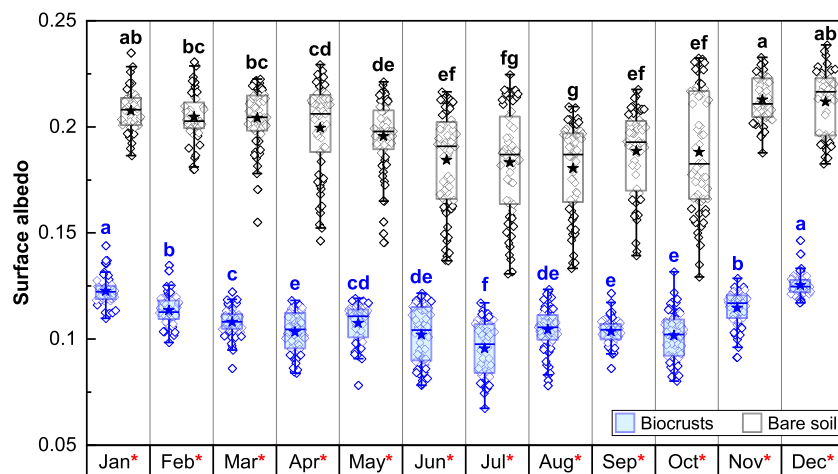


Fig. 7. Temporal variation in surface albedo of biocrusts and bare soil. The hanging bars, upper fence, lower fence, line, and star on plots indicate whiskers (scores outside the middle 50%), upper quartile (75% of the scores fall below the upper quartile), lower quartile (25% of the scores fall below the upper quartile), median (the mid-point of the data), and arithmetic mean, respectively. An asterisk (*) designates a significant difference between the biocrusts and bare soil at a 0.05 level of probability, and the different letters presented in each soil treatment indicate significant differences among different months at a 0.05 level of probability.

Table 3

Results of repeated measures ANOVA showing the effects of crust (biocrusts vs. bare soil), time (12 months from January to December), and experimental site on soil surface albedo, as well as their interaction effect.

Factor	Sum of square	df	Mean square	F	P
Crust	0.279	1	0.279	164.85	0.001
Time	0.018	1.623	0.011	28.87	0.002
Site	0.002	1	0.002	0.925	0.407
Crust × Time	0.004	1.623	0.002	5.78	0.055
Time × Site	<0.001	1.623	<0.001	0.500	0.599

system and thus decrease surface albedo (Roxly et al., 2010). Accordingly, our biocrusts should have lower surface albedo because they generally had higher surface soil moisture in comparison to the bare soil (Figs. S6B and S7B). For uncrusted soil, it has been reported that the higher the soil moisture content, the darker the color and the lower the albedo (Roxly et al., 2010). Beside this direct effect, the soil moisture had another indirect but vital influence on the surface albedo of biocrusts, which is that increasing soil moisture will activate the mosses and thus increase the greenness, darkness, and roughness (due to swelling) of the biocrust surface. This extra chain of events occurring in biocrust surfaces, but not in bare surfaces, would magnify the effects of moisture on albedo.

We found both the biocrusts and bare soil had strong seasonal variation in surface albedo, and the seasonal variation of the biocrusts was obviously stronger than that of the bare soil. The climate of our study area was characterized as a monsoonal climate region, which has concentrated and abundant rainfall in summer but few rainfall events in other seasons. This climate determined the overall trend of soil moisture change (both of the biocrusts and bare soil), which was certainly increased in summer and decreased during other seasons. Due to the negative correlations between soil moisture and surface albedo (Roxly et al., 2010), the monsoonal climate appears to explain the seasonal variation pattern of surface albedo well, which decreased from January to July and then increased from July to December (Fig. 7). Particularly for the biocrusts, the seasonal variation of their surface albedo may be explained by the combination of changing biocrust color, surface roughness, air temperature, and soil moisture, rather than soil moisture alone. In our study, the mosses had different colors under different conditions, which was generally grey to black under dry and cold conditions but green or light-yellow under wet and warm conditions. Also, these mosses are capable of absorbing many times volume of their own body in water (Tao and Zhang, 2012); thus, their height and volume

and also surface roughness would increase after rainfall but contract after drying. This may explain the apparent interactive effects between season and biocrust cover, i.e., biocrust presence magnifies seasonal moisture-driven albedo dynamics.

4.3. Effects of biocrusts on soil temperature and connections with decreased surface albedo

In this study, our biocrusts increased soil temperature in the dry periods but decreased soil temperature in the wet periods, which once again confirmed our previous findings (Xiao et al., 2013; Xiao et al., 2016; Xiao et al., 2019a). Actually, the phenomenon of biocrusts warming soils to varying extent has been reported in several studies (Belnap, 1995; George et al., 2003; Kidron and Tal, 2012; Couradeau et al., 2016), but the ability of biocrusts to decrease temperature has seldom been reported. A detailed discussion and explanation for our results follows.

Biocrust covering induced a net decrease in soil temperature over two years. This net change included a cooling effect in the summer, and a lesser warming effect in the winter. Thus, biocrusts thermally buffer the soil. The winter warming effect of the biocrusts is much easier to understand, because warming is the expected outcome under lowered albedo. Decreased surface albedo of the biocrusts indicates that more solar radiation was absorbed by the biocrust covered soil and correspondingly less solar radiation was reflected as compared with the bare soil. As a result, the biocrusts would certainly have higher temperature if they had the same thermal properties as the bare soil, because they absorbed more solar energy.

Complicating matters, biocrusts modify multiple thermal properties of soil, magnifying heat capacity, thermal conductivity, and thermal diffusivity of surface soil through holding more soil water (Xiao et al., 2019a). Water has much higher heat capacity compared to soil particles (4.18 vs. $-2.20 \text{ MJ m}^{-3} \text{ K}^{-1}$) or air-filled pores (Breen and Lévesque, 2008). Changes in this thermal property mean that it requires more energy to raise the soil temperature the wetter it is. Another possible reason for the lower temperature of biocrusts in summer in contrast to bare soil is that, by generating a more moist soil environment and delaying surface drying, biocrusts are subject to greater evaporative cooling than bare soil (Xiao et al., 2010; Kidron and Tal, 2012; Xiao et al., 2016).

Actually, the soil temperature dynamic of the biocrusts was likely affected not only by soil surface albedo and soil thermal properties but also by sensible and latent heat flux and soil heat flux, which should be investigated to further understand the biocrust effects on surface

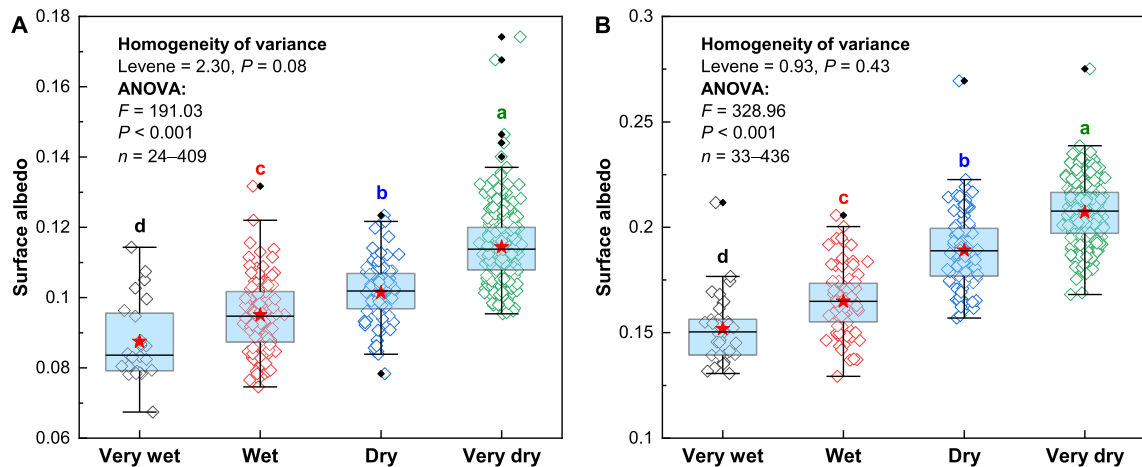


Fig. 8. Surface albedo of biocrusts (A) and bare soil (B) under different soil moisture conditions. The hanging bars, upper fence, lower fence, line, and star on plots indicate whiskers (scores outside the middle 50%), upper quartile (75% of the scores fall below the upper quartile), lower quartile (25% of the scores fall below the upper quartile), median (the mid-point of the data), and arithmetic mean, respectively. The different letters presented in each panel indicate significant differences among different soil moisture conditions at a 0.05 level of probability.

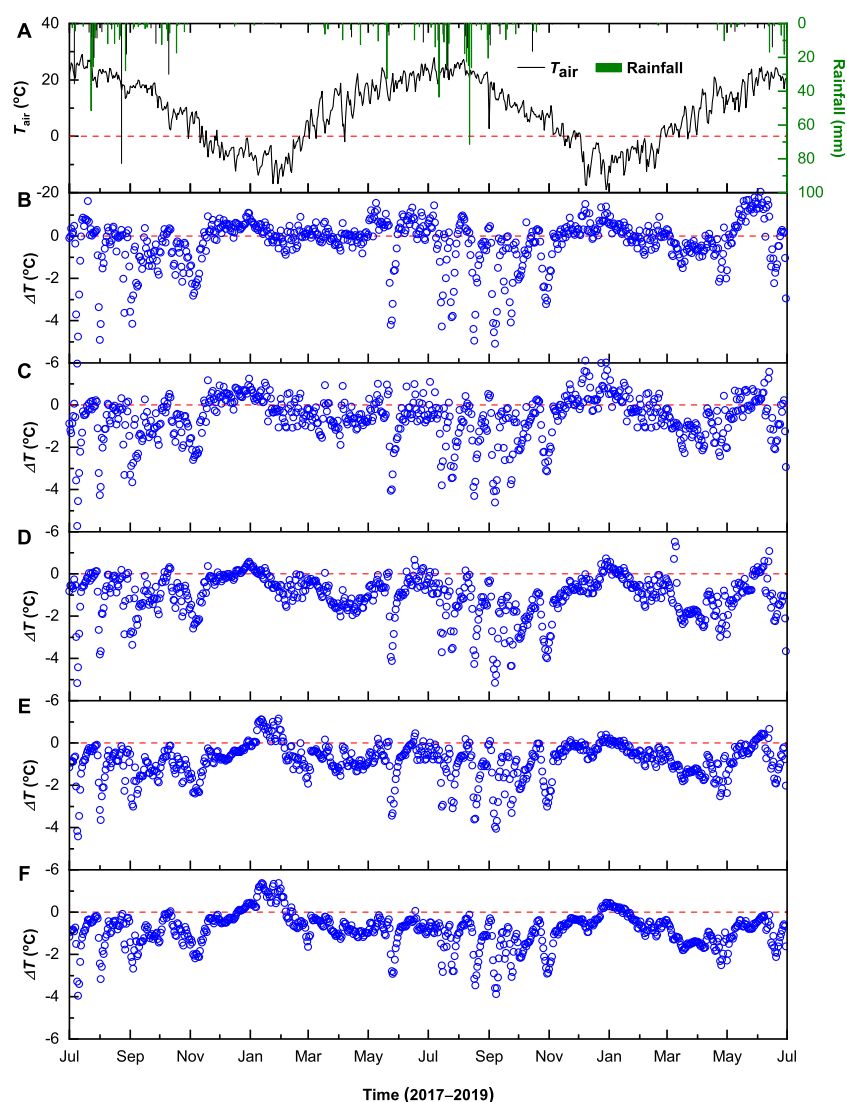


Fig. 9. Differences in soil temperature ($\Delta T, \Delta T = T_{\text{biocrusts}} - T_{\text{ck}}$) between biocrusts ($T_{\text{biocrusts}}$) and bare soil (T_{ck}) at 0–30 cm depths, as well as their responses to air temperature (T_{air}) and rainfall events. (A) T_{air} and rainfall; (B) ΔT at 2 cm depth; (C) ΔT at 6 cm depth; (D) ΔT at 10 cm depth; (E) ΔT at 20 cm depth; (F) ΔT at 30 cm depth.

soil heat balance. Except for the soil temperature, it has been reported that the diurnal range of soil temperature of the biocrust covered soil was sometimes as much as 6.8–9.4 °C lower than that of the bare soil, indicating that biocrusts acted as a buffer to temperature changes through holding more water in contrast to the bare soil (Xiao et al., 2019a). Such biocrusts effects on diurnal range of soil temperature are sometimes much more important than their effects on soil temperature, especially for microbial community and diversity, various soil biological

and biochemical processes, and annual grass establishment and growth in drylands.

4.4. Implications of biocrust effects on surface albedo and soil temperature regimes

We found that our biocrusts consistently had much lower surface albedo and significantly different soil temperature dynamics in

Table 4

Seasonal variation in accumulated daily mean temperature (AT) of biocrusts and bare soil at 0–30 cm depths over two years.

Solar depth	Spring (March–May)			Summer (June–August)			Fall (September–November)			Winter (December–February)		
	Biocrusts	Bare soil	ΔAT in % ^a	Biocrusts	Bare soil	ΔAT in % ^a	Biocrusts	Bare soil	ΔAT in % ^a	Biocrusts	Bare soil	ΔAT in % ^{a,b}
2 cm (°C)	3113.4	3133.7	−0.6	5255.9	5321.2	−1.2	1841.4	2008.3	−8.3	−1147.3	−1190.5	−3.6
6 cm (°C)	2907.3	3045.6	−4.5	5099.9	5259.9	−3.0	1853.4	2036.0	−9.0	−1089.5	−1120.1	−2.7
10 cm (°C)	2836.9	3061.6	−7.3	5034.3	5216.9	−3.5	1908.8	2188.0	−12.8	−1027.2	−965.1	−6.4
20 cm (°C)	2677.8	2855.9	−6.2	4902.2	5070.0	−3.3	1981.8	2206.7	−10.2	−956.0	−909.2	−5.2
30 cm (°C)	2566.1	2758.8	−7.0	4800.4	4987.6	−3.8	2063.4	2285.9	−9.7	−785.6	−769.3	−2.1

^a ΔAT in % = $(AT_{\text{biocrusts}} - AT_{\text{ck}}) / AT_{\text{ck}} \times 100\%$. $AT_{\text{biocrusts}}$ = accumulated daily mean temperature of biocrusts; AT_{ck} = accumulated daily mean temperature of bare soil.

^b The meaning of positive and negative values of ΔAT in % in winter is opposite to that in other seasons, because the accumulated daily mean temperature was negative in winter but positive in spring, summer, and fall.

Table 5

Daily mean soil moisture of biocrusts and bare soil at 0–30 cm depths over two years.

Soil depth	2017–2018				2018–2019				Two years			
	Biocrusts	Bare soil	F	P ^a	Biocrusts	Bare soil	F	P ^a	Biocrusts	Bare soil	F	P ^a
2 cm (cm ³ cm ⁻³)	0.074 ± 0.003	0.057 ± 0.002	59.10	0.002	0.067 ± 0.003	0.061 ± 0.002	7.58	0.051	0.070 ± 0.002	0.058 ± 0.001	27.31	0.006
6 cm (cm ³ cm ⁻³)	0.089 ± 0.002	0.060 ± 0.001	121.24	<0.001	0.084 ± 0.002	0.058 ± 0.001	76.74	0.001	0.086 ± 0.002	0.059 ± 0.001	96.17	0.001
10 cm (cm ³ cm ⁻³)	0.106 ± 0.002	0.059 ± 0.001	262.42	<0.001	0.106 ± 0.002	0.059 ± 0.001	252.89	<0.001	0.106 ± 0.002	0.057 ± 0.001	257.60	<0.001
20 cm (cm ³ cm ⁻³)	0.050 ± 0.001	0.072 ± 0.001	64.72	0.001	0.049 ± 0.001	0.077 ± 0.001	114.75	<0.001	0.050 ± 0.001	0.074 ± 0.001	88.51	0.001
30 cm (cm ³ cm ⁻³)	0.043 ± 0.001	0.092 ± 0.002	428.85	<0.001	0.042 ± 0.001	0.098 ± 0.002	477.72	<0.001	0.042 ± 0.001	0.095 ± 0.001	454.16	<0.001

^a Two-tailed P values.

comparison to the bare soil, and this feature could be used to distinguish biocrusts from bare land and the soil covered with various vegetation, which would be very helpful for mapping biocrust distribution (Rozenstein and Adamowski, 2017; Potter and Weigand, 2018) and further assessing their ecological contribution to ecosystems. Moreover, although the surface albedo of the biocrusts seasonally varied with soil temperature and soil moisture due to the shifting of color and roughness of biocrust community, surface albedo can be a very predictive parameter for evaluating biocrust activity and ecological function (Mallen-Cooper et al., 2020), such as an accurate and nondestructive method to estimate chlorophyll *a* (Román et al., 2019). Additionally, due to the biocrust spectral properties, considerable effort has been devoted to the identification of the main spectral characteristics of different biocrust communities (Escribano et al., 2017).

Soil surface albedo can be an important moderator of local microclimatic conditions and large-scale climate feedbacks (Mallen-Cooper et al., 2020), and changes in dryland albedo have the potential to disproportionately affect global energy balance as well as temperatures. As vegetation is increasingly depleted and perennial plant cover recedes in drylands, the proportion of bare land increases, which further enhances land surface albedo. Increasing surface albedo in dryland regions may create thermic depressions and subsequently impede cloud formation and possibly decrease rainfall through reducing temperature and decreasing. Fortunately, the wide distribution of biocrusts in arid and semiarid regions and their decreasing effects on soil surface albedo possibly relieve the severity of this problem. Our biocrusts successfully decreased surface albedo from bare “sand” (0.2–0.4) to “dark-colored soil surfaces” (0.1–0.2) or equal to that of “grassland” (0.1) (Lal, 2017), which equally increased soil surface net solar radiation by 13.7 J m⁻² s⁻¹. From this point of view, our biocrusts have made bare sand in degraded lands rapidly transition to a mature soil or even a soil covered by grasses with regard to albedo. At regional and global scales, such a huge decrease in surface albedo caused by biocrusts would substantially compensate or even offset the negative impacts of land degradation and desertification on large-scale temperature and precipitation pattern, water sustainability, and agricultural production (Smith et al., 2017), through regulating the shifting of the balance of land surface solar radiation. In other words, biocrusts maintain the surface albedo in arid and semiarid environments similarly to common vegetation covers worldwide and thus make a great contribution to combat global change (Condon and Pyke, 2020).

Soil temperature is a very important environmental factor influencing soil biological and biochemical processes in dryland ecosystems, and it regulates many ecosystem functions, including nitrogen and carbon fixation, microbial activity, plant nutrient uptake and growth, evaporation, and seed germination. Our study showed that biocrusts have the ability to greatly relieve the severity of extreme soil thermal conditions through smoothing and flattening diurnal soil temperature dynamics, indicating that they possibly generate positive influences on the soil, such as increasing water and nutrient availability, improving vegetation community structure, and decreasing land degradation susceptibility (Xiao et al., 2019a). Also, the soil temperature regimes regulated by biocrusts are very important for maintaining biocrust stability in

structure and function, because biocrusts themselves are sensitive to relatively small amounts of warming (2–3 °C) (Johnson et al., 2012; Maestre et al., 2015; Lafuente et al., 2018). More broadly, biocrust buffering effects on soil temperature could plausibly have positive influences on seedling establishment and plant growth, conservation of biodiversity of soil animals (Li et al., 2014; Xiao and Veste, 2017), and the thawing of permafrost in summer caused by global warming (Breen and Lévesque, 2008).

It is important to note that our results pertain to moss-dominated biocrusts which are more abundant in semiarid climate zones (annual precipitation = 250–500 mm; accounting for 15.2% of the total land area of the world (Safriel and Adeel, 2005)). However, in arid (annual precipitation = 25–250 mm; accounting for 10.6% of the total land area (Safriel and Adeel, 2005)) and hyper arid (annual precipitation < 25 mm; accounting for 6.6% of the total land area (Safriel and Adeel, 2005)) climate zones, biocrusts are also widely distributed but are mostly dominated by cyanobacteria or lichens rather than mosses (Rodríguez-Caballero et al., 2018). Because biocrusts include such a wide variety of different community types with distinct properties, it would be unsurprising if a different type of biocrust exerted very different effects on albedo and soil temperature through time. For example, cyanobacterial biocrusts may either be darkly pigmented or colored similarly to underlying soil and range from very flat to very rough in different environments. A fuller, global understanding of biocrust effects on albedo would require broader monitoring of year-round albedo and energy balance changes induced by different types of biocrusts in different environments. We might hypothesize that in general biocrusts may have an even stronger influence on albedo, energy balance and soil temperature in regions drier than our study area, because arid and hyper arid regions have much higher intensity and duration of solar radiation in comparison to semiarid areas, thus biocrust development could modulate net shortwave radiation and soil temperature to a greater extent.

5. Conclusions

In our study, the surface albedo, land-surface energy balance, temperature and moisture (0–30 cm), and closely related surface properties of moss-biocrust covered soil and bare soil were continuously measured across two years in a semiarid dryland on the northern Chinese Loess Plateau. We found that biocrusts greatly increased surface darkness, roughness, and soil moisture in contrast to bare soil; therefore, they highly decreased soil surface albedo and outgoing short-wave radiation, and on the contrary they increased net short-wave radiation and also net all-wave solar radiation. Due the biological responses (color and roughness) of biocrust mosses to the combination of changing moisture and temperature, biocrusts exhibited more intensive seasonal variations in surface albedo than the bare soil. Interestingly, contrary to our expectation, the increased solar radiation by the biocrusts did not consistently increase soil temperature in comparison to the bare soil. Instead, the soil temperature of biocrust covered soil was increased only under dry conditions but decreased under wet conditions, indicating that other factors (i.e., surface soil thermal properties) determined soil

temperature dynamics of the biocrust covered soil, together with surface albedo and solar radiation. We conclude that biocrust strongly decreased soil surface albedo and greatly changed land-surface energy balance in dryland ecosystem. Due to the wide distribution of the biocrusts in drylands, the decrease in surface albedo caused by biocrusts would possibly compensate or even offset the negative impacts of land degradation. Namely, biocrusts are capable of keeping the surface albedo of drylands at a relative low level and thus potentially made a great contribution toward combatting global change.

CRediT authorship contribution statement

Bo Xiao: Conceptualization, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Matthew A. Bowker:** Investigation, Formal analysis, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2020.140425>.

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