Received: 24 July 2024 | Revised: 8 October 2024 | Accepted: 10 October 2024
DOI: 10.1111/ejss.70004

RESEARCH ARTICLE

European Journal of Soil Science WILEY

Overlooked biocrust impacts on surface soil thermal properties: Evidence from heat-pulse sensing on large volume samples

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Funding information
National Natural Science Foundation of China, Grant/Award Number: 42077010

Abstract
Biocrusts are a critical surface cover in global drylands, but knowledge about their influences on surface soil thermal properties are still lacking because it is quite challenging to make accurate thermal property measurements for biocrust layers, which are only millimetres thick. In this study, we repacked biocrust layers (moss- and cyanobacteria-dominated, respectively) that had the same material as the original intact biocrusts but was more homogeneous and thicker. The thermal conductivity (λ), heat capacity (C) and thermal diffusivity (k) of the repacked and intact biocrusts were measured by the heat pulse (HP) technique at different mass water contents (θ_m) and mass ratios (W_t), and the differences between repacked and intact biocrusts were analysed. Our results show that biocrusts substantially alter the thermal properties of the soil surface. The average λ of moss (0.37 W m^{-1} K^{-1}) and cyanobacteria biocrusts (0.90 W m^{-1} K^{-1}) were reduced by 63.0% and 10.3% compared with bare soil (1.00 W m^{-1} K^{-1}), respectively. Edge effects including heat loss and water evaporation caused the λ and k of the biocrusts to be underestimated, but the C to be overestimated. The differences in thermal properties were significant (p <0.001), except for the differences in thermal conductivity between repacked and intact cyanobacteria biocrusts, which were not significant ($p = 0.379$). Specifically, in the volumetric water content (θ_v) range of 0 to 20%, the λ and k of the repacked moss biocrusts were underestimated by 59.1% and 61.8%, respectively, and the C was overestimated by 23.9% compared with the intact moss biocrusts. The λ and k of the repacked cyanobacteria biocrusts were underestimated by 15.8% and 79.2%, respectively, and the C was overestimated by 34.8% compared with the intact cyanobacteria biocrusts at the θ_v range of 0 to 30%. Typically, this difference increased as the θ_v rises between repacked and intact biocrusts. Our new measurements provide evidence that the thermal properties of biocrusts were previously misjudged due to the measurement limitations imposed by their limited thickness when measured in situ. Biocrusts are likely more significant in regulating soil heat and temperature in drylands than was previously assumed.

KEYWORDS
biological soil crust, heat pulse, thermal conductivity, thermal diffusivity, volumetric heat capacity

1 | INTRODUCTION

The soil surface is the interface between the soil and atmosphere, and among the main variables affecting the transport of matter and energy from the land surface to the atmosphere are its thermal properties, specifically its thermal conductivity (λ), volumetric heat capacity (C) and thermal diffusivity (k) (Khaledi et al., 2023; Xiong et al., 2023). Research on land surface heat balance and temperature change depends on an understanding of the thermal properties of the soil surface and the factors that affect them; such understanding is particularly pressing owing to concerns about global climate change (Nottingham et al., 2020; Ochsner et al., 2001). Thermal properties of the soil are mostly influenced by soil texture (Krishnaiah & Singh, 2003), mineral composition (Malek et al., 2021), bulk density (Tong et al., 2020) and soil water content (Liu et al., 2020). In addition, the nature and characteristics of the surface cover such as vegetation (Mendis et al., 2022; van der Velde et al., 2009), snow cover (Freppaz et al., 2018; Ge & Gong, 2010) and litter cover (Antisari et al., 2011; Pintaldi et al., 2016) can also affect thermal properties by altering, for example, organic matter content and mechanical composition of the soil. Thus, the thermal properties of the surface are highly complex and variable.

In dryland ecosystems, accounting for 38% of global land area, soil thermal properties strongly influence seed germination, plant growth, microbial activity and carbon emission processes due to limited rainfall and sparse vegetation (Reynolds et al., 2007; Zhang & Wang, 2017). More importantly, they are involved in the accelerated expansion of drylands, regulating dryland hydrological processes and temperature changes (Wang et al., 2022). Soil thermal properties affect evaporation processes from dryland surfaces and reduce soil water content (Guida et al., 2023). This may lead to an increase in sensible heat flux and a decrease in latent heat flux, and produce temperature extremes (Huang et al., 2016). Therefore, the study of surface thermal properties and their influencing factors is necessary to improve understanding of dryland ecosystems.

In recent years, biocrusts have been recognized as a widespread surface cover in drylands; they substantially modify soil properties and play an important role in controlling the energy balance in the soil surface layer

Highlights

- Repacking and thickening provide reliable measurements of biocrust thermal properties.
- Inappropriate measurement underestimated thermal conductivity of biocrusts by 38%.
- Biocrusts truly reduce surface soil thermal conductivity by 37% in contrast to bare soil.
- Errors of biocrust thermal properties are mainly due to edge effects and heat loss.
- Biocrusts are more significant in regulating soil heat and temperature than we thought.

(Weber et al., 2022; Xiao & Bowker, 2020). Biocrusts are essentially a dense-layered structure composed of cryptogams such as cyanobacteria, lichens and mosses, microorganisms such as fungi and bacteria, and soil surface particles which were bonded through pseudo roots, mycelium and secretions of the biological component (Weber et al., 2022). Biocrusts act as ecosystem engineers and have a significant role in regulating soil physical (Li, Bowker, & Xiao, 2022c), chemical (Xiao & Veste, 2017) and biological processes (De Guevara & Maestre, 2022). Specifically, biocrusts significantly improve the particle composition, pore structure and stability of surface soils (Baldauf et al., 2023; Xiao, Sun, et al., 2019). In addition, biocrusts participate in and regulate carbon cycle processes in drylands through respiration and photosynthesis (Dou et al., 2023; Lange et al., 1992; Rodriguez-Caballero et al., 2018). More importantly, biocrusts influence dryland water cycling by increasing topsoil evaporation and deep soil water storage (Kidron & Tal, 2012; Li, Bowker, & Xiao, 2022c; Sun et al., 2023). Although the improvement of soil properties and the influence of biocomponents of biocrusts on hydrological processes can dramatically change the thermal properties of the soil surface layer (Kidron & Kronenfeld, 2023; Xiao, Ma, & Hu, 2019), the thermal properties of the biocrusts and the factors influencing them are understudied.

Recently, several studies have measured the thermal properties of intact biocrusts (usually ≤2 cm from the surface) using heat pulse (HP) sensors (Li, Sun, et al., 2022; Xiao, Ma, & Hu, 2019). These studies have generally found that biocrusts buffer surface temperature.

However, prior thermal property data might not be representative due to several limitations in measurement approaches associated with HP sensing volumes (He et al., 2018; Ren et al., 1999). First, it has been demonstrated that the magnitude of error in estimating soil thermal properties is closely related to the distance of the heating needle of the HP sensor from the soil surface (Kluitenberg & Philip, 1999; Xiao et al., 2015). As the distance from the heating needle to the soil surface decreases, the error in thermal property measurements increases rapidly (Zhang et al., 2014). Theoretically, the measurement volume of a HP sensor is a cylinder centred on the heating needle, and the radius of the cylinder is approximately 2.3 times the probe spacing (Ren et al., 1999). For a sensor with a spacing of 6 mm, for example, the thickness of the biocrusts would need to be at least 3 cm to fulfil this requirement. This is much greater than the typical biocrust thickness in arid regions, which is 1–2 cm, especially for thinner cyanobacteria biocrusts. Thus, even the relatively small sensing volume of HP sensors leads to measurement error, such that the resulting soil thermal property estimates are a combination of the influences of both air and soil (Xiao et al., 2015). Secondly, biocrusts are typically a layered medium. It has been shown that the thermal properties of moss which is similar to that of water differ greatly from those of the underlying soil due to its large porosity (Moore et al., 2019). Thus, in practical terms, the heat that the HP sensor releases move through both the mineral soil that has a higher thermal conductivity and the biological components that have lower thermal conductivity, which biases the sensor response. Nonetheless, the assumption that the material to be measured is homogeneous is necessary to apply an analytical solution (De Vries, 1952). This is obviously not the case in reality, which can also cause misclassification of thermal property measurements.

In addition, studies on the thermal properties of biocrusts do not adequately consider biological components (biomass and organic matter particles) as a factor. Biomass and organic materials change with the development of biocrusts and show strong differences in different types of biocrusts (Xiao et al., 2022). However, tests on the effects of the gradients in biological component of biocrusts are difficult due to their small size in their intact condition (Karnieli et al., 1999). Thus, prior investigations on the thermal properties of biocrusts are imprecise and lacking in sufficient detail because of the aforementioned problems. This limits proper assessment of the impact of biocrusts on surface thermal properties and how much they contribute to variations in surface temperature in drylands. To improve upon prior investigations of biocrust effects on thermal properties, we hypothesized that repacking biocrust samples to provide adequate measurement volumes might be a useful strategy.

In this study, we separately considered the biological component and the underlying soil of the intact biocrusts to avoid 'edge effects' in the thermal property measurements of biocrusts (moss- and cyanobacteria-dominated, respectively) at various mass water contents (θ_m) and mass ratios (W_t) (i.e. the ratio of the mass of the dried biomass and organic materials fraction to the mass of the dry soil). We further compared and quantified the differences in thermal properties between the intact and repacked biocrusts. Our specific objectives were to: (i) quantify the effect of biocrusts on the thermal properties of the soil surface; (ii) analyse the effect of θ_m and W_t on the thermal properties of moss and cyanobacteria biocrusts; and (iii) better explain the effect of biocrusts on surface temperature by quantifying the error of edge effects in prior related work. Our experimental results provide important data on the thermal properties of biocrusts to aid in better understanding of the role of biocrusts in heat balance in drylands.

2 | MATERIALS AND METHODS

2.1 | Study area

The Loess Plateau is located in the northern region of China. It covers an area of about 6.3×10^5 km^2 and is one of the most severely eroded areas in the world. Our samples were collected from the Liudaogou watershed (38°46′–38°51′ N, 110°21′–110°23′ E; see Figure 1a) in Shenmu Country on the northern Loess Plateau. The site elevation and the watershed area are 1094–1274 m and 6.89 km^2, respectively. The region is characterized by a temperate continental climate and is a zone of 'Water-Wind Erosion Crisscross Region' (Xiao & Bowker, 2020). The average annual precipitation and evaporation are 454 and 1337 mm, respectively. The average annual temperature is 8.4°C. The soils are psamments (specifically an aeolian sandy soil) according to the USDA soil taxonomy with 81% of sand, 14% of silt and 5% of clay.

As a result of the 'Grain for Green Program', the vegetation in the watershed is well restored and provides good habitat for the extensive development of biocrusts. Now biocrusts widely develop on the soil surfaces and cover >30% and sometimes as much as 70%–80% of the land area (Xiao, Ma, & Hu, 2019). The biocrust types are mostly cyanobacteria, moss and their mixture, with mosses being the dominant species including *Didymodon vinealis* (Brid.) Zander and *Bryum arcticum* (R.Brown) B.S.G., and the dominant cyanobacteria species are

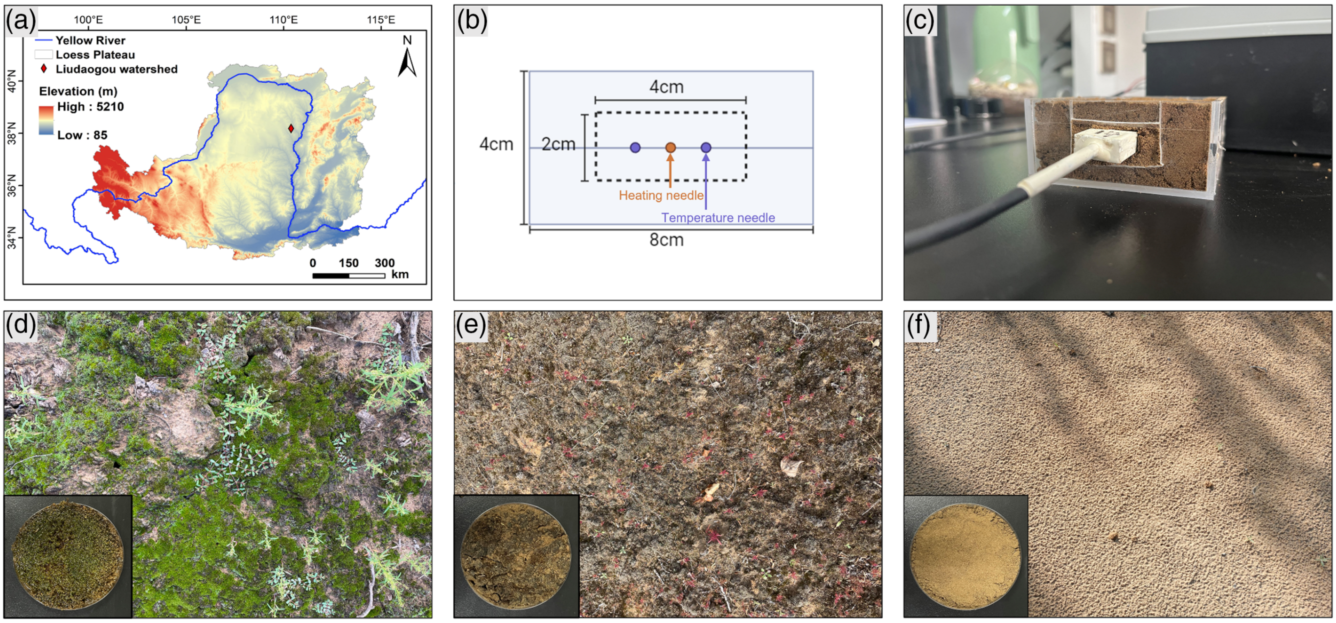

FIGURE 1 Sampling location and measurements for biocrusts and bare soil. (a) Liudaogou watershed in the Loess Plateau; (b) schematic diagram of the device for repacked biocrust samples; (c) measurements for repacked biocrust samples; (d) intact moss-dominated biocrusts and samples; (e) intact cyanobacteria-dominated biocrusts and samples; (f) intact bare soil and samples.

Lyngbya allorgei, *Oscillatoria granulata*, *Microcolus paludosus* and *Phormidium angustissimum* (Sun et al., 2022).

2.2 | Experimental design and sampling

For thermal properties of repacked biocrusts (refer to Section 2.4 for details), three influencing factors including soil cover types, θ_m and W_t were considered. Surface cover types included bare soil, cyanobacteria and moss biocrusts. Five levels of θ_m were set for each surface cover type (0, 5, 10, 15 and 20%), and five and six W_t levels were set for repacked cyanobacteria (3 (1:30), 4 (1:25), 5 (1:20), 7 (1:15) and 10 (1:10)%) and moss biocrusts (10 (1:10), 11 (1:9), 13 (1:8), 14 (1:7), 17 (1:6) and 20 (1:5)%), respectively. Thus, there were a total of 60 treatments (including 55 treatments of repacked biocrusts and 5 treatments of bare soil) with four replicates per treatment. Water contents were selected as relatively dry conditions to represent typical field moisture conditions. It is also worth mentioning that the mass ratios of intact cyanobacteria and moss biocrusts are 5 (1:20) and 14% (1:7), respectively. Since the biological component mass of intact cyanobacteria biocrusts is finite, setting larger ratios in the repacked cores was intended to produce sufficient gradients to clearly identify thresholds for thermal property differences. For intact biocrusts, two influencing factors including biocrust types (cyanobacteria and moss biocrusts) and θ_m were considered. We measured the thermal properties of intact cyanobacteria and moss biocrusts consecutively from saturation to air-drying, with four replicates of each type.

According to the experimental design, we selected a representative sample plot with a patchy distribution of moss biocrusts, cyanobacteria biocrusts and bare soil with no vegetation cover (Figure 1d–f). All samples were collected on a flat area of approximately 500 m^2 to limit variations in conditions such as biocrust characteristics, soil texture, slope and aspect. Petri dishes with a diameter of 9 cm and a height of 2 cm were used to collect the upper 2 cm of cyanobacteria and moss biocrust samples for measuring biocrust characteristics (thickness and total biomass). Soil cores (5 cm in height and 100 cm^3 in volume) were used to collect the topsoil (0–5 cm depth) of each treatment to measure soil properties (soil bulk density and saturated water content). All measurement properties are based on 15 replicate samples. In addition, four samples each of intact cyanobacteria and moss biocrusts were collected separately for thermal property measurements using PVC boxes (8 × 8 × 4 cm) after rainfall (to avoid crust breakage).

2.3 | Measurement of biocrust characteristics and soil properties

In the field, soil roughness was measured by using the chain method (Saleh, 1993). The samples consisted of the biological component and the soil naturally attached to their bottoms.

In the lab, the thickness of the biocrusts was measured using a digital vernier calliper. Moss biocrusts were separated from the soil with water through a 2-mm sieve and dried at 65°C for 24 h for the measurement of moss biocrust biomass. Chlorophyll content was determined using a UV–Vis spectrophotometer (DR 5000, Hach, USA) for cyanobacteria biocrust biomass. Dried cyanobacteria and moss biocrusts were crushed in a mortar and pestle and passed through a 2 mm sieve. Due to the difference in density between the biological component of the biocrusts and the underlying soil, manual shaking of the sieve results in stratification and separates them (visible as a tan coloured material for the biological component and earth coloured material for the mineral soil). Tan coloured material was sieved out until there were no visible fines, dried at 65°C for 24 h and then recorded as the biological component mass. In addition, the underlying mineral soil material of each biocrust sample was also weighed after drying at 105°C for 24 h. These data were used to calculate W_t of the biocrust samples. Soil bulk density and saturated water content were also measured after oven-drying at 105°C for 24 h with intact biocrust samples.

2.4 | Measurement of the thermal properties of repacked biocrust samples

After separating the biological component of the two biocrusts (Section 2.3), the biological component and the soil were placed in separate plastic bags. The experiment was carried out by filling the treated biocrust samples into a square box (8 × 8 × 4 cm) made of acrylic. This box has no lid, and the centre portion of one side (4 × 2 cm) is removed for HP measurements (Figure 1c). The W_t level was met by keeping the mass of the dried soil (m_s) constant and continuously increasing the mass of the dried biological parts (m_b). Then, different masses of deionized water were added to achieve a set gradient of θ_m. Specific mass ratios can be found in Table 1. To ensure homogeneous mixing, the samples were repacked in layers and measured after 24 h. The densities of bare soil, moss and cyanobacteria biocrusts samples were set to 1.5, 1.1 and 1.5 g cm^{-3}, respectively, which remained approximately the same as the densities of the intact samples (Table 2). Since the samples need to be reused, the samples for each θ_m need to be re-dried and separated after the measurements.

Thermal properties of the biocrusts were measured using HP sensors; a diagram of the experimental instrument was shown in Figure 1b. The HP sensor was a homemade three-needle probe, consisting of three stainless steel needles and a plastic mould. Each stainless steel needle is 4 cm long, and the physical spacing of the stainless steel needles is 6 mm (Chen et al., 2024). Each needle contained a type E thermocouple to sense the temperature. The centre needle also contains a resistance to generate the heat pulse. All needles are filled with thermally conductive resin, while the sensor body is filled with epoxy resin. The actual spacing of the probes was calibrated in an agar solution (5 g L^{-1}) prior to measurement (Ren et al., 1999). During the measurement, the HP probe was inserted horizontally into the biocrust samples at a depth of 2 cm (Figure 1c) and connected to a CR5000 datalogger (Campbell Scientific, Inc., USA). A program was written to control its heating duration and strength. The heating duration for this experiment was 8 s, and the heating strength was 66.6 W m^{-1}. The ambient temperature was held constant, and the datalogger recorded the value of temperature change (ΔT) within 5 min after heat was released from the sensor's heating needle. The measurement was repeated every 20 min, and the thermal properties of the samples were calculated from the collected data of ΔT over time.

TABLE 1 Experimental design of mass ratios (W_t) of repacked biocrusts.

Treatments	Moss biocrusts			Cyanobacteria biocrusts		
	W_t (%)	m_b (g)	m_s (g)	W_t (%)	m_b (g)	m_s (g)
T_1	10	26.00	260.00	3	14.59	437.71
T_2	11	28.89	260.00	4	17.51	437.71
T_3	13	32.50	260.00	5	21.89	437.71
T_4	14	37.14	260.00	7	29.18	437.71
T_5	17	43.33	260.00	10	43.77	437.71
T_6	20	52.00	260.00	—	—	—

Note: T_3 = the mass ratios in the intact state of the biocrusts. W_t = the ratio of the mass of the dried biomass and organic materials fraction to the mass of the dried soil; m_b = the mass of the dried biological parts; and m_s = the mass of the dried soil.

TABLE 2 Physical properties of intact biocrusts and bare soil ($n = 15$).

Measurements	Moss biocrusts	Cyanobacteria biocrusts	Bare soil
Bulk density (0–5 cm) (g cm^{-3})	1.12 ± 0.05 b	1.51 ± 0.07 a	1.54 ± 0.12 a
Surface roughness (%)	7.31 ± 0.37 a	6.05 ± 0.21 a	1.21 ± 0.19 b
Biocrust thickness (mm)[a]	12.04 ± 0.82 a	5.97 ± 0.54 b	—
Moss and cyanobacteria biomass (g cm^{-2})	0.27 ± 0.04 a	0.09 ± 0.01 b	—
Saturated water content (cm^3 cm^{-3})	0.45 ± 0.04 a	0.38 ± 0.05 b	0.34 ± 0.02 c

Note: Different letters (a, b and c) presented within the same line indicate significant differences among different types of soil cover at a 0.05 probability level.
[a]Thickness includes the biocrust layer and the soil that was naturally adhered to the biocrust layer.

For a short-duration linear-heat source applied to an infinite line source in a homogeneous and isotropic medium at a uniform initial temperature, the analytical solution is (De Vries, 1952):

$$\Delta T(r,t) = \begin{cases} -\dfrac{q}{4\pi t\lambda} E_i\left(\dfrac{-r^2}{4kt}\right) & 0 < t \le t_0 \\ \dfrac{q}{4\pi t\lambda}\left[E_i\left(\dfrac{-r^2}{4k(t-t_0)}\right) - E_i\left(\dfrac{-r^2}{4kt}\right)\right] & t > t_0 \end{cases}, \quad (1)$$

where λ is thermal conductivity (W m^{-1} K^{-1}); k is the thermal diffusivity ($k = \lambda/C$, m^2 s^{-1}); C is the volumetric heat capacity of the material (kJ m^{-3} K^{-1}); $\Delta T(r, t)$ is the value of temperature change at radial distance r from the linear heater at time t; q is the total heat released by the linear heat source (J m^{-1}); t_0 is the heating duration (s); and $E_i(-x)$ is the exponential integral. A nonlinear model fit method (NMF) based on least squares can be used to calculate thermal properties by fitting Equation (1) to the temperature change as a function of time $\Delta T(r, t)$.

2.5 | Measurement of the thermal properties of intact biocrusts

The PVC box containing the intact biocrusts (described in Section 2.2) had small, uniform holes in the bottom, and we wrapped the bottom of the box with non-woven fabric and saturated it with water for 48 h. The boxes were then placed in a cool place with the tops were covered with cling film so that excess water drained by gravity through the bottom holes. A HP sensor was inserted horizontally 1 cm from the surface to measure the thermal properties of the biocrusts (0–2 cm). After saturation, the boxes were left at room temperature (20°C) with their tops open, and the water within the soil gradually evaporated. The samples were weighed every 4 h, and their thermal properties were measured (refer to Section 2.4 for methodology) until the samples were air dry. At the end of the test, the samples were dried at 105°C for 24 h and weighed, and their water content and bulk densities were calculated.

2.6 | Data analysis

One-way ANOVA ($\alpha = 0.05$) followed by the Tukey HSD post hoc test were employed to test the differences in characteristics of intact biocrusts, soil properties, the thermal properties of repacked biocrusts among different θ_m and W_t, and the differences in thermal properties of intact and repacked biocrusts. Pearson correlation analysis was used to evaluate the extent to which θ_m and W_t influence the thermal properties of the biocrusts. All statistical analyses were conducted using IBM SPSS Statistics 27.0. The final results reflect the mean values of the replicates, expressed as the mean ± standard error.

3 | RESULTS

3.1 | Biocrust effects on surface soil properties and thermal properties after repacked

The physical properties of the biocrusts and bare soil are distinctly different at 0–2 cm (Table 2). Specifically, the bulk density of cyanobacteria and moss biocrusts was lower than that of bare soil, while roughness and saturated water content were significantly higher. In particular, the bulk density of moss and cyanobacteria biocrusts was 27.2% and 1.9% lower than that of bare soil, respectively. Meanwhile, biocrusts significantly increased surface roughness and saturated water content (mean increases of 452.1% and 22.1%, respectively). In addition, the roughness and thickness of moss biocrusts were 7.31% and 12.04 mm, respectively, which were 1.2- and 2.0-fold that of cyanobacteria biocrusts. The moss biocrusts had a higher biomass by 200.0% (0.27 vs. 0.09 g) compared with the cyanobacteria biocrusts (Table 2, $p < 0.05$).

Thermal properties (λ, C and k) of repacked biocrusts are typically lower than bare soil, especially moss biocrusts (Figure 2). Additionally, repacked cyanobacteria biocrusts had significantly higher thermal properties than the repacked moss biocrusts (p <0.05), but there was no statistical difference in the thermal properties of cyanobacteria biocrusts and bare soil. In particular, the average λ for the repacked moss biocrusts, cyanobacteria biocrusts and bare soil was 0.37 ± 0.14, 0.90 ± 0.42 and 1.00 ± 0.53 W m^{-1} K^{-1}, respectively. Moss and cyanobacteria biocrusts had 63.0% and 10.3% lower λ than bare soil, respectively. The mean C of moss and cyanobacteria biocrusts decreased by 28.2% (0.70 ± 0.08 vs. 0.98 ± 0.25 MJ m^{-3} K^{-1}) and 8.0% (0.90 ± 0.17 vs. 0.98 ± 0.25 MJ m^{-3} K^{-1}), respectively, in comparison with bare soil. Both cyanobacteria biocrusts and bare soil had an average k of 9.44×10^{-7} m^2 s^{-1} (standard deviation is 3.51 and 3.60×10^{-7} m^2 s^{-1}, respectively), which is 1.8 times that of moss biocrusts ($5.13 \pm 1.51 \times 10^{-7}$ m^2 s^{-1}). Furthermore, the thermal properties of cyanobacteria biocrusts vary more widely than those of moss biocrusts, which might indicate that the thermal properties of cyanobacteria biocrusts are more affected by gradients of θ_m and W_t.

3.2 | Response of repacked biocrust thermal properties to increasing water content

Figure 3 showed the fluctuation of the repacked biocrust thermal properties (λ, C and k) as a function of five θ_m levels (0, 5, 10, 15 and 20%), with all W_t treatments included in each θ_m level. The thermal properties of repacked moss and cyanobacteria biocrusts were seen to vary significantly across the θ_m range ($p < 0.01$), and there was a noteworthy positive association observed between the biocrust thermal properties and θ_m (Table 3). At the same W_t, the thermal properties of the biocrusts become larger with increasing θ_m (Figure 5). Specifically, there was an average increase of 29.7% in the λ of moss biocrusts, which varied from 0.20 to 0.57 W m^{-1} K^{-1}. The average λ of cyanobacteria biocrusts ranged from 0.23 to 1.39 W m^{-1} K^{-1}, with an average increase of 68.7% (Figure 3a). The average C of moss and cyanobacteria biocrusts ranged from 0.66 to 0.81 MJ m^{-3} K^{-1} and from 0.70 and 1.17 MJ m^{-3} K^{-1}, respectively (Figure 3b). It is notable that, at the same θ_m, cyanobacteria biocrusts normally had higher values of λ, C and k than moss biocrusts. Conversely, at $\theta_m = 0\%$, there was very little variation in their thermal properties (λ: 0.20 vs. 0.23 W m^{-1} K^{-1}, C: 0.66 vs. 0.70 MJ m^{-3} K^{-1}, k: 3.06 vs. 3.30×10^{-7} m^2 s^{-1}). In addition, the relationship of θ_m and biocrust thermal properties was well-explained by linear or non-linear fitting ($R^2 > 0.5$), and thermal properties of the cyanobacteria biocrusts are more susceptible to the influence

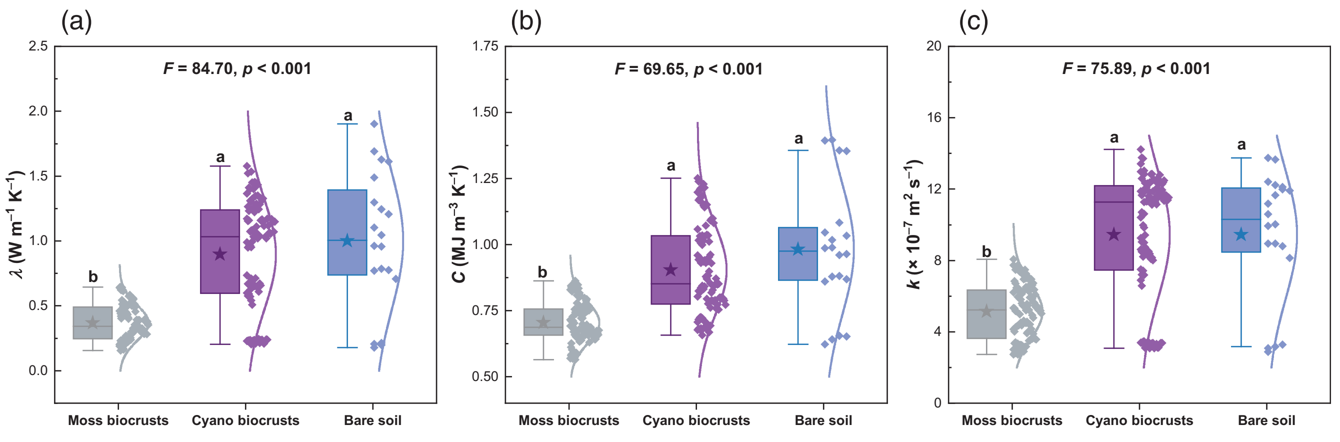

FIGURE 2 Differences in thermal properties of repacked biocrusts and bare soil in all treatments. All treatments included five mass water content (θ_m) treatments for both repacked biocrusts and bare soil. (a) λ; (b) C; (c) k.

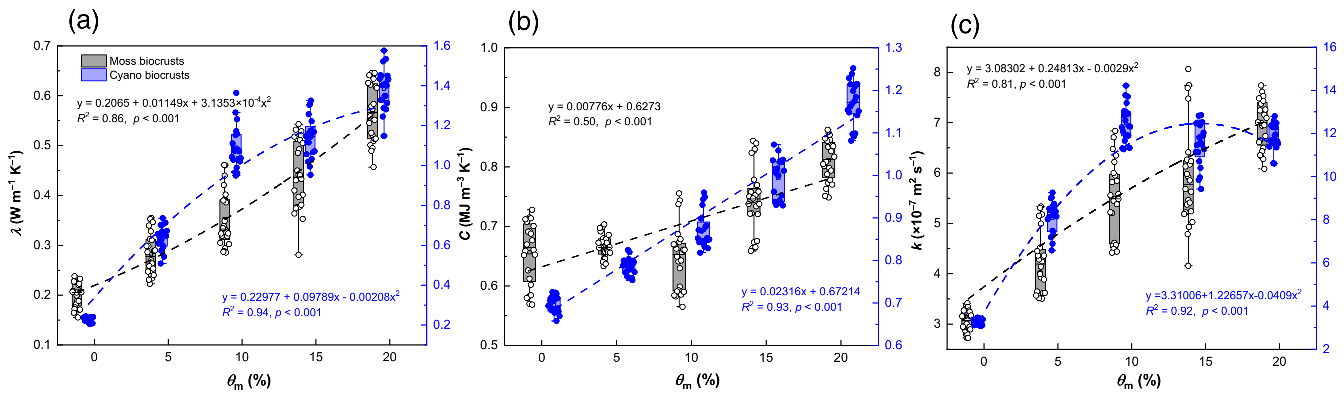

FIGURE 3 Thermal properties of the repacked moss and cyanobacteria biocrusts under five mass water content (θ_m) levels (0, 5, 10, 15 and 20%). (a) λ; (b) C; (c) k.

TABLE 3 Pearson correlation analysis (significance in bracket) of water content (θ_m) and mass ratio (W_t) on thermal properties of repacked moss and cyanobacteria biocrusts.

	Moss biocrusts			Cyanobacteria biocrusts		
Factor	λ	C	k	λ	C	k
θ_m	0.920 (<0.001)**	0.709 (<0.001)**	0.894 (<0.001)**	0.947 (<0.001)**	0.963 (<0.001)**	0.763 (<0.001)**
W_t	0.309 (<0.001)**	0.268 (0.003)**	0.303 (<0.001)**	0.127 (0.207)	0.098 (0.332)	0.098 (0.334)

The ** means the coefficient is significant at 0.01 level of probability (two-tailed).

of θ_m, as the slopes of the fitted lines for these properties were all higher than those of the moss biocrusts.

3.3 | Effect of repacked biocrust mass ratio on their thermal properties

According to Figure 4, repacked biocrusts, particularly repacked moss biocrusts ($p < 0.05$), displayed a fluctuating downward trend in their thermal properties (λ, C and k) as W_t increased. Specifically, there was an average 6.3% drop in the average λ of moss biocrusts with increasing W_t, ranging from 0.43 to 0.31 W m^{-1} K^{-1}. The mean C of the moss biocrusts decreased by 1.0% on average, ranging from 0.75 to 0.67 MJ m^{-3} K^{-1}. The range of the average k of the moss biocrusts was 5.73–4.42 × 10^{-7} m^2 s^{-1} with an average decrease of 5.4%. Furthermore, a substantial negative correlation was found between W_t and the thermal properties of moss biocrusts, as demonstrated by Pearson correlation analysis (Table 3). By contrast, there was no significant difference observed in the thermal properties of the cyanobacteria biocrusts at different W_t ($p > 0.05$), and the W_t of cyanobacteria biocrusts showed a non-significant negative correlation with thermal properties (Table 3). Figure 5 showed that the highest values of the thermal properties of cyanobacteria and moss biocrusts typically occurred at the lowest W_t and the highest θ_m, even though the correlation was not significant.

3.4 | Influence of edge effects on biocrust thermal properties

The λ and k of the repacked moss biocrusts samples were consistently greater than those of the intact moss biocrusts throughout the θ_v, as shown in Figure 6. However, the C of the repacked moss biocrusts was lower than that of the intact moss biocrusts (except for $\theta_v = 0$ cm^3 cm^{-3}). Specifically, the mean values of λ were 0.35 ± 0.12 and 0.22 ± 0.09 W m^{-1} K^{-1} for the repacked and intact moss biocrusts (with an increase of 59.1%), respectively. The k of the repacked moss biocrusts (4.74 ± 1.39 × 10^{-7} m^2 s^{-1}) increased by 61.8% compared with the intact moss biocrusts (2.39 ± 0.49 × 10^{-7} m^2 s^{-1}). In addition, the C of the repacked moss biocrusts (0.70 ± 0.08 MJ m^{-3} K^{-1}) decreased by 23.9%, in comparison with the intact moss biocrusts (0.92 ± 0.24 MJ m^{-3} K^{-1}). In addition, the thermal properties of repacked and intact moss biocrusts exhibited statistical differences ($p < 0.001$).

The variation in the thermal properties of the intact and repacked cyanobacteria biocrusts is displayed in Figure 7. It is evident that the moss and cyanobacteria

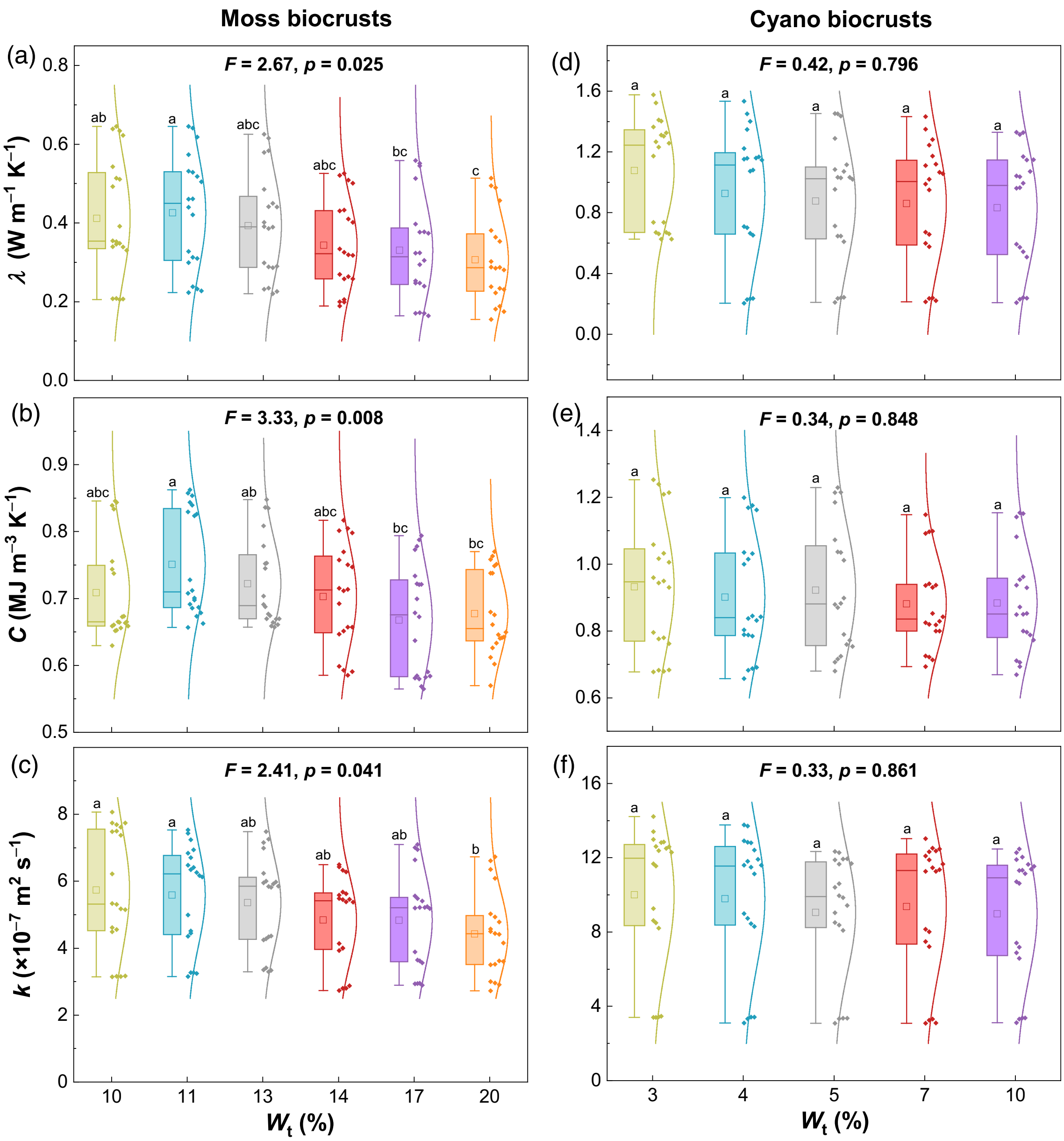

FIGURE 4 Thermal properties (λ, C and k) of repacked moss (a–c) and cyanobacteria biocrusts (d–f) at different mass ratios (W_t).

biocrusts showed a similar trend; that is, while the C was lower than the intact cyanobacteria biocrusts, the λ and k of the repacked cyanobacteria biocrusts were greater. Specifically, the λ and k of the repacked cyanobacteria biocrusts increased by 15.8% (0.88 vs. 0.76 W m^{-1} K^{-1}) and 79.2% (9.03 vs. 5.04 × 10^{-7} m^2 s^{-1}), respectively, and the C decreased by 34.8% (0.92 vs. 1.41 MJ m^{-3} K^{-1}) compared to that of the intact cyanobacteria biocrusts. In addition, the C and k of repacked and intact cyanobacteria biocrusts showed a statistical difference ($p < 0.001$). It is worth mentioning that the difference in thermal properties between repacked and intact biocrusts generally tends to increase with increasing θ_v.

4 | DISCUSSION

4.1 | Our advancement based on repacked biocrusts

In our study, we measured the thermal properties (λ, C and k) of the intact and repacked biocrusts with the HP technique. The thermal properties of intact biocrusts, which are only a few millimetres thick and have enormous unknown edge effects, were not accurately estimated by direct measurements, as we had anticipated. In particular, the λ and k were underestimated by 59.1% and 61.8%, respectively, for moss biocrusts and by 15.8% and 79.2%, respectively, for cyanobacteria

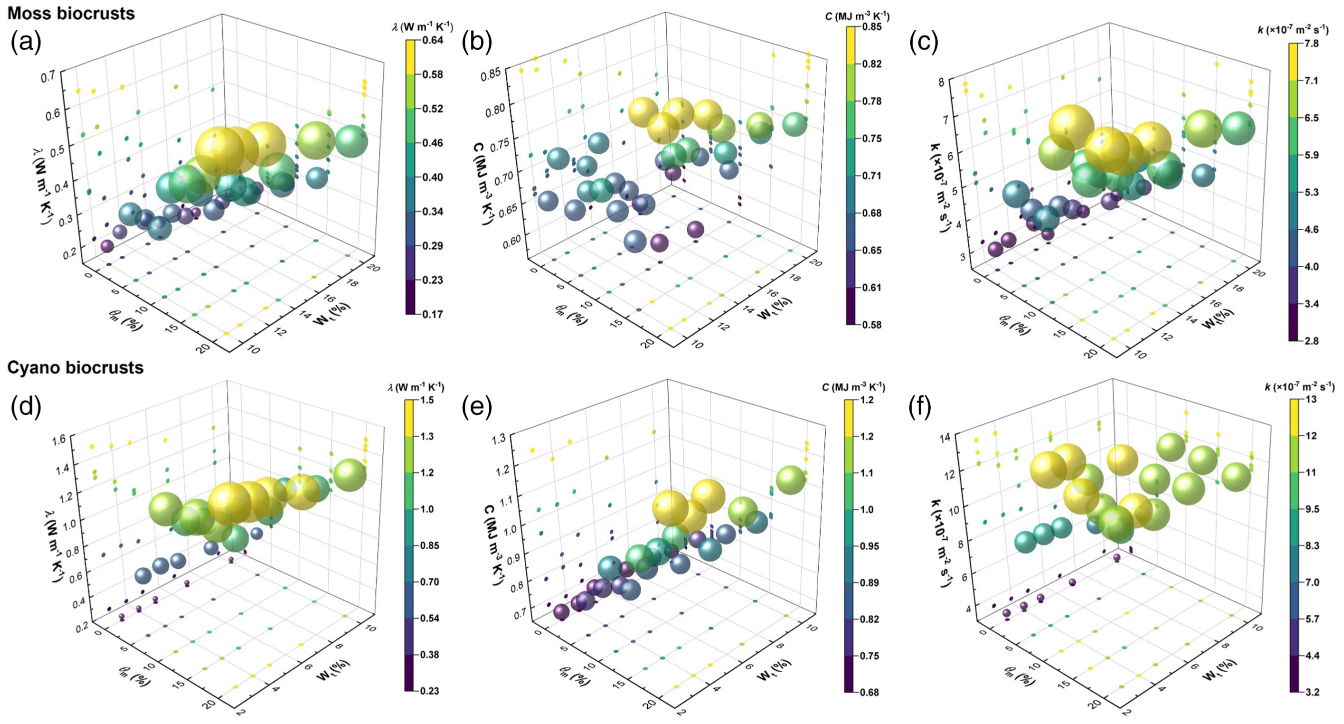

FIGURE 5 Three-dimensional thermal properties (λ, C and k) of repacked moss (a–c) and cyanobacteria biocrusts (d–f) to all levels in mass water content (θ_m) and mass ratios (W_t).

biocrusts (Figures 6 and 7). The thin biocrusts transported the released heat to the surrounding environment when the HP sensor was positioned parallel to the ground (Ren et al., 2005). As a result, the measured properties were actually a biased combination of air and biocrusts. This accounted for the majority of the inaccuracy in the results and clarified low λ and k values of the intact biocrusts. Other articles testify to the reliability of this study. For example, with $\theta_v = 0.16$ cm^3 cm^{-3}, Xiao, Ma, and Hu (2019)'s results showed that the λ and k of the moss biocrusts were 0.23 W m^{-1} K^{-1} and 3.41 × 10^{-7} m^{-2} s^{-1}, respectively. This is similar to the results of the thermal properties of the intact biocrusts in the present experiment but significantly lower than those of the repacked biocrusts (λ and k were reduced by 86.6% and 62.7%, respectively). If measurement of the thermal properties of intact biocrusts is performed, an adjustment for soil-air interface effects must be done (Zhang et al., 2014). Furthermore, ambient temperature drift needs to be considered in the field, but this is a laborious process (Kluitenberg & Philip, 1999). By contrast, the repacked biocrusts have the same material composition as the intact biocrusts, but are thicker and homogeneous, which fulfils the measurement conditions of the HP technique. This allows us to rationalize the use of the analytical solution of the heat conduction equation. Ultimately, we obtained representative thermal properties of the biocrusts through use of larger volume samples.

It is worth noting that the C of the intact biocrusts demonstrates the different results under the traditional measurements. To prevent disrupting the structure of the intact biocrusts, we saturated the intact biocrusts and then allowed them to dry, with the HP sensor heating the soil surface (0–1 cm) every 4 h. The results showed that the C of moss and cyanobacteria biocrusts were overestimated by 23.9% and 34.8%, respectively (Figures 6 and 7). The results of another study in which intact moss biocrusts were tested were also significantly higher than in this study (C of this study vs. Xiao, Ma, and Hu (2019) = 0.76 vs. 1.02 MJ m^{-3} K^{-1}). We suggest that this may be related to two things. Firstly, it has to do with the loss of heat released by the HP. This means that the maximum ΔT detected by the temperature probe is limited. It has been shown that the C of the medium is linearly related to the inverse of the maximum ΔT (Campbell et al., 1991). This leads to calculating the C higher than the actual value, and the errors will become more pronounced as the water content of the medium increases (Xiao et al., 2015), which can explain the difference in the thermal properties of intact and repacked biocrusts that increased with increasing θ_v (Figures 6 and 7). Secondly, the evaporation process leads to moisture

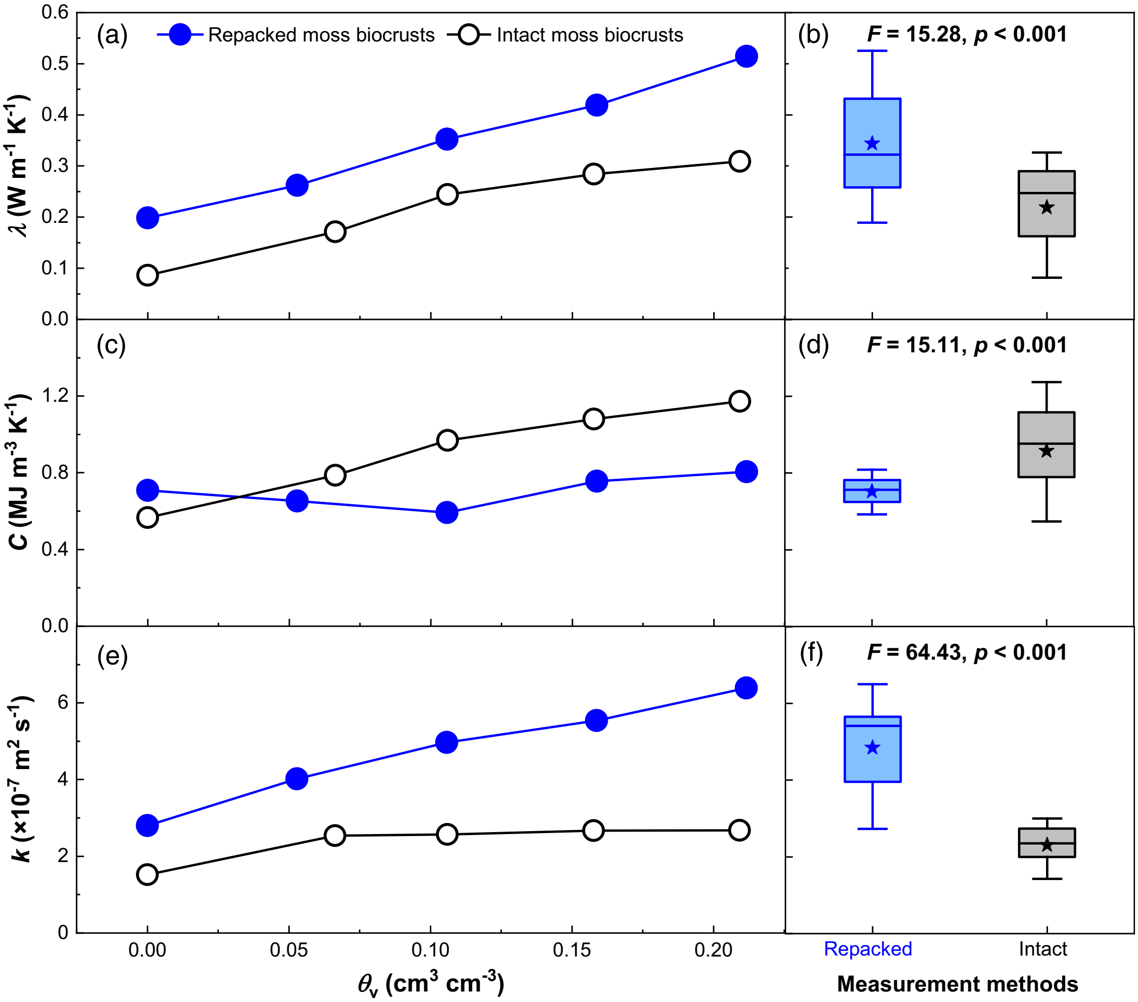

FIGURE 6 Thermal properties (λ, C and k) of repacked and intact moss biocrusts at different volumetric water content (θ_v). (a) λ of repacked and intact moss biocrusts; (b) differences in λ between two measurement methods; (c) C of repacked and intact moss biocrusts; (d) differences in C between two measurement methods; (e) k of repacked and intact moss biocrusts; (f) differences in k between two measurement methods.

inhomogeneity in the soil profile, which is inconsistent with the theoretical assumption of the analytical solution of heat transfer, that is, an infinite homogeneous medium (He et al., 2018). This may lead to errors in the calculation results. In addition, the heating of the HP may also accelerate the evaporation of the soil surface. Although the design of the HP and the heating strategy in the experiments have tried to avoid disturbing the soil as much as possible, this factor still cannot be ignored (Kamai et al., 2015; Kluitenberg & Philip, 1999). Xiao et al. (2015) employed a comparable method to assess the impact of the HP probe installation depth on the measurement outcomes. Their findings indicated that the thermal property errors were considerably higher in wet soil compared with dry soil conditions. Free convection and heat loss in saturated soils were blamed for this. These findings are corroborated by our results. Nonetheless, the biocrust repacking strategy suggested in this work can more effectively circumvent the issues highlighted above and does not call for additional secondary correction of the data (Heitman et al., 2008).

Furthermore, repacked biocrusts make it simple to control θ_m and W_t values and see how they affect thermal properties. As is widely known, there is a large positive association between θ_m and the thermal properties of the biocrusts (Table 3). Heat transfer is enhanced as air is replaced by water in the biocrusts and water bridges are formed between soil particles (Gamage et al., 2019; Krishnaiah & Singh, 2003). Also, water has higher λ (0.6 vs. 0.026 W m^{-1} K^{-1}), C (4.20 vs. 1.00 MJ g^{-1} K^{-1}) and k (1.43 vs. 0.21 $\times$ 10^{-7} m^2 s^{-1}) at room temperature and atmospheric pressure compared with air (Ochsner

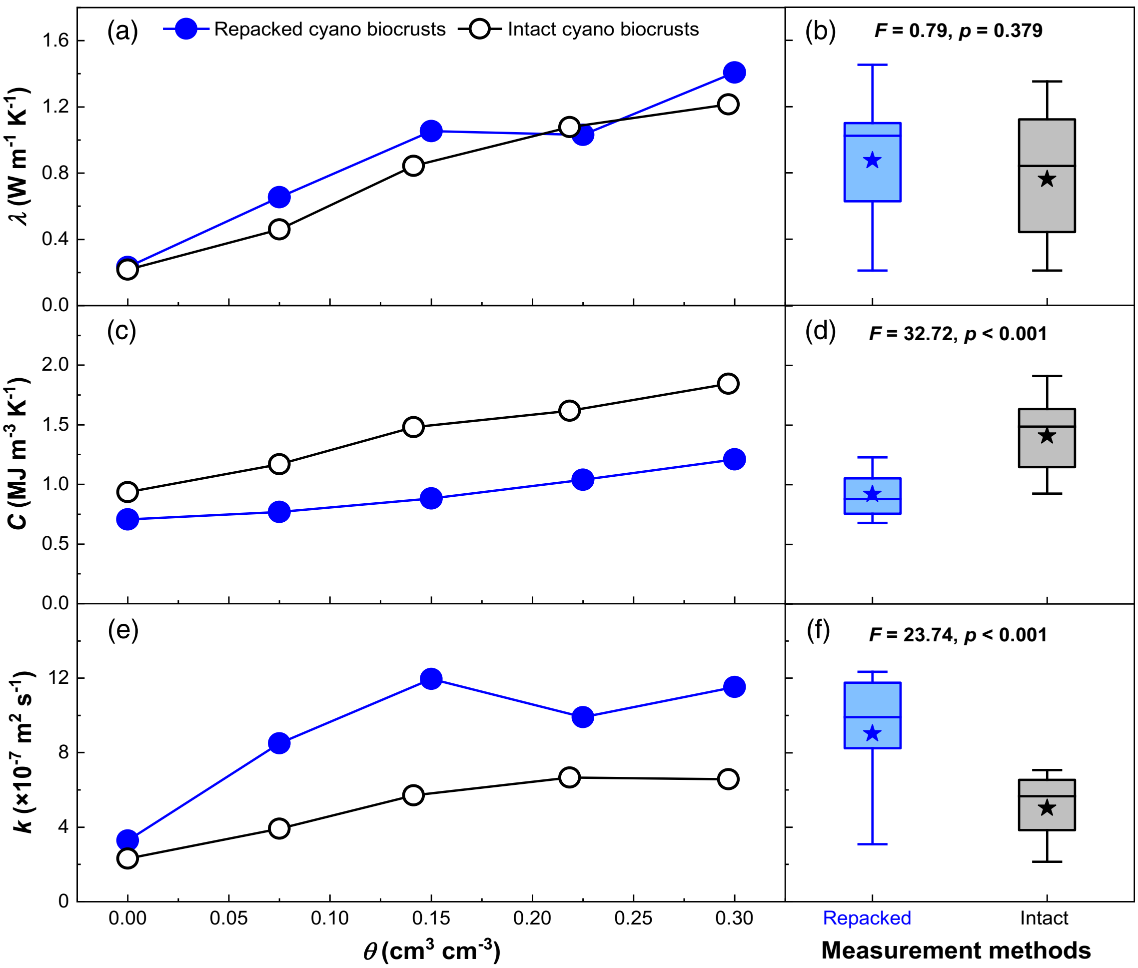

FIGURE 7 Thermal properties (λ, C and k) of repacked and intact cyanobacteria biocrusts at different volumetric water content (θ_v). (a) λ of repacked and intact cyanobacteria biocrusts; (b) differences in λ between two measurement methods; (c) C of repacked and intact cyanobacteria biocrusts; (d) differences in C between two measurement methods; (e) k of repacked and intact cyanobacteria biocrusts; (f) differences in k between two measurement methods.

et al., 2001; Zhang & Wang, 2017). Accordingly, the contact between the components inside the soil is poor under dry conditions and the thermal properties of the biocrusts tend to obtain minimum values (Heitman et al., 2003). Moreover, the W_t of the biocrusts significantly affects the thermal properties. Notably, this phenomenon was found only for moss biocrusts, and the W_t was significantly negatively correlated with the thermal properties of moss biocrusts (Table 3). This might be because of the moss's low density and high porosity (Moore et al., 2019), which result in a lower bulk density of moss biocrusts (Table 2) and hinder heat transmission by making the repacked moss biocrust samples more akin to loose porous media. This may also account for the fact that, for the same thermal parameter, the slopes of linear fits for cyanobacteria biocrusts are often greater than those for moss biocrusts (Figure 3). In addition, there was no statistical difference between the thermal properties (λ, C and k) of the cyanobacteria biocrusts and the bare soil (Figure 2), as the thermal properties of them are primarily driven by θ_m and the mass of biological component of the cyanobacteria biocrusts is limited.

4.2 | Our limitations and uncertainties analysis

Despite the fact that the strategy of repacking the biocrusts yields a more accurate representation of the thermal properties of the biocrusts, we must acknowledge the potential drawbacks of this approach. Firstly, the lamellar structure of the intact biocrusts was destroyed. This undoubtedly skewed the measurements away from the actual values. The biological component of the biocrusts has a low λ, while the underlying soil has a higher λ (Moore et al., 2019). This structure is more in favour of the tandem model in λ evaluation, which is considered to be the upper limit of the λ of the soil (Zhang &

Wang, 2017). Therefore, the thermal property results may be biased low even though we have made corrections to the conventional measurements. It is worth mentioning that the magnitude of the error is determined by the biomass of the intact biocrusts (Rice et al., 2018). This indicates that the thermal properties of low biomass moss and cyanobacteria biocrusts will not be significantly impacted by the repacking strategy (Rappoldt et al., 2003). We propose that independent calculations of biomass and underlying soil may result in more accurate thermal properties for high biomass biocrusts. Series modelling may then be used to calculate the findings and reduce errors. Furthermore, we have attempted an alternative solution, which involves mixing two biocrusts to enhance the thickness. Nevertheless, it was discovered during the test that an air layer could not be fully sealed and inexorably existed between the two pieces of biocrusts. The air layer would be more noticeable, particularly during the continuous rainy and dry alternation. As a result, this approach was dropped.

In addition to the previously listed limitations, the determined biological component in this study was the mass of both biomass and organic matter fragments because the biomass of cyanobacteria biocrusts is extremely limited and difficult to separate from fragments of organic matter. Research has demonstrated that a key element influencing the k at high northern latitudes is the amount of organic matter (particularly organic carbon) in the soil (Zhu et al., 2019). The strong coupling pattern between the two is shown by a decreasing trend in k with increasing organic matter. Therefore, when it comes to biocrusts with rich organic components, the impact of organic matter on thermal properties needs to be examined individually. However, due to its smaller bulk density, this has limited effects on the thermal properties of cyanobacteria biocrusts. In addition, the C of repacked biocrusts may not show a perfect linear relationship with θ_m as before (Xiao, Ma, & Hu, 2019), especially moss biocrusts (Figure 3). This may be related to the inhomogeneous mixing of the materials. This means that the moisture is not sufficiently homogeneous in the samples.

4.3 | Applications of our results

Thermal properties of the biocrusts, as an important cover on dryland surfaces, severely affect the surface water–heat balance and multifunctional changes in the soil system (Xiao et al., 2022). Thus, precise assessments of the thermal properties of biocrusts can enhance our comprehension of variations in surface temperature and the functioning of the hydrological cycle. Our results, obtained through the use of more appropriate measurement techniques, revealed that the λ and k of biocrusts were underestimated while their C was overestimated (Figures 6 and 7). As the θ_m grew, this mis-estimation became more apparent. Put differently, the biocrusts transmit heat more efficiently than previously thought, particularly during the rainy season. The temperate semi-arid continental climate of our sampling area features distinct wet and dry seasons, with a hot and mostly brief rainy season (Dou et al., 2023). As a result, strong evaporation from the surface layer happens often due to the high water-holding capacity of the biocrusts (Sun et al., 2022). Thus, during routine measurements, in addition to heat loss, evaporation is also an important cause of errors in C of the biocrusts (Kidron et al., 2022). In addition, heat dissipation surely causes an underestimation of λ and k as HP probes are often put horizontally into the soil surface during field experiments, 1 cm below the surface.

Although this study did not focus on evaporation rates from biocrusts, previous studies in the region have shown that evaporation rates from moss biocrusts are much higher (>27.2%) than from bare soil (Li, Bowker, & Xiao, 2022a). This phenomenon is usually attributed to the effect of the biocrusts on the physicochemical properties and hydraulic parameters of the underlying soil, such as fine particle content, organic matter content and saturated hydraulic conductivity (Kidron & Tal, 2012). Subsequent studies have gradually focused on the effect of thermal properties of biocrusts and surface albedo on evaporation (Li, Sun, et al., 2022; Xiao & Bowker, 2020). It was shown that moss biocrusts buffer surface temperatures during the growing season through high evaporation rates and lower thermophysical properties. However, few studies have directly measured the thermal properties of cyanobacteria biocrusts. The present study gives more accurate thermal properties of cyanobacteria biocrusts, which provides reliable basic data for subsequent studies on the water–heat transport process of cyanobacteria biocrusts.

Xiao, Ma, and Hu (2019) pointed out that biocrusts relied mainly on changes in water balance to influence surface temperature during the wet season, whereas, during the dry season, they primarily relied on their lower bulk density. Li, Sun, et al. (2022) showed that there was a significant increase in the C of the biocrusts in the summer. As a result, the biocrusts might act as a temperature buffer for the soil, reducing summertime surface temperatures and raising them in the winter. The results of this study supported these findings. Our results support this view and highlight the more accurate thermal properties of biocrusts. It is commonly acknowledged that the temperature of the soil plays a significant influence in the cycling of water in dryland soils, as well as in plant development and ecosystem succession (Belnap, 1995). Furthermore, by affecting the water–heat balance of the soil, biocrusts may change the composition of vascular plant communities. As distinct vascular plant species (trees, shrubs and herbs) have varying ranges of tolerance to soil temperature (Brooker & Van der Wal, 2003), one possible mechanism for vegetation and ecosystem succession in drylands could be biocrusts and their thermal properties.

However, the effect of biocrusts on surface temperature is controversial on a worldwide scale. For instance, numerous studies conducted in the Negev and Tabernas deserts have demonstrated that biocrusts raise surface temperature (Chamizo et al., 2013; Kidron & Tal, 2012). We suggested that this may be the result of the combined effects of evaporation and the thermal properties of the biocrusts. Although the thermal properties of the biocrusts help to better retain heat at the surface compared with bare soil, surface temperatures in the dryland can drop and fluctuate due to alternating wet and dry impacts. Thus, a key element in the dispute might be the latent heat of evaporation from the surface, which is mediated by the hydrothermal conditions of the region. It is crucial to understand that surface evaporation and the biocrust thermal properties must be separated. Because edge effects are present, conventional measurements probably misjudged the thermal properties of biocrusts, yet the measurements in this study quantified the effect on thermal properties.

In conclusion, this study presents a fresh viewpoint on the debate over the impact of biocrusts on surface temperature while accurately illustrating how biocrusts affect soil thermal properties. The thermal properties of biocrusts, the 'living skin' of dryland surfaces, are essential for our comprehension of the water–heat balance in drylands and for our proactive adaptation to future climate change (Rodriguez-Caballero et al., 2018). The measurement object is restricted, though this work offers a more sensible measurement technique. Thus, accurate thermal properties of biocrusts on larger scales may be needed in the future.

5 | SUMMARY AND CONCLUSIONS

In this study, we reconstructed a repacked biocrust layer and thickened its structure. Meanwhile, the HP technique was used to measure its thermal properties at different θ_m and W_t, and the differences in thermal properties between the intact and repacked biocrusts were compared. The results show that the presence of edge effects underestimated the λ and k of the biocrusts. For moss biocrusts, λ and k were underestimated by 59.1% and 61.8%, respectively, and by 15.8% and 79.2% for cyanobacteria biocrusts, respectively. Furthermore, the latent heat of vaporization due to water evaporation overestimated the C of the biocrusts. The C of moss and cyanobacteria biocrusts were overestimated by 23.9% and 34.8%, respectively. In addition, moss biocrusts significantly reduced surface thermal properties. The λ and C of moss biocrusts were reduced by 63.0% and 28.2%, respectively, in comparison with bare soil. Additionally, the thermal properties of biocrusts were mainly mediated by θ_m, and there was a substantial negative correlation between the thermal properties of the moss biocrusts and W_t. Based on these findings, we conclude that the contribution of biocrusts to the thermal properties of the surface was previously misrepresented, and repacking biocrusts may be a more reasonable way to obtain accurate thermal property estimates.

AUTHOR CONTRIBUTIONS

Junru Chen: Conceptualization; methodology; software; formal analysis; visualization; funding acquisition; investigation; writing – original draft; writing – review and editing. **Bo Xiao:** Conceptualization; methodology; resources; writing – review and editing; funding acquisition. **Joshua Heitman:** Conceptualization; methodology; writing – review and editing.

ACKNOWLEDGEMENTS

This study was funded by the National Natural Science Foundation of China (grant no. 42077010).

CONFLICT OF INTEREST STATEMENT

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.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Chen, J., Xiao, B., & Heitman, J. (2024). Overlooked biocrust impacts on surface soil thermal properties: Evidence from heat-pulse sensing on large volume samples. *European Journal of Soil Science*, *75*(6), e70004. https://doi.org/10.1111/ejss.70004