Research article

Insights into variations of seasonal and daily soil temperatures under the effect of biocrusts in central-western Argentina

Panorama sobre las variaciones estacionales y diarias de la temperatura del suelo bajo el efecto de las costras biológicas en el centro-oeste de Argentina

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Abstract:

Background and Aims: Biocrusts play an essential role on the earth's surface and have a direct influence on soil parameters. Their effects on soil temperature are considered one of the most important because they affect ecological and hydrological processes, as well as the diversity of natural ecosystems. Although there are several studies concerning biocrust effects on the soil surface, investigations about the effect of the biocrust on soil temperature are still scarce. Our objective was to evaluate the influence of biocrusts on soil temperature conditions in drylands of central-western Argentina.

Methods: Temperature values were recorded in the Monte phytogeographic region in the central-western part of Argentina, in three sites, during the dry and wet seasons in 2017-2018. We collected samples from a total of 30 randomly selected plots. We recorded daily temperatures values in two paired plots with crusted and uncrusted zones using a calibrated data logger Ibutton. The sampling took 18 days in total, three days on each site.

Key results: Our results indicate that biocrusts produce a change in micro-soil temperatures. Areas in which biocrusts are present show a temperature reduction both in the wet and dry seasons. This effect is observed in the three studied sites. Temperature reduction varies according to the time of the day, study site and season. The morning, noon, and afternoon recorded the highest mean temperatures.

Conclusions: The presence of biocrusts reduces soil temperatures in drylands of central-western Argentina. Large differences in mean temperature values between crusted and uncrusted zones were observed. The thermal reduction was more notorious in the hyper-arid site. How they affect their surrounding environment can be related to multiple factors, such as the composition of the microphytic community, the local climate and environmental conditions.

Key words: arid lands, crusted soil, Monte region, soil thermal conditions, uncrusted soil.

Resumen:

Antecedentes y Objetivos: Las costras biológicas del suelo juegan un papel esencial en la superficie terrestre y tienen una influencia directa en los parámetros del suelo. Sus efectos sobre la temperatura del suelo se consideran uno de los más importantes debido a que afectan los procesos ecológicos e hidrológicos, así como la diversidad de los ecosistemas naturales. Aunque existen varios estudios sobre los efectos de la costra biológica en la superficie del suelo, las investigaciones sobre el efecto de la costra biológica en la temperatura del suelo aún son escasas. Nuestro objetivo fue evaluar la influencia de las costras biológicas en las condiciones de temperatura del suelo en zonas áridas del centro-oeste de Argentina.

Métodos: Se registraron valores de temperatura en la región fitogeográfica del Monte en la parte centro-oeste de Argentina, en tres sitios, durante las estaciones seca y húmeda de 2017 y 2018. Colectamos muestras de un total de 30 parcelas seleccionadas al azar. Registramos valores de temperatura diarios en dos parcelas emparejadas con zonas con costras biológicas y sin costras biológicas utilizando un registrador de datos calibrado tipo Ibutton. El muestreo se llevó a cabo durante un total de 18 días, tres días en cada sitio.

Resultados claves: Nuestros resultados indican que las costras biológicas producen un cambio en las temperaturas microambientales del suelo. Las áreas donde están presentes las costras biológicas muestran una reducción de la temperatura tanto en las estaciones húmedas como en las secas. Este efecto se observa en los tres sitios estudiados. La reducción de la temperatura varía de acuerdo con la hora del día, el sitio de estudio y la estación del año. La mañana, el mediodía y la tarde registraron las temperaturas medias más altas.

Conclusiones: La presencia de costras biológicas reduce las temperaturas del suelo en las zonas áridas del centro-oeste de Argentina. Se observaron grandes diferencias en los valores medios de temperatura entre las zonas con costras biológicas y las zonas sin costras biológicas. La reducción térmica fue más notable en el sitio hiperárido. Cómo afectan su entorno circundante puede estar relacionado con múltiples factores, como la composición de la comunidad microfítica, el clima local y las condiciones ambientales.

Palabras clave: condiciones térmicas del suelo, región del Monte, suelo sin costra, suelo con costra, zonas áridas.

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Introduction

Biological soil crusts (biocrusts) are communities that aggregate the soil particles on the surface, forming a layer usually only a few millimeters thick that has been compared to a living skin on the Earth's surface (Bowker et al., 2018). They are a close association of soil and primary producers (algae, cyanobacteria, bryophytes, and lichens) and secondary consumers or decomposers (e.g., non-lichenized fungi, heterotrophic bacteria, animals) (Belnap et al., 2016). Their presence significantly modifies the soil surface that they occupy, and their micro-environmental effect, in most cases, depends on the composition of the microphytic community (Rozenstein and Karnieli, 2015). Biocrusts are spread in many natural ecosystems all over the world, especially in arid and semi-arid regions. They can dominate the soil surface, commonly exceeding the cover of vascular plants due to their extraordinary ability to survive under desiccation processes and extreme temperatures (Bowker et al., 2018; Xiao et al., 2019a).

Biocrusts are an important component in drylands providing relevant ecosystem functions such as soil stabilization, prevention of wind and water erosion, carbon sequestration, and moisture retention (Maestre et al., 2013; Cantón et al., 2014; Bowker et al., 2018; Elridge et al., 2020). They contribute to biogeochemical cycling by fixing soil carbon and nitrogen (Burgheimer et al., 2006; Wu et al., 2009; Xiao and Hu, 2017; Hu et al., 2019; Duran et al., 2021; Wang et al., 2021, 2022), participating in hydrological processes (Belnap, 2006), adhering to soil particles, fixing CO_2 (Zhao and Zhang, 2021), and having interactions with the vascular vegetation (Serpe et al., 2006).

Studies carried out in drylands around the world postulate that biocrusts produce an impact on the upper few millimeters of the soil. Physical and chemical characteristics of soils, such as roughness, soil stability, carbon and nitrogen content, and water availability, are influenced by their presence (Belnap, 2006; Zhao et al., 2010; Chamizo et al., 2016a, b; Navas-Romero et al., 2019, 2020a, b; Xiao et al., 2019b; Su et al., 2021; Li et al., 2022). Biocrusts regulate the soil temperature and moisture conditions with a strong influence on biological processes such as germination, survival rates and nutrition of vascular plants, water cycle, biochemical reactions, and plant growth (Belnap et al., 2003; Xiao et al., 2019a). Micro-environmental changes in soil due to biocrusts can reduce or increase the rate of decomposition and nutrient availability, producing important positive effects on ecosystem processes (Prescott et al., 1993).

Biocrusts have demonstrated direct effects on soils (Chamizo et al., 2012; Reed et al., 2012; Kakeh et al., 2018, 2021, among others) and a strong influence on soil temperatures in drylands (Xiao et al., 2019a; Li et al., 2022). However, results from studies made on soil thermal effects of biocrusts in different arid lands are divergent. In the semi-arid region of Loess (China), biocrusts considerably decreased soil temperatures in the first millimeters of the soil during the wet season (summer) but increased them during the dry season (winter) (Xiao et al., 2016, 2019a). On the other hand, an increase in soil temperatures was detected in the Negev desert (Israel) and the Colorado Plateau (North America) (Kidron and Tal, 2012; Couradeau et al., 2016).

The effect of biocrusts on soil temperature may be related to the composition of the biocrust communities and it has been previously shown that the dominant organisms of biocrusts produce differences in soil water and heat transport processes (Zhang et al., 2009; Xiao et al., 2016; Li et al., 2022). For example, moss-dominated biocrusts showed a decrease in temperatures compared with bare soil in the Chinese Loess Plateau (Li et al., 2022), and the opposite was reported in the Negev Desert by Kidron and Tal (2012), i.e., that soil temperatures increased when biocrusts were dominated by mosses or cyanobacteria in comparison to bare sand. These effects could be compared to similar biocrust types present in the drylands of central-western Argentina, as previous studies made here indicated that the biocrust composition is different depending on the aridity conditions of the ecosystem (Navas-Romero et al., 2020a).

In South America, biocrusts are distributed in many arid and semi-arid lands (Büdel, 2001; Navas-Romero et al., 2020a, b; Garibotti and Gonzalez-Polo, 2021). In Argentina, the semi-arid regions, located in the central-western part of the country are places with an important coverage of biocrusts (García et al., 2015, 2021; Navas-Romero et al., 2020a; Videla et al., 2021; Aranibar et al., 2022). Currently, the knowledge about the effect of biocrusts on soil thermal conditions in southern South America is still scarce. A better understanding of their effect on soil conditions is fundamental to improving our comprehension of the role of biocrusts in the ecological and hydrological processes in these drylands. Our main hypothesis is that the presence of biocrusts affect soil temperatures. Also, we hypothesized that the effect of biocrusts on soil temperature changes according to the aridity conditions and seasonality. Therefore, our goal is to analyze the effect of biocrusts on soil temperature. For this, we measured seasonal and daily temperature variations in both crusted and uncrusted zones located in three different ecosystems along an aridity gradient in the central-western part of Argentina.

Materials and Methods

Study sites

This research was conducted along an aridity gradient in three different study sites, arid, semi-arid and hyper-arid, during 2017-2018. Sampling sites were located in the Monte phytogeographic region in the central-western part of Argentina (Fig. 1). The region corresponds to a semi-desert, with a wide latitudinal range and altitude variations with elevations that reach up to 2800 m a.s.l. Around 75% of the total annual rainfall in the area occurs during the spring and summer seasons (Morello, 1958). Complementary information of the environmental characteristics for each studied site such as sedimentation (ml/%/g) pH, conductivity (µS/cm), shrub stratus height (m), and biocrust thickness (mm) are summarized in Table 1.

The semi-arid site (Fig. 2A) is located in the southwest of the province San Juan (32°00'8.43''S; 68°45'10.18''W) at 1139 m a.s.l., in the area called “Paisaje Protegido Pedernal” (Dalmasso et al., 2011). The mean annual temperature is around 18 °C with a mean minimum of 6 °C and a

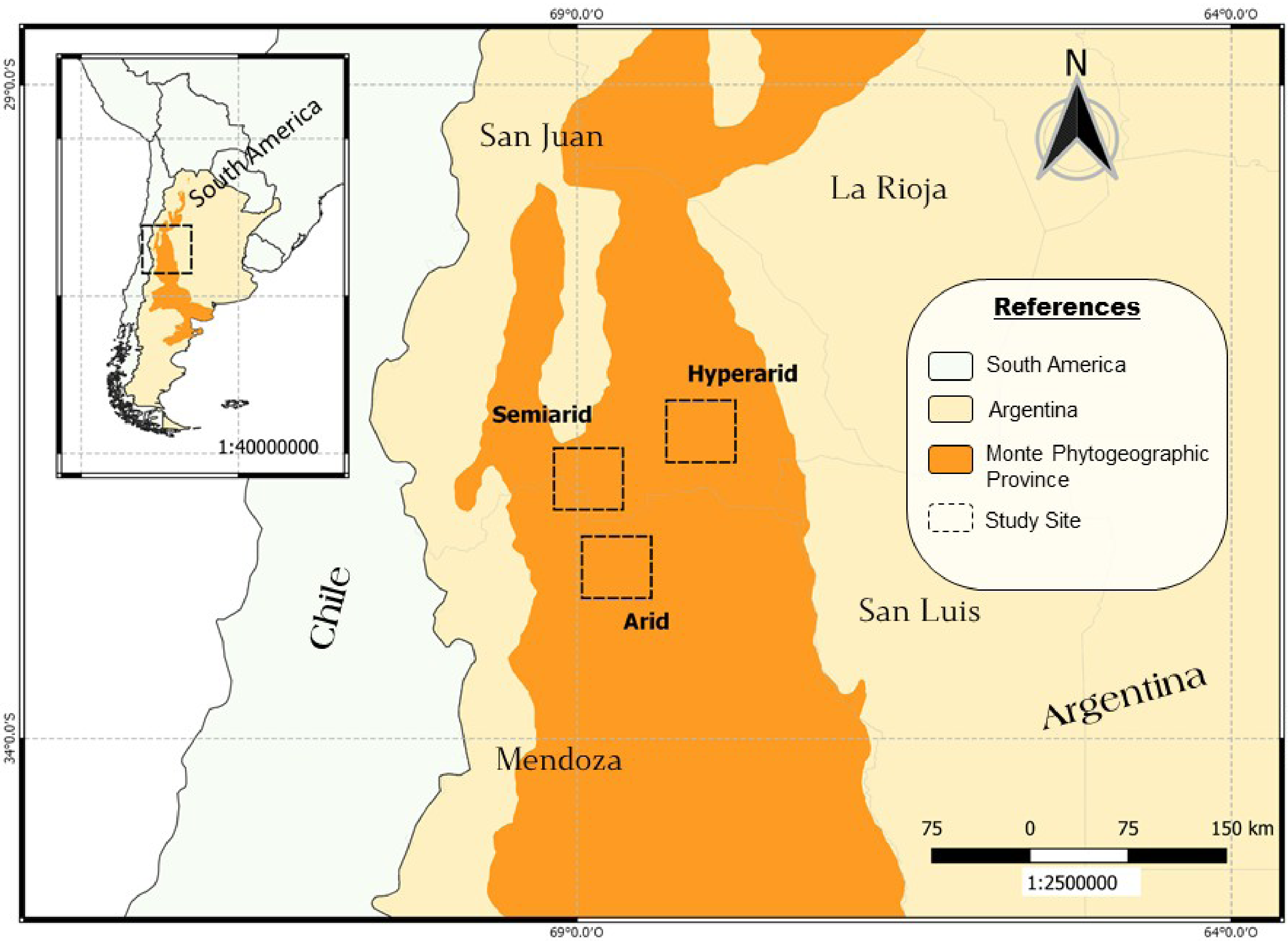

Figure 1: Map showing the studied sites along an aridity gradient in central-western Argentina.

Table 1: Climate and environmental information recorded during the field tasks in the study sites in central-western Argentina. Data were collected during the sample tasks except for those with asterisk that come from Navas-Romero (2019). PAR=Photosynthetically Active Radiation.

Variables	Semi-arid	Arid	Hyper-arid
*Sedimentation (ml/%/g)	90	85	75
*pH	8.1	8.4	8.2
*Conductivity (µS/cm)	651.2	414.9	311.7
*Shrub stratus height (m)	2.5	1.5	0.8-1
*Biocrust thickness (mm)	6-14	4-13	2-9
PAR (µmol·m-2·s-1) Dry season	507.2±8	720.8±8.5	902.3±9.8
PAR (µmol·m-2·s-1) Wet season	644.1±7.5	796.7±6	994.4±7.8
Temperature (°C) Dry season	10.6±1.1	11.5±1.8	13.5±1.7
Temperature (°C) Wet season	21.8±2.1	22.7±2.5	25.5±2.4
Precipitation (mm) Dry season	0	0	1
Precipitation (mm) Wet season	0	0	2.6

mean maximum of 20.7 °C, and the precipitation is 370 mm (Norte and Simonelli, 2010; Dalmasso et al., 2011). The aridity index is 10.9 according to Martonne (1942). Soils correspond to entisols in the typic torriorthents with a sandy loam texture (68% sand, 22% silt, 15% clay) (Regairaz, 2000). The plant communities of *Zuccagnia punctata* Cav., *Larrea divaricata* Cav., *Baccharis salicifolia* (Ruíz & Pav.) Pers., together with *Hyalis argentea* D. Don ex Hook. & Arn. var. *argentea*, are dominant in the area with a coverage of 54% (Dalmasso and Márquez, 2004). In this site, biocrusts cover around 21% of soils and are dominated by the mosses *Pseudocrossidium arenicola* (Dusen) M. J. Cano, and *Tortula atrovirens* (Sm.) Lindb, and by lichens such as *Enchylium coccophorum* (Tuck) Otálora, P. M. Jørg. & Wedin and *Placidium lachneum* Ach. Breuss (Navas-Romero et al., 2020a).

The arid site (Fig. 2B) is located in the Capdeville district (32°43'24.3''S, 68°50'29.69''W), at 741 m a.s.l. in the province Mendoza. The mean annual precipitation is 220 mm and around 38% of the precipitation occurs during the summer season (December-February). The mean annual temperature is 17.5 °C with a mean minimum of 3 °C and a mean maximum value of 30 °C (Norte and Simonelli, 2010; Dalmasso et al., 2011). The aridity index is 6.2 according to Martonne (1942). Soils correspond to entisols in the typic torrifluvents with a sandy loam texture (72% sand, 19% silt, 17% clay) (Regairaz, 2000). *Larrea cuneifolia* Cav. is the dominant shrub accompanied by *Atriplex lampa* (Moq.) D. Dietr., *Bulnesia retama* (Gillies ex Hook. & Arn.) Griseb., and *Lycium tenuispinosum* Miers var. *tenuispinosum* with a coverage of 40% (Roig, 1976; Martínez-Carretero and Dalmasso, 1992). Biocrusts are dominated by mosses such as *Pseudocrossidium arenicola*, *Bryum argenteum* Hedw., and *Tortula atrovirens*, lichens such as *Catapyrenium squamulosum* (Ach.) Breuss, *Enchylium coccophorum*, and the cyanobacteria are represented by *Scytonema tolypothrichoides* Kützing ex Born. & Flah, being the mean coverage value for biocrusts is 42.3% (Navas-Romero et al., 2020a).

The hyper-arid site (Fig. 2C) is located in a sand dune area called "Médanos Grandes" on the eastern edge of the Sierra Pie de Palo, at 729 m a.s.l., province of San Juan (31°47'10.13''S, 67°58'55.75''W). The mean annual precipitation is 103 mm and it occurs from December (early summer) to May (autumn). The mean annual temperature is 18 °C with a mean minimum of 10 °C and a mean maximum of 40 °C (Norte and Simonelli, 2010; Dalmasso et al., 2011). The aridity index is five according to Martonne (1942). Soils correspond to entisols in the typic torripsamments with a sandy texture (93% sand, 2% silt, 5% clay) (Regairaz, 2000). The vegetation is dominated by species of the family Zygophyllaceae. The dominant vegetation consists of shrubs such as *Bulnesia retama* and *Larrea divaricata*, with some representatives of *Neltuma flexuosa* (DC.) C.E. Hughes &

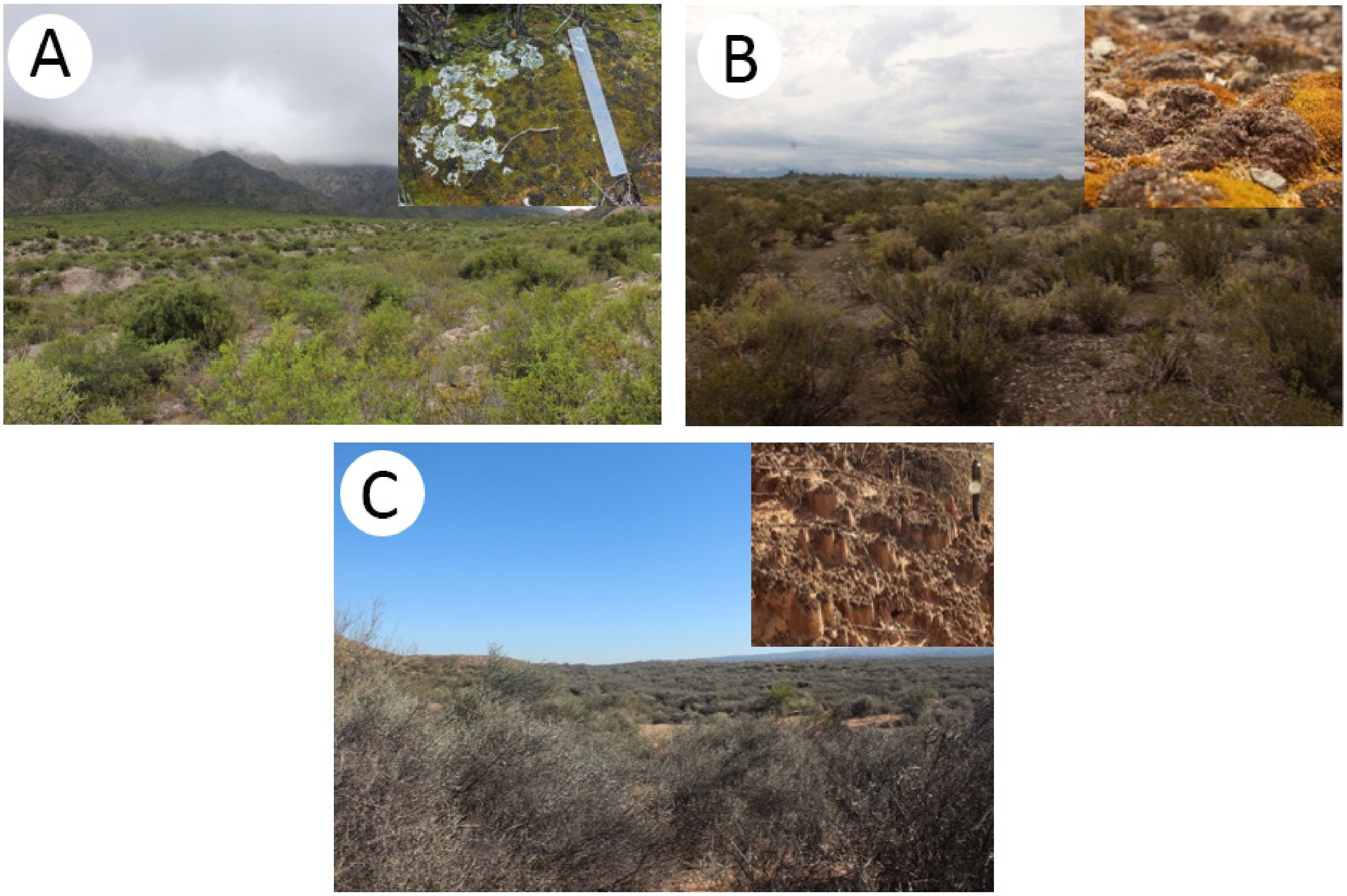

Figure 2: Photographs of the different biocrusts found in the three studied sites in central-western Argentina. A. semi-arid site; B. arid site; C. hyper-arid site. Author: Ana Laura Navas Romero.

G.P. Lewis. Other species present in the area are *Tricomaria usillo* Hook. & Arn., *Senna aphylla* (Cav.) H.S. Irwin & Barneby var. *aphylla*, *Larrea cuneifolia*, *Lycium* sp., *Atamisquea emarginata* ex Hook. & Arn., and *Bougainvillea spinosa* (Cav.) Heimerl with a coverage of around 50% (Pastrán et al., 2011). Biocrusts cover around 25% of soils and are dominated by mosses such as *Pseudocrossidium arenicola*, *Bryum argenteum*, and the cyanobacteria *Scytonema tolypothrichoides* and *Oscillatoria* sp. (Navas-Romero et al., 2020a).

Experimental design

We collected samples from a total of 30 randomly selected plots. We selected paired plots by close distance and micro-environment conditions, 15 with the presence of biocrusts (crusted) and 15 with bare soil (uncrusted). Plots were distributed ten in each of the three studied sites (five crusted and five uncrusted) with a distance of approximately 10-15 cm. We employed this separation according to the natural distribution of biocrusts in the field. The crusted zones were totally covered by biocrusts, while the uncrusted zones were bare soil without vegetation or mulch (naturally uncrusted).

Soil temperature measurement

We recorded soil thermal values for three consecutive days at each study site in two different seasons. We collected data in the wet season (December) and the dry season (September). The sampling took 18 days in total: three consecutive days at each site in two different field trips during the dry and wet seasons. We recorded daily temperature values made in each plot considering a small sampling area of approximately 2 cm using a calibrated data logger Ibutton. We measured soil temperature values with a Ibutton Ds1921 G Thermochron logger 2kb Itytarg (Mendoza, Argentina; from -40 °C to +85 °C with an error of 0.5 °C). We installed two data loggers in the central section of each plot and at 2 cm depth in the crust layer and bare soil. We recorded the temperature at 30 second intervals and calculated the mean value every hour for 72 hours. Soils were free of rainy events previous to the sampling tasks, except for the hyper-arid site where a heavy rain occurred the day before the sampling. We also measured the air temperature to compare the records made with the sensors and the photosynthetically active radiation (PAR) at 1.50 m over the soil surface for the wet and dry seasons during the field tasks (Table 1). For measures, we used a thermometer with a remote sensor Gesa 810-012 (Gesa Termómetros, S.L., Urduliz, Spain) and an integrating linear radiometer MQ-500 full spectrum (Apogee Quantum, Chicago, Illinois, USA), respectively. These measures were taken in each plot three times a day (7 am, 12 pm, and 6 pm) for all the study sites and the mean value was calculated. Additionally, we recorded the mean precipitation data from the nearest local meteorological station (Table 1).

Data analysis

We tested the statistical data normality using the Kolmogorov-Smirnov test and checked the homoscedasticity of variance by employing Levene's test. We examined the effects of biocrusts on soils analyzing soil temperature values between crusted and uncrusted zones. As data did not have a normal distribution, we analyzed them using Friedman's test to detect differences in temperature values between crusted and uncrusted zones and Kruskal-Wallis H test to analyze the variables soil temperature and seasonality at each site. Significant results are reported at $\alpha=0.05$. We constructed all graphs using SigmaPlot v. 11 software (Systat, 2008) and conducted the statistical analyses with the program Infostat v. 16 (Di Rienzo et al., 2016).

Results

Semi-arid site

Temperature mean values for both dry ($F=1$; $p<0.0001$) and wet ($F=4.52$; $p<0.0346$) seasons resulted in lower temperatures in the crusted zones compared with the uncrusted zones (Fig. 3A). In the dry season, crusted zones maintained temperatures below 8 °C throughout the day. In contrast, uncrusted zones showed higher values that reached up to 20 °C. The morning, noon, and afternoon recorded the highest mean temperatures both in crusted and uncrusted zones. During daytime, values ranged from -5.8±1.4 °C to 7.8±1.4 °C and -3.3±1.2 °C to 22.7±1.7 °C in crusted and uncrusted zones, respectively. In the wet season, crusted zones recorded temperatures below 15 °C during the morning,

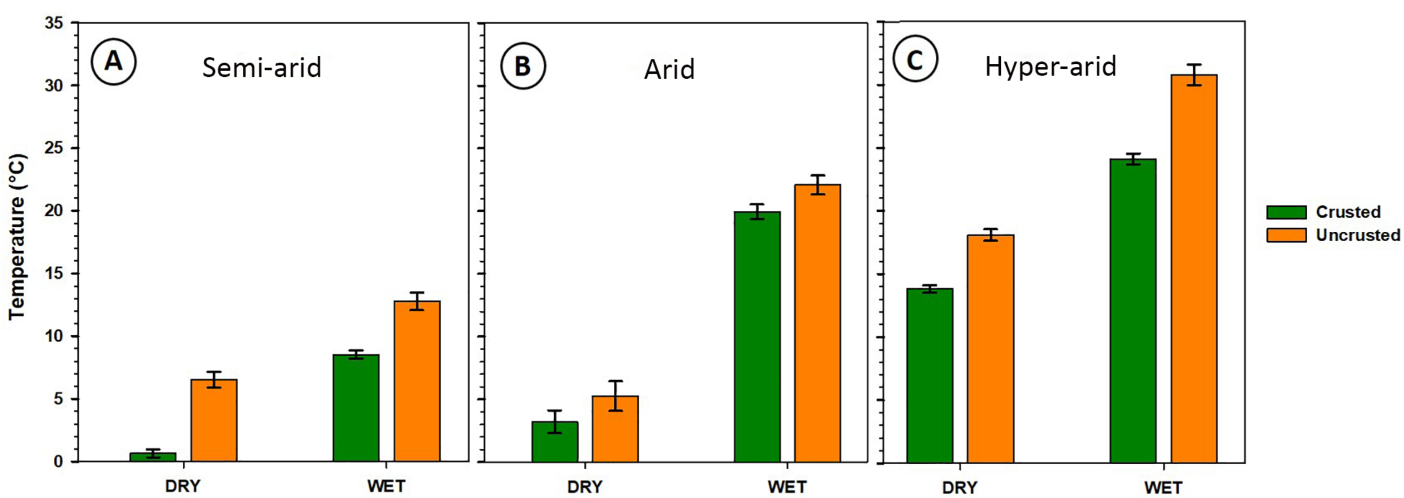

Figure 3: Temperature values of crusted and uncrusted soil for the wet and dry seasons in the three studied sites in central-western Argentina. A. semi-arid site; B. arid site; C. hyper-arid site. Bars represent the standard deviation.

noon, and the afternoon, while uncrusted zones presented higher values and reached a peak of around 30 °C at noon and afternoon. In this season, temperatures ranged from 2.1±0.5 °C to 15.5±2.5 °C and 0.6±0.2 °C to 32.5±3.7 °C in crusted and uncrusted. respectively. During the mentioned daytime, differences in the mean temperatures between crusted and uncrusted zones were significant (F=1.0; p<0.0001) and presented the highest mean difference of approximately 15 °C and 18 °C for the dry and wet seasons, respectively (Fig. 4A, B; Table S1).

Arid site

In this area, temperature mean values for both dry (F=4.04; p<0.0471) and wet (F=3.6; p<0.0401) seasons resulted lower in the crusted zones compared with the uncrusted zones (Fig. 3B). In the dry season, crusted zones maintained temperatures below 20 °C during the morning and noon. Uncrusted zones showed higher values with a peak of 30 °C at noon. The morning and noon showed the highest mean temperatures both in crusted and crusted zones. Mean values ranged from -7.01±1.2 °C to 21.2±1.5 °C in crusted zones and -7.7±1.6 °C to 26.3±1.9 °C in uncrusted zones. In the wet season, crusted zones recorded temperatures below 30 °C during the morning and noon, while uncrusted zones presented higher values and reached a peak of around 40 °C at noon time. Temperatures ranged from 13.8±3.6 °C to 32.4±1.3 °C and 13.5±3.7 °C to 39.3±3.2 °C in crusted and uncrusted zones, respectively. Differences in the mean temperatures between crusted and uncrusted zones were significant during daytime (F=1.0; p<0.0001) with the highest value of 5 °C and 7 °C for the dry and wet seasons, respectively (Fig. 4C, D; Table S2).

Hyper-arid site

Temperatures for both dry (F=45.7; p <0.0001) and wet seasons (F=34.2; p<0.0001) were lower in crusted than uncrusted zones (Fig. 3C). In the dry season, crusted zones values maintained temperatures below 20 °C. Uncrusted zones showed higher values with a peak of more than 30 °C at noon. The morning, noon, and afternoon recorded the highest mean temperatures in both zones. In the dry season, mean values ranged from 7.1±2.8 °C to 21.8±2.7 °C in crusted zones and 8.2±1.5 °C to 32.6±2.8 °C in uncrusted zones. In the wet season, crusted zones showed temperatures below 30 °C during the daytime, while uncrusted zones reached a peak of around 50 °C at noon time. In this season, temperatures ranged from 15.7±1.5 °C to 32.6±6.5 °C and 16.5±1.2 °C to 51.1±6.2 °C in crusted and uncrusted zones, respectively. Differences in the mean temperatures between crusted and uncrusted zones were significant during the daytime (F=1.0; p<0.0001) with the highest value of 11 °C and 21.5 °C for the dry and wet seasons, respectively (Figs. 4E-F; Table S3).

Discussion

Thermal effect of biocrusts at different aridity levels

Biocrusts decreased soil temperature by up to 3-5 °C in semi-arid and arid sites, respectively, and by up to 7 °C in the hyper-arid site in both the dry and wet seasons (Figs. 3A-C; 4A-F). The highest temperature value was recorded in bare soils with mean maximum values of 13 °C, 23 °C, and 32 °C in the semi-arid, arid, and hyper-arid sites, respectively. Su et al. (2021) indicated that biocrusts' effect influencing pathways on soil multifunctionality is different in arid and semi-arid regions. Biocrusts respond to local climate and environmental conditions that determine their structure and function, affecting their influence on soil parameters (Belnap, 2006). Micro-climate conditions were more similar between semi-arid and arid sites compared with the hyper-arid site (Table 1). Hence, this site has extremely high temperatures and a sandy soil texture that would increase the infiltration rates in bare soil, making the temperature differences between crusted and uncrusted zones more significant than in the arid and semi-arid sites (Fig. 4E, F). Sandy soils exhibit high infiltration rates with high saturated hydraulic conductivity and low unsaturated hydraulic conductivity which can affect evaporation (Kidron et al., 2022). Moreover, the impact of biocrusts in the hydrological cycle played an important role in the evaporation process in the arid and semi-arid ecosystems of China (Xiao et al., 2016). Large mean temperature differences during the diurnal time in all the studied sites were probably affected by sun radiation with changes in the evaporation rates. Evaporation is strongly coupled with soil water and temperature regimes (Li et al., 2022). As soil temperature

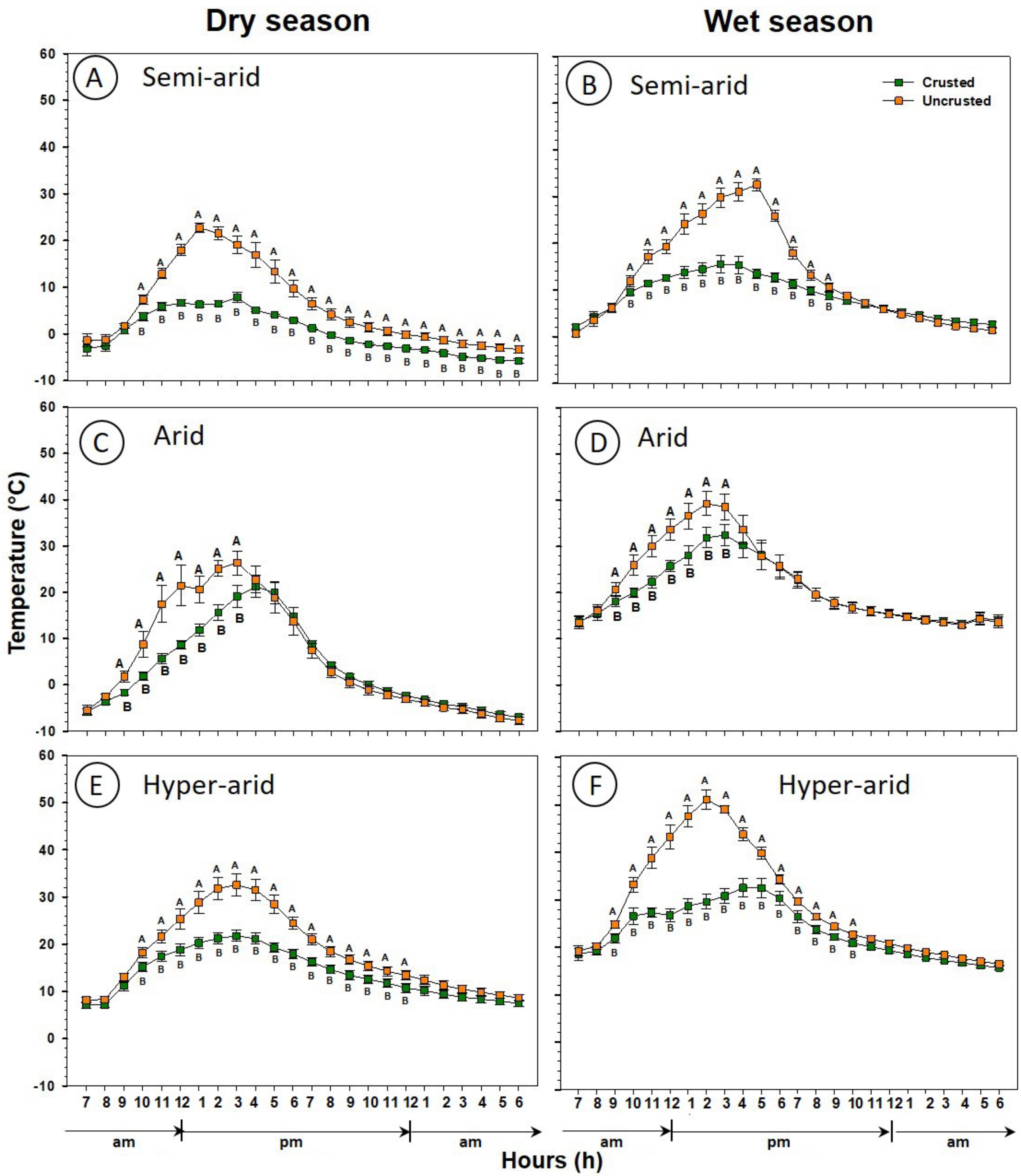

Figure 4: Soil mean temperature values recorded during the dry and wet seasons considering crusted *vs.* uncrusted zones in semi-arid (A, B), arid (C, D), and hyper-arid (E, F) sites in central-western Argentina. Points represent the mean values, and bars represent the standard deviation. Different letters indicate significant differences (α=0.05).

increases, there is a growth in the evaporation rate that leads to a decrease in soil moisture (Xiao et al., 2016). The humidity retained by the presence of biocrusts enhances the heat capacity of the soil, accelerating the evaporation from the surface layer of topsoil, with a consequent decrease in soil temperature (Guan et al., 2019). However, the effect of biocrusts on evaporation has been controversial, and a recent study postulated that results depend on the timing (evaporation stages) and the devices used for measurements (Kidron et al., 2022). A heavy rain event occurred in the hyper-arid site the day before our field tasks (Table 1), probably producing a saturated soil surface that corresponds to stage I according to Kidron et al. (2022). As a consequence, biocrusts probably retained water and increased the evaporation rates, resulting in larger differences with bare soil, where infiltration might occur (Fig. 4E, F). On the other hand, available soil moisture and lower albedo surface are key to raising soil temperatures (Li et al., 2022). Biocrusts act to deplete the amount of soil moisture due to the reduction of the surface albedo, increasing the soil temperatures, as a consequence of the dark-colored pigments and their micro-relief (Kidron and Tal., 2012; Kidron et al., 2022). Thus, biocrusts with rough surfaces and dark colors would increase the potential evaporation (Chamizo et al., 2013). It is known that organisms forming biocrusts strongly influence evaporation rates; therefore, mosses and cyanobacteria increase evaporation by regulating surface soil moisture and temperature (Li and Xiao, 2022). An elevation in soil temperatures was reported by Couradeau et al. (2016) in crust dominated by cyanobacteria and their effect on heat and evaporation rates. In the hyper-arid site, the crust dominated by dark-colored cyanobacteria showed high maximum temperatures compared with the arid and semi-arid sites. Therefore, they can contribute to an albedo reduction, less sunlight absorption, and less thermal reduction, especially during the wet season (Fig. 4E, F). Additionally, lichens are able to synthesize hydrophobic components that diminish water retention in soils (Shokri et al., 2008; Chamizo et al., 2013). They were an important component of biocrusts in the arid site and could produce lower water retention and a slight soil temperature increase in the arid site (Fig. 4C, D).

Soil thermal effect of biocrusts during day-night time

Soil temperature values in crusted zones were higher during the morning, noon, and afternoon than at nighttime in all the studied sites. Biocrusts decreased diurnal temperature by approximately 10 °C, in the semi-arid and arid sites, and by 20 °C in the hyper-arid site (Fig. 4A-F). The reduction in soil temperature by biocrusts decreases in the evening and night probably due to the sun's inclination with a cooling effect and a less marked difference concerning bare soil. Biocrusts decreased the diurnal range soil temperature by up to 6.8-9.4 °C at 0-10 cm compared to bare soil in the Loess Plateau (Xiao et al., 2019a), due to the effect of solar radiation, evaporation, and heat absorption (Gao et al., 2010; Xiao et al., 2016). Diurnal and night differences in soil temperatures in the semi-arid, arid, and hyper-arid sites can be related to the albedo and the main organisms that form biocrusts. The albedo is largely affected by soil surface characteristics, especially color, roughness, and moisture, but these features may change depending on the type of biocrust. For example, surface albedo is negatively related to soil darkness (Post et al., 2000) and soil roughness (Matthias et al., 2000). Thus, organisms present in the biocrusts have different pigmentation and morphological structure producing characteristic responses to precipitation and temperature (Belnap et al., 2004). Navas-Romero et al. (2020a) found for our study area that mosses and cyanobacteria were dominant in the hyper-arid site, lichens in the arid site, and mosses and lichens in the semi-arid one. In the hyper-arid site, cyanobacteria had a dark pigmentation and a high degree of roughness, which may produce a reduction in the albedo, and increase the soil mean temperatures (Figs. 3C; 4E, F). The arid site is dominated by lichens such as genera *Endocarpon* Ach., *Placidum* Ach., and *Enchylium* Bornet of dark pigmentation and less roughness (Navas-Romero et al., 2020a) that probably had a warming effect on soils (Figs. 3B; 4C, D). The decrease in soil temperature can occur because biocrusts blocked the formation of a dry layer on the soil surface, resulting in a higher soil water evaporation and longer time during the constant rate drying stage (Kidron and Tal, 2012; Xiao et al., 2016). Moreover, biocrusts affect soil thermal properties by increasing the organic matter content (Ochsner et al., 2001). The layer of organic matter is an additional barrier to the caloric exchange with the environment, preventing the temperature from reaching extreme values (Guan et al., 2019). Even though the presence of some dark-pigmented lichens in the semi-arid site (Fig. 4A, B), the predominance of light pigmentation and less rough mosses as *Pseudocrossidium* E. F. P. Bornmüller (Navas-Romero et al., 2020a) can contribute to the largest temperature decline (Fig. 4A, B).

Seasonal thermal effect by biocrusts

In all the studied sites, maximum temperatures in crusted and uncrusted zones were higher during the wet season which is coincident with summer. During this season, temperatures reach higher values with sporadic and intermittent heavy rainfall, providing moisture to the soil. Unfortunately, at the time of field work and sampling tasks, technical problems with devices did not allow us to record soil humidity values. On the other hand, the dry season corresponds to the winter season occasionally with temperatures below zero and scarce precipitations (Table 1). The presence of biocrusts influenced the thermal soil properties, reducing temperatures during both the wet and dry seasons (Fig. 3A-C). The temperature difference between crusted and uncrusted zones in both seasons was around 6 °C in the semi-arid site (Fig. 3A) and 3 °C in the arid site (Fig. 3B). In the hyper-arid site, differences were around 5 °C and 7 °C in the dry and wet season, respectively (Fig. 3C). The effect of biocrusts on soil properties was strongly related to the moisture percentage and temperature (Xiao et al., 2016), while the organisms in biocrusts contribute to a higher water-holding capacity and lower infiltration rates (Xiao and Hu, 2017). Thus, biocrusts would keep higher moisture levels that can aid to dissipate heat and reduce temperatures in the wet season. On the contrary, bare soils would absorb more heat and less moisture producing higher temperatures for a longer time during the wet season (Fig. 4B, D, F).

In semi-arid lands of the Loess Plateau in China, moss-dominated biocrusts decreased soil infiltrability mainly by the increase of their biomass and exhibited different seasonal variation patterns than bare soils (Xiao et al., 2019b). The presence of biocrusts decreased soil temperature in hot and wet summers and increased soil temperature in cold and dry winters (Xiao et al., 2013). In central-western Argentina, the observed pattern for summer and winter time is similar with a temperature reduction when biocrusts were present (Fig. 3A-C). Different responses have been found in moss-dominated biocrusts that increased the surface soil temperature by almost 28% in the wet season and decreased them by 22.9-54.9% in the dry season (Xiao et al., 2019a). In uncrusted zones, maximum temperatures at all sites reached higher values during the wet than during the dry season, with mean values among 14 °C to 30 °C, and 6 °C to 18 °C, respectively (Fig. 3A-D). Moreover, lower soil temperatures recorded in the semi-arid site can be related to the moss-dominated crust at this site (Fig. 3A). Decreasing soil temperature by moss-dominated biocrusts under hot and wet conditions was produced because biocrusts blocked a dry layer at the soil surface and increased the evaporation, thus dissipating more heat from the soil (Xiao et al., 2013). On the other hand, biological soil crust organisms are only metabolically active when wet, and as soil surfaces dry quickly in deserts during late spring, summer, and early fall, the amount and timing of precipitation are likely to have significant impacts on the physiological functioning of these communities (Belnap et al., 2004). The influence of biocrusts on soil properties can be conditioned by local climate conditions that make differences in the moisture and temperature patterns among worldwide drylands. In our study sites, rainfall generally occurs during the summer when temperature and solar radiation are higher with a low available moisture percentage, which is not enough to allow the liberation of large heat concentration, producing high maximum temperatures, especially in the hyper-arid site (Fig. 4B, D, F). In the Loess Plateau and the Negev desert, biocrusts were dominated almost exclusively by mosses and they increased soil moisture at a surface level and decreased the infiltration rates compared to bare soil (Kidron and Tal, 2012; Xiao et al., 2016; Xiao and Hu, 2017). Moreover, moss-dominated crusts increased soil moisture by 500% due to their higher water-holding capacity of moss-crusts and their availability for reducing the soil heat flux (Li et al., 2022). They can retain more water due to their large biomass and thickness; thus, the thermal reduction effects are higher than those biocrusts dominated by lichens, cyanobacteria, or bare soil (Xiao et al., 2007; Belnap et al., 2003; Chamizo et al., 2013). In the Mu Us desert in China, both lichen and moss-covered biocrusts reduced the infiltration rates compared with bare soil; however, water retention on moss-covered soils was higher than on lichen-covered soils (Guan and Liu, 2021). The effect of biocrusts on infiltration rates depends on the organisms that form the crust (Guan and Cao, 2021).

Conclusions

In this work, we studied the effect of biocrusts on soil temperatures from three sites with different aridity levels during the wet and dry seasons in central-western Argentina. Our results showed clear thermal differences under biocrusts presence independently of the site, season, or diurnal hour, with a reduction in soil temperatures.

There were clear differences in soil mean temperatures between crusted and bare soils. Both crusted and uncrusted soils exhibited significant seasonal variations and their patterns were different. This response can be related to the available moisture in soils and the seasonal rainfall. Temperature values were lower in crusted zones than in bare soil independently of the aridity conditions, but the thermal reduction was more notorious in the hyper-arid site, probably as a consequence of the soil texture, evaporation, and infiltration rates, and the organisms that formed the biocrusts mainly dominated by dark-colored cyanobacteria.

The crust composition would influence the heat concentration and water retention and subsequently affect the soil temperature. Large differences in mean temperature values between crusted and uncrusted zones were observed (from 10 °C to 20 °C), and they occurred during morning and afternoon when solar radiation was high, which could be related to the albedo and the pigmentation of organisms forming the biocrusts.

Soil thermal reductions during the dry and wet seasons were detected in the studied sites. The biocrusts decreased soil temperature by as much as 3-7 °C in the wet season (summer) and 4-6 °C in the dry season (winter). Soil temperature is known to be coupled with the available moisture, rainfall events, and water retention by biocrusts in other sites. However, future research analyzing both temperature and humidity may reveal further results about the effect of biocrusts in the soil thermal conditions of central-western Argentina.

Here, we have shown that the presence of biocrusts considerably reduces temperatures in drylands of central-western Argentina. How they affect their surrounding environment can be related to the composition of the microphytic community and the local climate and environmental conditions. This work highlights the importance of the biocrusts as drivers of changes in the micro-environmental soil conditions, reducing temperatures, and is a contribution to future management practices such as the use of biocrusts as natural components of dryland ecosystems in the restoration of natural areas.

Author contributions

ALN, MHM, and EMC conceived and designed the study. ALN and MHM collected field data and conducted the analyses. EMC, MCFB, and BV contributed to data acquisition and interpretation. ALN wrote the manuscript with the assistance of MHM, EMC, BV, and MCFB. All authors contributed to the discussion, review, and approval of the final manuscript.

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Supplementary material

Table S1: Mean temperature values and standard deviation (S.D.) of crusted and uncrusted soil per hour for the three measurement days in the wet and dry seasons in the semi-arid site in central-western Argentina.

SEASON		DRY				WET			
CONDITIONS		CRUSTED		UNCRUSTED		CRUSTED		UNCRUSTED	
HOUR		Mean	S.D.	Mean	S.D	Mean	S.D	Mean	S.D
12	am	-3.1	0.2	-0.1	0.8	5.9	0.7	5.8	0.7
1	am	-3.4	0.2	-0.6	0.7	5.1	0.7	4.7	0.6
2	am	-4.1	0.2	-1.3	0.7	4.5	0.6	4	0.6
3	am	-4.8	0.2	-2.1	0.7	3.8	0.6	3.0	0.6
4	am	-5.1	0.3	-2.5	0.7	3.2	0.6	2.2	0.6
5	am	-5.5	0.3	-2.9	0.7	2.9	0.5	1.7	0.5
6	am	-5.7	0.4	-3.3	0.7	2.6	0.5	1.3	0.5
7	am	-3.1	1.6	-1.3	1.4	2.1	0.5	0.6	0.5
8	am	-2.5	1.2	-1.3	1.2	4.3	1.0	3.4	1.2
9	am	0.8	0.8	1.7	0.4	6.1	0.7	6.1	0.9
10	am	3.7	0.8	7.3	0.9	9.5	0.	11.8	1.1
11	am	5.8	0.8	12.8	1.0	11.3	0.5	17.1	1.5
12	pm	6.6	0.6	17.9	1.1	12.5	0.6	19.3	1.4
1	pm	6.3	0.5	22.7	1.0	13.7	1.2	24.1	2.2
2	pm	6.4	0.5	21.5	1.4	14.4	1.3	26.3	2.2
3	pm	7.8	1.1	19.0	1.9	15.5	1.8	29.8	2.1
4	pm	5.0	0.3	16.9	2.6	15.3	1.7	31	1.9
5	pm	4.0	0.2	13.3	2.4	13.4	0.9	32.5	1.2
6	pm	2.9	0.2	9.6	1.7	12.6	0.9	25.8	1.2
7	pm	1.2	0.2	6.4	1.3	11.2	0.9	17.8	1.2
8	pm	-0.3	0.3	4.2	1.1	9.7	0.9	13.1	1.0
9	pm	-1.4	0.3	2.	1.0	8.7	0.8	10.6	0.8
10	pm	-2.2	0.3	1.4	0.9	7.6	0.7	8.7	0.7
11	pm	-2.6	0.2	0.6	0.9	6.8	0.7	7.2	0.7

Table S2: Mean temperature values and standard deviation (S.D.) of crusted and uncrusted soil per hour for the three measurement days in the wet and dry seasons in the arid site in central-western Argentina.

SEASON		DRY				WET			
CONDITIONS		CRUSTED		UNCRUSTED		CRUSTED		UNCRUSTED	
HOUR		Mean	S.D.	Mean	S.D	Mean	S.D	Mean	S.D
12	am	-2.3	0.43	-3.12	0.6	15.4	0.8	15.3	0.7
1	am	-3.2	0.3	-3.9	0.6	14.8	0.7	14.6	0.6
2	am	-4.1	0.3	-4.9	0.6	14.2	0.7	13.9	0.5
3	am	-4.7	0.6	-5.3	0.9	13.7	0.7	13.5	0.6
4	am	-5.5	0.7	-6.3	0.8	13.2	0.7	12.9	0.5
5	am	-6.3	0.6	-7.1	0.8	14.5	1.2	14.2	1.2
6	am	-7.0	0.5	-7.7	0.7	13.9	1.1	13.6	1.2
7	am	-5.8	0.6	-5.5	1.0	13.7	1.2	13.5	1.3
8	am	-3.6	0.6	-2.5	0.5	15.3	1.4	16.0	1.3
9	am	-1.6	0.6	1.7	1.1	18.0	1.1	20.7	1.3
10	am	1.8	0.8	8.7	2.8	19.9	0.9	25.9	2.1
11	am	5.7	1.0	17.4	4.0	22.3	1.2	30	2.2
12	pm	8.5	0.8	21.4	4.3	25.7	1.1	33.6	2.3
1	pm	11.8	1.3	20.6	2.9	28.0	2.0	36.6	2.7
2	pm	15.6	1.6	25.0	1.6	31.9	2.1	39.2	2.6
3	pm	19.0	2.4	26.3	2.5	32.4	2.3	38.5	2.7
4	pm	21.2	2.3	22.7	2.8	30.2	2.7	33.6	3.0
5	pm	19.8	2.3	18.8	3.3	28.2	3.1	27.8	2.8
6	pm	14.8	1.9	13.7	2.9	25.5	2.5	25.7	2.3
7	pm	8.8	0.7	7.4	1.6	22.6	1.6	22.9	1.5
8	pm	4.3	0.4	2.8	1.1	19.5	1.3	19.5	1.3
9	pm	1.7	0.6	0.4	1.1	17.6	1.3	17.7	1.2
10	pm	-0.0	0.8	-1.1	1.1	16.7	1.1	16.7	1.1
11	pm	-1.3	0.6	-2.1	0.9	15.9	1.0	15.9	0.9

Table S3: Mean temperature values and standard deviation (S.D.) of crusted and uncrusted soil per hour for the three measurement days in the wet and dry seasons in the hyper-arid site in central-western Argentina.

SEASON		DRY				WET			
CONDITIONS		CRUSTED		UNCRUSTED		CRUSTED		UNCRUSTED	
HOURS		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
12	am	10.7	0.9	13.4	0.9	19.3	0.5	20.8	0.6
1	am	10.1	0.9	12.4	0.9	18.5	0.5	19.8	0.4
2	am	9.4	0.9	11.2	0.9	17.8	0.4	18.9	0.4
3	am	8.8	0.8	10.4	0.8	17.2	0.5	18.3	0.4
4	am	8.3	0.7	9.8	0.8	16.7	0.5	17.6	0.4
5	am	7.9	0.7	9.2	0.7	16.1	0.5	17.0	0.4
6	am	7.4	0.6	8.6	0.6	15.7	0.5	16.4	0.4
7	am	7.1	0.6	8.2	0.6	18.5	1.2	19.2	1.1
8	am	7.1	0.5	8.3	0.5	19.2	0.9	20.2	0.7
9	am	11.1	0.9	13.0	0.8	21.9	0.9	24.7	0.7
10	am	15.1	1	18.2	1.0	26.5	1.7	33.2	1.5
11	am	17.4	1.1	21.6	1.4	27.3	0.9	38.8	2.2
12	pm	18.8	1.3	25.3	2.1	26.7	1.3	43.3	2.5
1	pm	20.2	1.2	28.8	2.3	28.6	1.5	47.6	2.2
2	pm	21.2	1.1	31.8	2.3	29.	1.5	51.1	2.0
3	pm	21.7	1.1	32.5	2.3	30.8	1.5	49.0	0.8
4	pm	21.1	1.1	31.5	2.2	32.5	1.8	43.7	1.3
5	pm	19.2	1	28.4	1.9	32.4	2.0	39.8	1.3
6	pm	17.9	0.9	24.4	1.3	30.3	1.5	34.2	0.9
7	pm	16.2	0.8	21.0	1.1	26.4	1.2	29.6	0.8
8	pm	14.6	0.9	18.4	1.0	23.7	0.8	26.4	0.7
9	pm	13.4	0.9	16.7	1.0	22.1	0.7	24.3	0.6
10	pm	12.5	0.9	15.3	1.0	20.8	0.6	22.6	0.5
11	pm	11.8	0.9	14.2	0.9	20.1	0.6	21.7	0.6