The Influence of Moss Colonization and Biochar Application on Evaporation Losses and Surface Crack in Shallow Carbonate-Derived Laterite During Dry-Wet Cycles

Lulu Che
Guizhou University

Dongdong Liu (✉ liudongdongcn@foxmail.com)
Guizhou University  https://orcid.org/0000-0001-8834-9167

Dongli She
Hohai University

Research Article

Keywords: Carbonate-derived laterite, Moss colonization, Biochar application, Soil evaporation, Surface crack.

Posted Date: December 8th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-1109021/v1

License: ☑️ This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License
The influence of moss colonization and biochar application on evaporation losses and surface crack in shallow carbonate–derived laterite during dry–wet cycles

Che Lulu¹, Liu Dongdong¹*, She Dongli²

¹College of Resource and Environmental Engineering, Key Laboratory of Karst Georesources and Environment, Ministry of Education, Guizhou University, Guiyang, 550025, China

²College of Agricultural Sciences and Engineering, Hohai University, Nanjing 210098, China

*Corresponding author. Liu Dongdong, Email: ddliu@gzu.edu.cn

Tel: 86+15185160228
Abstract

Aims  Soil water deficit in karst mountain lands is becoming an issue of concern owing to porous, fissured, and soluble nature of underlying karst bedrock. It is important to identify feasible methods to facilitate soil water preservation in karst mountainous lands. This study aims to seek the possibility of combined utilization of moss colonization and biochar application to reduce evaporation losses in carbonate-derived laterite.

Methods  The treatments of the experiments at micro-lysimeter included four moss spore amounts (0, 30, 60, and 90 g·m\(^{-2}\)) and four biochar application levels (0, 100, 400, and 700 g·m\(^{-3}\)). The dynamics of moss coverage, characteristics of soil surface cracks and surface temperature field were identified. An empirical evaporation model considering the interactive effects of moss colonization and biochar application was proposed and assessed.

Results  Moss colonization reduced significantly the ratio of soil desiccation cracks. Relative cumulative evaporation decreased linearly with increasing moss coverage under four biochar application levels. Biochar application reduced critical moss coverage associated with inhibition of evaporation by 33.26%-44.34%. The empirical evaporation model enabled the calculation of soil evaporation losses under moss colonization and biochar application, with the R\(^2\) values ranging from 0.94 to 0.99.

Conclusions  Our result showed that the artificially cultivated moss, which was induced by moss spores and biochar, decreased soil evaporation by reducing soil
surface cracks, increasing soil moisture and soil surface temperature. Moss colonization and biochar application has the potential to facilitate soil moisture conservation in karst mountain lands.

**Keywords** Carbonate-derived laterite; Moss colonization; Biochar application; Soil evaporation;

Surface crack.
Introduction

The karst landform, which plays a significant role in water supply and consumption, covers approximately 10% of the Earth’s land surface (Yang et al. 2017). It covers extensive parts of China (~3,440,000 km²), especially in southwestern China. These lands are usually characterized by a surface–underground structure. This sieve-like structure enhance soil water loss, soil drought, and rocky desertification. Because of the unrestrained water loss and the low water storage capacity, flora in karst lands grow slowly and exposed soils are easily eroded, which accelerate soil drought and pose threats to the stability of local ecosystems (Yang et al. 2017). Since the 1980s, a large number of vegetation restoration projects have been implemented to control rocky desertification in degraded karst ecosystems (Li et al. 2018). Although the efforts of large-scale afforestation drives should be applauded, the high cost of afforestation in karst lands and the low stability of restored areas remain a challenge (Chen et al. 2019). It is, therefore, important to identify viable and sustainable methods to facilitate soil water preservation in karst lands.

Evaporation plays a critical role in the terrestrial hydrological cycle and impacts water resource management directly and significantly (Liu et al. 2016). In particular, a wide range of negative effects, such as unrestrained water losses, poor water retention, and low storage capacity, are triggered by cracks in the soil–epikarst zone, which considerably limits vegetation restoration in karst ecosystems (Zhou et al. 2012). Although the climate is humid with abundant precipitation in karst ecosystems, water
deficits and drought events happen frequently due to shallow soil layer and weak soil water storage capacity. Therefore, evaporation is a dominant water flux of karst ecosystems, reducing excess of evaporation losses to retain more available water. Furthermore, there is difficult to implement water conservation measures in large scale underground. Most studies focused on how to reduce water losses in shallow soil (Table 1). In these studies, the complex effects of typical additives on evaporation processes, surface crack, and soil temperature in shallow soils were quantified and discussed (Xiao et al. 2010; Kidron et al. 2012; Chamizo et al. 2012, Zribi et al. 2015; Wang et al. 2018; Ni et al. 2018; Jiang et al. 2018; Wang et al. 2019; Zhang et al. 2020; Li et al. 2021). The effects of different vegetation types on soil evaporation and water balance in karst ecosystems were investigated. For example, Zhang et al. (2018) found that soil evaporation in the forest–grass ecosystems was significantly higher than that in crop and grass ecosystems of subtropical humid karst lands. A study by Swaffer et al. (2015) confirmed that the restriction of invasive alien species of plants could slightly reduce soil water losses in karst Pinus massoniana plantations. Nevertheless, the roles of moss colonization or other biological modifiers in soil evaporation processes during the forward succession of karst ecosystems have received little attention. The contribution of moss colonization and biochar application to the restoration and reconstruction of degraded karst ecosystems should be investigated.
Greater number of scientists have realized that the moss crust plays an essential role in ecological restoration in a great variety of climate zones (Xiao et al. 2010; Yang et al. 2012; Xiao et al. 2016; Liu et al. 2020). Moss effectively improves soil structural stability and soil water holding capacity in extreme environments (such as rocky desertification areas and desertification areas (Chen et al. 2019; Xie et al. 2019). Gao et al. (2012) found that moss could improve soil structure to reduce soil erosion in desertification areas. Moss has remarkable effects on reserving soil water, and that plays an important role in pedogenesis in karst rocky desertification areas (Li et al. 2009). Recently, artificial moss colonization was confirmed as an effective method that provides incentives to soil stability, water-holding capacity, and land alleviated degradation (Antoninka et al. 2015; Xiao et al. 2015). Zhao et al. (2014) found that artificial biocrusts could be formed rapidly, i.e., within a short-term period, thus improving micro-environment of soil surface. However, Xiao et al. (2011) showed that artificial moss crust under low-stress conditions differed from the natural ones in shape and species composition, which likely accounted for differences in the functions of the biocrust. Functions of biocrust in the terrestrial hydrological cycle is a matter of long-standing debate. Biocrusts increased soil infiltration ability by significantly upgrading hydraulic conductivity and surface macro-porosity (Jiang et al. 2018). Biocrusts also observably reduced surface soil infiltration capability and impeded soil water infiltration under ponding conditions (Xiao et al. 2019). Moreover, several studies have reported that the role of biocrusts in soil evaporation depends on
species, soil characteristics, and climates. Biocrusts greatly influenced evaporation process of sandy soil in the Loess Plateau but no significant effect on sandy loam soil (Xiao et al. 2011). Liu et al. (2020) concluded that for carbonate-derived laterite, moss crusts could inhibit significantly evaporation losses and increase soil surface temperature. Whereas moss colonization might be an attempt to address the obvious problems that we face in holding sufficient soil water for ecosystems in karst lands, more needs to be done to reduce the detrimental impact soil drought would have on the ecosystem.

Several studies have claimed that biochar is conducive to improving soil structure and properties, absorbing pollution, and promoting soil water retention (Wang et al. 2018; Lei et al. 2019). Biochar seems to be an ideal soil amendment. Zhang et al. (2016) reported that the biochars decreased saturated hydraulic conductivity of sandy soil but did not reduce evaporation losses in the soil itself. Zhang et al. (2020) found that biochar addition (0.5%, 2%, 4%, 6%, and 10%) decreased evaporation rate of low-plasticity clay. Biochar also has positive effects on plant growth. There was sufficient evidence that biochar could significantly facilitate the growth of *Abutilon theophrasti* and *Prunella* by alleviating the side effects of salt stress (Thomas et al. 2013). The most positive benefits of biochar, however, were that it can enhance biocrust formation on the sand soil surface in a dry climate (Meng et al. 2014). Few studies have focused, however, on the potential effects of biochar on moss growth in karst ecosystems faced with water shortages.
In accordance with recent surveys, we assume that the combined utilization of moss colonization and biochar application should have favorable impacts on soil hydrology, which will impede rocky desertification and contribute to restoring and conserving fragile ecosystems. Therefore, we conducted a series of evaporation experiments to determine the effects of moss colonization and biochar application on evaporation losses of carbonate-derived laterite during six dry–wet cycles. This study aimed to (1) determine the effects of moss colonization and biochar application on evaporation losses, variations in the surface temperature field, and development of soil surface cracks; (2) unravel the complicated relationship between moss colonization and soil evaporation under biochar application; and (3) develop a soil evaporation model that considers the moss colonization and biochar application.

**Materials and methods**

**Study area**

The sampling site was located in a *Pinus massoniana* forest (26°26′59.72″–26°26′43.01″ N and 106°39′2.23″–106°39′18.85″ E) in western Huaxi District, Guiyang City, Guizhou Province, China (Fig. 1a). This site is characterized by a subtropical monsoon climate. The annual mean precipitation and potential evaporation are 1,185 and 830 mm, respectively. Rainfall mainly occurs between May and October. The annual mean temperature is 14.9 °C, with the highest mean temperature (23.4 °C) in summer and the lowest mean temperature (4.9 °C) in winter. The site is covered with mixed soils—mainly sedimentary red soil and yellow soil
(carbonate-derived laterite). The lithology is dominated by limestone and dolomite with typical karst characteristics. Soil thickness is highly heterogeneous and the soil is characterized by large areas of exposed rock. The soil thickness is only 3-10 cm in most areas with severe rocky desertification (Ding et al. 2019). The landscape of the test site accurately represents the karst mountainous landform during the vegetation restoration process. Soil basic properties were determined by standard soil test methods and are shown in Table 2. Because of the underlying epikarst zone and poor soil water holding capacity, soil water deficits may occur frequently. Moss landscape patches are becoming fragmented and their spatial distribution is becoming homogenized and isolated, with coverage ranging from 0.32 to 0.95 kg·m⁻² (Liu et al. 2020). The main moss species is Hypnum Hedw, which has homomorphic branches and leaves (Fig. 1b).

Experimental setup

The evaporation experiments were conducted from October 1, 2019, to January 2, 2020, under dry–wet cycles in closed greenhouse in the Key Laboratory of Karst Geological Resources and Environment in Guizhou University. A sampled carbonate-derived laterite collected in August 2019 from the upper 20 cm layer of the study site were used in these experiments. The sampled soils were passed through a 2 mm sieve and mixed after being air-dried. The biochar materials were bought from Laboratory of LiZhe Environmental Technology and produced from pyrolysis pine (Pinus sylvestris) at 450 and 550 °C. Subsequently, the biochar materials were sieved
through a 2 mm sieve. The moss was artificially cultivated by mixing different amounts of spores with soil materials found on the soil surface. The species of moss spores was *Hypnum Hedw.*, produced from Cao Mu Ji Plant Research Center. The effects of moss colonization and biochar application on moss growth, soil evaporation, and development of soil crack in carbonate-derived laterite were evaluated using 16 treatments with different amounts of biochar and moss spores. The treatments included four moss spores (0, 30, 60, and 90 g·m⁻²) and four biochar applications (0, 100, 400, and 700 g·m⁻³). The bare soil (0 g·m⁻² moss spores and 0 g·m⁻³ biochar) were regarded as the control. Three replicates were prepared for each treatment and, thus, a total of 48 microlysimeters (10 cm diameter, 4 cm soil thickness, and free drainage at the bottom) were operated (Fig. 1c). The microlysimeter scale referenced to previous studies on shallow soil amelioration (Table 1). It should be noted that using a microlysimeters in this study not give a complete soil evaporation processes occurring under field conditions. However, this microlysimeter scale of study enables systematic studies to be carried out under controlled conditions that enable insights into the changes in soil evaporation process under dynamic of soil surface characteristic. The soil materials were firstly divided into two layers to pack into these microlysimeters and biochar materials were added into the middle of the microlysimeter as a layer (Meng et al. 2014). The dry bulk density of the soil-biochar in the microlysimeter was controlled at 1.3 g·cm⁻³. The moss spores were mixed with the soil materials and evenly seeded onto the microlysimeter surface. After that, these
microlysimeters were saturated from the bottom by capillary action (self-absorption method) until the top surface of soil column got wet and soaked for 72h to ensure saturation. Finally, the bottom of microlysimeter was sealed with polyvinyl chloride film to prevent drainage.

Evaporation experiments took place over six dry–wet cycles (D–W1, DW–2, D–W3, D–W4, D–W5 and D–W6) (Fig.1 c). During each dry–wet cycle, evaporation lasted for 12 days and saturation lasted for 3 days. The air temperature and atmospheric relative humidity in the greenhouse were automatically measured using a temperature and humidity recorder (Testo 174H, Testo SE & Co. KGaA, Germany), which recorded data every 10 minutes. Because this study was conducted in the closed greenhouse, the influence of wind was negligible. The microlysimeters were weighed at 12:00 h every 2 days with an electronic precision balance of 0.01 g. Evaporation losses were determined by applying the differences between the masses of the microlysimeter. Simultaneously, thermal radiation of the soil surface were recorded using a thermal camera (Testo 865, Testo SE & Co. KGaA, Germany). Real soil surface images were also recorded by a high pixel digital camera (Eos 850D, 24.1 million pixels, Japan) to monitor the development of moss coverage and soil surface crack. The vertical distance between the camera and the soil surface was set at 0.2 m. All experiments were carried out within 10 min to ensure the accuracy of the data.

The initial variables were the number of moss spores, the number of biochar applications, and sampled soil properties. Various evaporation indicators were
determined, including cumulative evaporation \((E_c, \text{ mm})\), cumulative evaporation of bare soil \((E_{c0}, \text{ mm})\), evaporation rate \((E, \text{ mm} \cdot \text{d}^{-1})\), relative cumulative evaporation \((E_c/E_{c0}, \text{-})\), and mean soil water content \((SWC_{\text{mean}}, \text{ g} \cdot \text{g}^{-1})\). \(E_c\) was determined by the total evaporation losses during the entire evaporation time. \(E\) was calculated as the ratio of the cumulative evaporation to evaporation time. \(E_c/E_{c0}\) was calculated as the ratio of cumulative evaporation to bare soil evaporation for each treatment. \(SWC_{\text{mean}}\) was determined by the conservation of mass.

\[
E_c = 10 \frac{E_m}{\rho \pi r^2} \quad (1)
\]

where \(E_c\) is the cumulative evaporation (mm), \(E_m\) is the total evaporation loss during a given duration (g), \(\rho\) is the density of water (1.0 g·cm\(^{-3}\)), and \(r\) is the radius of the microlysimeter (10.0 cm).

\[
SWC_{\text{mean}} = \frac{S_m \times \theta + S_w - E_m}{S_m (1-\theta)} \quad (2)
\]

where \(SWC_{\text{mean}}\) is the mean soil water content (g·g\(^{-1}\)), \(S_m\) is the initial soil mass (g), \(S_w\) is the increased water mass when microlysimeter saturated (g), and \(\theta\) is the initial soil water content (0.15 g·g\(^{-1}\)).

Image processing

Information on the development of moss coverage and soil surface crack was extracted from real surface images using a Python script. The image processing was conducted in the following two parts.

**Part 1: Crack-recognition module.** The soil surface cracks were discriminated using a method similar to that used in Wang et al. (2017). Initially, this script picked
and cropped the edge areas and reserved the soil areas by threshold image segmentation and edge recognition. Subsequently, all the source images were converted into grayscale images, which switched from color differences between soil and crack to pixel difference. Owing to the visible difference in grayscale between cracks and soil blocks, these grayscale images were segmented into binary images by an automatic threshold method, called the OTSU method, implemented in the software package, Python OpenCV. If the grayscale values of some areas were higher than the threshold value, these areas were judged as cracks and shifted to black. Conversely, those areas below the threshold value were voted as soil materials and changed to white. The optical threshold value was automatically determined. It must be noted that very few isolated black spots could not be distinguished owing to the microtopography of the soil surface. Eventually, threshold denoising and characterization of cracks were performed (Fig. S1a). Several crack parameters were determined (see Section 2.4).

**Part 2: Moss recognition module.** There were obvious color differences between moss and soil, and thus color segmentation was applied to extract the dynamics of moss coverage. First, the mean filtering method was used to enhance the moss pixels. Later, the color mode of the source images was converted to HSV mode by the cvtColor function in OpenCV. The converted pictures were handled with color gamut segmentation by the THRESH_BINARY function in OpenCV. If the gray values were higher than the threshold value, these areas were judged as soils and
shifted to black. These areas below the threshold value were regarded as moss and changed to white. The optical threshold value was also automatically determined. Because the moss surface was irregular, there were a few noise points after image binarization and segmentation. Finally, mathematical morphology processing was conducted to fill holes after image binarization and segmentation (Fig. S1b).

The temporal and spatial evolution of the surface temperature for different treatments were determined from these images using the IRSoft 4.5 software. The thermal images of soil surface were collected using a thermal camera (Testo 865, Testo SE & Co. KGaA, Germany). The IRSoft 4.5 software was used to automatically analyze a thermal image. These thermal images were, then, imported into IRSoft 4.5 software to calculate the average temperature of the surface temperature for different treatments (Fig. S1c).

Soil surface cracks, moss coverage, and moss growth

The crack ratio ($R_{cr}$) was calculated to illustrate the crack dynamics during the dry–wet cycles. The crack ratio was determined as the ratio of crack pixels to total pixels in the binarization images (Tang et al. 2011b; Wang et al. 2017).

$$R_{cr} = \frac{P_{black}}{P_{total}} \times 100$$

where $R_{cr}$ is the crack ratio (%), $P_{black}$ is the pixel of the cracks in the binarization images (-), and $P_{total}$ is the pixel of soil in binary images (-).

Moss coverage was used as an indicator to reveal the moss growth during the experiment. Moss coverage ($M_{c}$) was defined as the ratio of moss pixels to the total
pa.\text{pixels.}

\[ M_c = \frac{P_{\text{white}}}{P_{\text{total}}} \times 100 \]  

(4)

where \( M_c \) is moss coverage (\%), \( P_{\text{white}} \) is pixels referring to moss in binary images (-), and \( P_{\text{total}} \) is pixels representing soil surface areas in binary images (-).

A logistic growth model was built to unravel the dynamics of moss coverage (Wu et al. 2020).

\[ M_c = \frac{M}{1 + be^{(-kt)}} \times 100 \]  

(5)

where \( M \) is the upper limit to moss coverage (cm\(^2\) cm\(^{-2}\)), \( b \) is the mutation time for growth rate (day), \( k \) is the growth rate of moss (cm\(^2\) cm\(^{-2}\) day\(^{-1}\)), and \( t \) is the growth time (day).

Evaporation model considering the role of moss colonization

We used an empirical model to calculate the effects of moss colonization and biochar application on evaporation of carbonate-derived laterite. The model focused on the relationship between dynamics of moss coverage and soil evaporation in dry–wet cycles. The empirical model consisted of two parts: moss coverage estimation, and evaporation calculation. We introduced the logistic growth equation to characterize the dynamics of moss coverage, which included three critical parameters—moss growth rate \( k \) (cm\(^2\) cm\(^{-2}\) day\(^{-1}\)), time for mutation of growth rate \( b \) (day), and upper limit to moss coverage \( M \) (cm\(^2\) cm\(^{-2}\)). There was a significant linear relationship between the value of \( E_c/E_{c0} \) and moss coverage \( M_c \) (see Section 3.4).

Based on the variation of this linear fitting relationship, the cumulative evaporation
was calculated as follows:

\[ E = E_{c0}(aM_c + c) \] (6)

where \( E \) is the predicted evaporation (mm), \( E_{c0} \) is the evaporation of bare soil (mm), \( M_c \) is the moss coverage (cm\(^2\) cm\(^{-2}\)), and \( a \) and \( c \) are empirical coefficients (-).

Data collected over the 88 days included evaporation for each treatment within the given duration \( E_c \), evaporation of bare soil \( E_{c0} \), and moss coverage with each day \( M_c \). The data were applied to test the empirical model.

Data analysis

All statistical analyses were performed using Python version 3.6. Partial correlation and ANOVA analyses were conducted using a significance level of 0.05 and 0.01, respectively. The partial correlation coefficient measured the degree of association between the two variables, with the effects of a set of controlling variables removed. Means were compared using the least significant difference determined by one-way analysis of variance. Regression analysis was conducted to determine the relationships between each variable, and the determination coefficient (R\(^2\)) and root mean square error (RMSE) were used to evaluate the performance of the applied regression equations. We used structural equation modeling (SEM) to separate the effects of moss colonization and biochar application on evaporation of carbonate-derived laterite. The SEM was conducted using AMOS 2.1 software.
Results

Dynamics of moss coverage

The moss coverage versus time under different biochar application (B0, B1, B2, and B3) and moss spores (M1, M2, and M3) during six dry–wet cycles was indicated in Fig. 2. The soil surface of the moss colonization treatments showed similar changing patterns in the moss growth during each dry–wet cycle. In particular, moss coverage considerably increased, but dramatically decreased after approximately 3 days of evaporation. Another notable finding is that the mean growth rate of moss in the first three dry–wet cycles (D–W1, D–W2, and D–W3) was higher than in the last two dry–wet cycles (D–W4 and D–W6) and, therefore, it appears that the dynamics of moss coverage were greatly affected by evaporation times and dry–wet cycles.

The logistic growth equation could estimate the dynamics of moss coverage, but there were some restrictions in explaining the wilt of moss under drought conditions (Table 3). The determination coefficients $R^2$ (dimensionless) ranged from 0.60 to 0.74 and the RMSE (dimensionless) values were between 0.02 and 0.16. The $M$ values (upper limit to moss coverage) and $k$ values (moss growth rate) increased with the initial amount of moss spores, but they were not affected by the biochar application for all treatments.

The initial amount of moss spores and soil water content significantly increased moss coverage with partial correlation coefficients (pr) of 0.64 and 0.48, respectively (Table 4). However, moss coverage significantly reduced with the increase of biochar
application (pr = -0.11, P < 0.01) and atmospheric relative humidity (pr = -0.33, P < 0.01). These results suggested that the initial amount of moss spores and soil water content had the largest impact on the growth of moss, whereas the biochar application had the lowest influence. These trends were also confirmed by the functional relationship among initial amount of moss spores, soil water content, air temperature, and atmospheric relative humidity ($M_c = 0.08 + 0.001M_b + 0.12SWC_{mean} - 0.04T_{air} - 0.01RH_{mean}$, $R^2 = 0.56$), where $M_b$ is the initial amount of moss spores, $SWC_{mean}$ is the mean soil water content during the drying process, $T_{air}$ is the air temperature, and $RH_{mean}$ is the mean atmospheric relative humidity.

Characteristics of soil surface cracks

The ratio of soil surface crack fluctuated significantly during dry–wet cycles. For example, the mean ratio of soil surface crack at the end of the D–W6 was 42.5% higher than that at the end of the D–W1 (Fig. 3). In each dry–wet cycle, there were significant differences in the mean soil surface crack ratio between different initial amounts of moss spores (P < 0.05), especially for the M3 treatment. In contrast, there were no significant differences in the mean soil surface crack ratio between different biochar applications (P > 0.05). The further fitting analysis showed that the mean ratio of soil surface crack declined linearly with an increase in the number of moss spores for the B0, B1, B2, and B3 treatments ($R^2 = 0.76, 0.99, 0.25, and 0.59$, respectively) (Fig. 4). The mean soil surface crack ratio increased linearly with an increase in the amount of biochar application for the M1 and M3 treatments ($R^2 = 0.25$ and 0.96,
respectively). Nevertheless, the mean ratio of soil surface crack was not influenced by the biochar application for the M0 and M2 treatments ($R^2 = 0.02$ and 0.08, respectively). It seems that the moss colonization significantly impeded the development of soil surface cracks in most cases, but the effects of biochar application on the development of soil surface cracks could not reach a clear conclusion.

The above fitting results were slightly contradicted the results of the partial correlation analysis. The partial correlation analysis indicated that the biochar application and initial amounts of moss spores did not have significant effect on the development of soil surface cracks (Table 4). This was mainly because the fitting analysis did not considered the effects of moss coverage on the formation of soil surface cracks (see Section 3.1). On the other hand, the ratio of soil surface crack significantly decreased with an increase in the mean atmospheric relative humidity ($pr = -0.18, P < 0.01$), but it significantly increased with an increase in the mean air temperature ($pr = 0.34, P < 0.01$).

Relationship between growth of moss, soil water content and crack development

The ratio of soil surface crack increased significantly with the decreasing soil water content (Fig. S2). The soil water content at the occurrence of cracking was defined as critical water content ($\theta_c$). The $\theta_c$ in the first dry–wet cycle (D–W1) does not synchronize with that in the sixth dry–wet cycle (D–W6). For D–W1, $\theta_c$ varied in the range of 39%–43%. On the other hand, $\theta_c$ ranged from 58% to 64% for all
treatments in D-W6. The most interesting discovery was that the moss growth could impede the formation of soil surface cracks for most dry–wet cycles, except for the first and fourth dry–wet cycles (D–W1 and D–W4) (Fig. 5). The main reason for the exceptions was that the moss coverage in D–W1 was too low to affect the formation of soil surface cracks, whereas the formation of soil surface cracks in D–W4 was inactive owing to the relatively low evaporation losses.

Soil evaporation process

Evaporation processes had gone through a constant rate stage and a falling rate stage in most dry–wet cycles (D–W1, D–W2, D–W3 and D–W5) (Table S1). The evaporation remained at a constant rate stage in D-W4 and D-W6 due to the decreasing atmospheric energy (Fig. S3). Despite the existence of moss colonization and biochar, the cumulative evaporation showed fitting relationships with evaporation time, and $R^2$ ranged from 0.77 to 0.97 (Table S1). For all dry-wet cycles, the lowest soil evaporation was observed in treatment with moss colonization and biochar application. For instance, the value of $\lambda_1$ for B1M1 treatment was the lowest in D–W1, D–W2 and D-W3, which were 5.87, 4.27 and 4.75, respectively. The value of $\lambda_2$ for B1M3 treatment was the lowest in D–W4 and D–W6, which were 0.66 and 0.88, respectively. These results showed that the moss colonization and the biochar application could reduce evaporation losses.

The relative cumulative evaporation $E_c/E_{c0}$ (the ratio of cumulative evaporation $E_c$ to cumulative evaporation of bare soil $E_{c0}$) was calculated to eliminate the
influence of the atmospheric condition. The dynamics of relative cumulative evaporation for the M1, M2, and M3 treatments largely depended on the changes in moss coverage (Fig. S4). For all treatments of moss colonization and biochar application, the $E/E_{c0}$ was significantly lower in D–W6 than D–W1, and the moss coverage was significantly higher in early D–W6 than the initial moment of D–W1 (Fig. 6). In other words, the moss colonization and biochar application over six dry-wet cycles decreasing evaporation losses by 4.9%-28.3%. However, the effects of moss colonization and biochar application on the relative cumulative evaporation were hard to distinguish due to moss coverage was fluctuated in six dry-wet cycles.

The further fitting analysis indicated that moss colonization and biochar application could decrease greatly evaporation losses. The fitting analyses showed that the relative cumulative evaporation linearly decreased with an increase in moss coverage for the B0, B1, B2, and B3 treatments ($R^2 = 0.34, 0.44, 0.46, \text{ and } 0.49$, respectively) (Fig. 7). The relative cumulative evaporation for different biochar applications (B0, B1, B2, and B3) decreased with increasing moss coverage by 27.07%, 40.69%, 37.73%, and 31.37%, respectively. The relative cumulative evaporation was 1 as the moss coverage reached a critical value. In other words, the moss enhanced the evaporation losses when the moss coverage was below the critical value, and reduced the evaporation losses when the moss developed to the critical moss coverage. The critical moss coverage was 4.51%, 2.51%, 3.01%, and 0% for B0, B1, B2 and B3 treatments, respectively. The critical moss coverage decreased with the
increasing biochar dosage even further to 0 percent. Partial correlation analyses indicated that the mean evaporation rate significantly increased with air temperature, the initial moss spore amount, and soil water content (pr = 0.42, 0.11, and 0.12, respectively) (Table 4). Moss coverage reduced significantly the mean evaporation rate with a partial correlation of -0.21. These results showed that the effects of moss colonization on evaporation losses were strengthened by the biochar application reduced critical moss coverage.

Surface temperature field

The comparison of the surface temperature during six dry–wet cycles under moss colonization and biochar application is shown in Fig. 8. The difference of surface temperature between moss cover and bare soil \((T_{moss}-T_{bare-soil})\) in the D–W1 are less than zero. Moss colonization with biochar application at D–W1 decreased the soil surface temperature by 0.21, 0.56, 0.48 and 0.55 °C respectively. The values of \(T_{moss}-T_{bare-soil}\) became more than zero from D–W2 to D–W6 when the mature moss was observed. These results indicted that mature moss increased the soil surface temperature.

Partial correlation analyses indicated that the mean surface temperature significantly increased with increasing moss coverage (pr = 0.11 P < 0.01) and air temperature (pr = 0.43, P < 0.01). However, the mean surface temperature not significantly affected by the biochar application (pr = 0.01 P > 0.05) (Table 4). These results indicated that the of mature moss on the surface temperature significantly
increased the soil surface temperature, and the effects of the moss on the surface temperature were not largely affected by the biochar.

Evaporation estimation considering the role of moss colonization

Fig. 7 suggests that there was a linear relationship between $E_c/E_{c0}$ and $M_c$. One variation in this relationship was to formulate an equation between $E_c$ and $M_c$. Table 3 shows that the moss growth could be unraveled by a logistic growth equation. The combination of the two equations allows us to predict the effects of moss colonization on soil evaporation, and the model performances are shown in Table 3. The $R^2$ values ranged from 0.94 to 0.99, and the RMSE values varied between 0.16 and 0.43. These results showed that the combination of the two equations worked very well in 62.5% of all treatments with a low RMSE of less than 0.30. The combination of the two equations was an attempt to address the challenges in simulating the effects of moss growth on evaporation processes in carbonate-derived laterite. However, further work is needed to reduce the inaccuracy in the remaining 37.5% of treatments.

Discussion

Shifting relationships among moss colonization, biochar application, and soil evaporation

The effects of moss colonization and biochar application on the evaporation process of carbonate-derived laterite during the dry–wet cycles could originate from three important “dynamics”: (1) dynamics of moss coverage due to dry–wet cycles, (2)
dynamics of soil surface cracks owing to the influences of biochar application and
growth of moss, and (3) dynamics of surface temperature due to moss cover.

**Dynamics of moss coverage due to dry–wet cycles.** This study indicated that
the growth trend of artificially cultivated moss was classically vulnerable to dry–wet
cycles (Fig. 2). Moss coverage could reach only 25% after approximately 13 weeks
when the moss had suffered six dry–wet cycles. This result was very similar to the
conclusions by Antoninka et al. (2015). However, Zhao et al. (2014) showed that
moss coverage linearly increased in a well-hydrated greenhouse, and reached more
than 65% after only weeks. The main reason for the difference was probably that
moss colonization was largely restricted in serious water scarce conditions, and the
moss could reproduce very quickly under wetting conditions (Wei et al. 2010).
Another possible reason is that the artificial moss differed in shapes and species from
wild moss (Xiao et al. 2011), and thus the adaptation of artificial moss to the soil
water deficit was weaker than that of wild moss. What is new is the urgent need to
scale up this technology to accommodate the field scale, such as the field of rocky
desertification regions.

**Dynamics of soil surface cracks owing to the influences of biochar
application and moss growth.** Moss coverage reduced significantly soil surface
cracks (Figs. 4 and 6). Moss crusts significantly enhanced the water retention
characteristics in shallow soils (Mager et al. 2011; Chamizo et al. 2012; Xiao et al.
2016), which probably restrained the development of soil surface cracks. Although
biochar application had no direct influence on soil surface crack development, and biochar could inhibit slightly the growth of moss during the dry–wet cycles (Fig. 2 and 3). Normally, difference in matrix potential among soil materials leads to the development of cracks on the soil surface (Chen et al. 2019). Biochar in soil materials can change the soil cohesive power to affect the desiccation cracking characteristics of clay (Zhang et al. 2020). The development of soil surface cracks has several negative impacts, such as threatening soil stability and facilitating evaporation and infiltration (Wan et al. 2019; Poulsen, et al. 2020). However, unexpectedly, our results showed that the biochar played no direct role in soil surface crack under moss cover (Table 4). This may be due to the moss affected swelling–shrinkage characteristics of carbonate-derived laterite. The effects of the swelling–shrinkage on the development of soil surface cracks outperformed those of biochar applications (Zong et al. 2014; Zhang et al. 2020).

**Dynamics of surface temperature due to moss cover.** The mature moss had a considerable heat preservation effect on carbonate-derived laterite, which was indicated by the clear differences in surface temperature between soil and moss ($T_{moss} - T_{bare\ soil}$) (Fig. 8). This result was consistent with our previous finding, that moss crusts could increase the surface temperature of soil column by changing the soil surface reflectivity (Liu et al. 2020). However, this result was different from the results reported by Xiao et al. (2016), that moss crust could reduce significantly the underlying soil temperature by up to 11.8 °C in summer in semi-arid regions. The
most likely reason for this is that the moss was able to adapt to the diurnal temperature variations for survival. Another possible reason was that moss coverage increased the soil water content during the dry–wet cycles (pr = 0.48, P < 0.01) (Table 4). The moss crust can reserve soil water, and soil water can delay the decrease in soil temperature (Kidron et al. 2012; Chamizo et al. 2013). As the soil evaporates, the soil layer becomes dry, and water in the soil becomes a prime factor affecting the soil temperature (Liu et al. 2020).

In response to this, we drew a mind map of the effects of moss colonization and biochar application on the evaporation losses of carbonate-derived laterite, and constructed a SEM based on the mind map and partial correlation analyses (Fig. 9).

Moss colonization and biochar application played an important role in evaporation processes in three primary ways. First, the increase of initial amount of moss spores promotes the growth of moss (pr = 0.64, P < 0.01), but biochar application reduced slightly moss coverage (pr = -0.11, P < 0.01). Second, moss covers promoted the development of soil surface cracks (pr = -0.13, P < 0.05), and the increasing soil surface cracks enhanced evaporation losses (pr = 0.32, P < 0.01). Moreover, the moss decreased evaporation losses by reserving soil water content (pr = 0.47, P < 0.05), and the increasing soil water underlying the moss layer decreased evaporation losses (pr = -0.21, P < 0.05). Finally, the moss increased soil surface temperature (pr = 0.11, P < 0.01), and the increasing soil surface temperature enhanced evaporation loss (pr = 0.28, P < 0.01). In addition, our SEM explained 71% of variation in soil evaporation
under moss colonization and biochar application. Moss spores (standardized coefficients = 0.48, P < 0.001) and soil water content (standardized coefficients = 0.6, P < 0.001) had positive effects on moss growth. Atmospheric humidity (standardized coefficients = -0.12, P < 0.001) and atmospheric temperature (standardized coefficients = -0.37, P < 0.001) had negative effects on moss growth. Moss (standardized coefficients = -0.98, P < 0.001) and biochar (standardized coefficients = -0.17, P < 0.001) had negative effects on soil evaporation.

Implications for and limitations to field situations

The prospect of applying moss colonization to hold water in karst lands is promising. Moss colonization could help to create supplementary approach during the high-cost afforestation in karst lands. The results of this study showed that growing moss significantly increased soil water holding capacity by reducing evaporation losses. In addition, as confirmed by the different slopes of the linear fitting equations, and the role of moss in reducing soil evaporation could be slightly enhanced by biochar application (Fig. 6 and 7). One of the most important findings in this study is that moss colonization could inhibit significantly surface crack development of carbonate-derived laterite (Fig. 3–5). This means that soil surfaces without moss colonization behave in completely different ways from those that retain them.

Our results shows that moss growth is not merely linear and irreversible, but that the moss can degrade after drying and recover after wetting. The relationship between moss growth and soil evaporation, therefore, fluctuates (Fig. 2). In Chen et al.’s (2018)
study, however, the model hypothesis was that moss coverage was always increasing and did not respond to natural disturbances (that is, dry–wet cycles). Therefore, the response of moss coverage to water stress should be considered in the eco-hydrology model to improve accuracy.

If moss colonization was used as a supplementary approach to afforestation in karst lands, the dynamic and ever-shifting relationships between moss growth and soil evaporation under dry–wet cycles should be emphasized. First, this study showed that moss growth was highly vulnerable to water deficits, especially in their early stages (Fig. 3). Therefore, the dampening effects of moss colonization on soil evaporation performed poorly with low coverage but worked well with high coverage (Fig. 7). A few previous studies have discussed the effects of biocrust with a high moss coverage (60% or 75%) on soil water movement (Berdugo et al., 2014; Zhao et al., 2014). However, moss coverage in this study was only up to 25%, due to cultivation time. It is also important that these findings be extended to other moss species. *Hypnum Hedw.*, which was used in this study, might be unique, or it might represent a broader pattern among other moss species. Previous experiments and this study had ignored the moss transpiration due to the limitation of measurement method (Table 1). More measurement method should be performed for distinguishing between evapotranspiration and soil evaporation in future research. In addition, the usage of moss colonization might be limited to the shallow soil, making it difficult to
contribute significantly to deep soil in rocky desertification land (Xiao et al. 2014; Chen et al. 2019; Liu et al. 2020).

Conclusions

The effects of moss colonization and biochar application on the evaporation processes of carbonate-derived laterite were studied using four moss spore amounts (0, 30, 60, and 90 g·m⁻²) and four biochar application levels (0, 100, 400, and 700 g·m⁻³) during six dry–wet cycles. The following results regarding the effects of moss colonization and biochar application were obtained: 1) The increase of initial amount of moss spores promotes the growth of moss (pr = 0.64), but biochar application reduced slightly moss coverage (pr = -0.11); 2) Moss colonization decreased clearly soil surface cracks (pr = -0.13), whereas biochar application had no distinguishable influences on soil surface cracks (P > 0.05); 3) The relative cumulative evaporation for the different biochar applications decreased with increasing moss coverage by 27.07%, 40.69%, 37.73%, and 31.37%, respectively. Biochar application reduced critical moss coverage associated with inhibition of evaporation by 33.26%-44.34%; 4) The mean surface temperature increased with an increase in the moss coverage (pr = 0.11); 5) A simplified empirical evaporation model could accurately estimate the evaporation losses that were affected by the moss colonization and biochar application, and the R² values ranged from 0.94 to 0.99.

These results suggested that moss colonization and biochar application played an important role in evaporation processes in three primary ways. The artificially
cultivated moss, which was induced by moss spores and biochar, could decrease soil evaporation by reducing soil surface cracks, increasing soil moisture and soil surface temperature. It was concluded that the combination of moss colonization and small amount biochar could be used as a supplementary approach to facilitate soil water preservation in karst lands. However, there are still many questions to be answered in future studies, including the role of moss colonization in the whole karst hydrology (that is, infiltration, interception, runoff, and soil erosion).
Acknowledgments

We acknowledge and are grateful for the financial support provided by the National Natural Science Foundation of China through grant no. 41807016, the Guizhou Science and Talent Project ([2020]4Y010), the Science and Technology Funding of Guizhou Provincial Water Resources Department KT201803, the first class subject foundation of Guizhou Province (GNYL[2017]007) and the Guizhou Province Graduate Research Fund YJSCXJH[2020]094.
Conflict of interest

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

Antoninka A, Bowker MA, Reed SC, Doherty K (2015) Production of greenhouse-grown biocrust mosses and associated cyanobacteria to rehabilitate dryland soil function. Rest Ecol 24:324-335

Berdugo M, Solivieres S, Maestre FT, (2014) Vascular plants and biocrusts modulate how abiotic factors affect wetting and drying events in dry lands. Ecosystems 17:1242-1256

Chamizo S, Cantón Y, Lázaro R, Domingo F (2013) The role of biological soil crusts in soil moisture dynamics in two semiarid ecosystems with contrasting soil textures. J Hydrol 489:74-84

Chamizo S, Cantón Y, Miralles I, Domingo F (2012) Biological soil crust development affects physicochemical characteristics of soil surface in semiarid ecosystems. Soil Biol Biochem 49:96-105

Chen K (2019) Evolution law of fissures of red clay slope under dry-wet cycles J Journal of Architecture and Civil Engineering. 36:52-61

Chen N, Wang X, Zhang Y, Yu K, Zhao C (2018) Ecohydrological effects of biological soil crust on the vegetation dynamics of restoration in a dryland ecosystem. J Hydrol 563:1068-1077

Ding YL, Zhou YC (2019) Study on the coupling relationship between slope-soil thickness and rock exposed ratio in small karst watershed. Chinese Journal of Soil Science 5:51-59

Felde VJMLN, Chamizo S, Felix-Henningsen P, Drahorad SL (2018) What stabilizes biological soil crusts in the Negev Desert? Plant soil 29:9-18.

Gao LQ ,Zhao YG, Qin NQ, Zhang GX, Yang K (2012) Impact of Biological Soil Crust on Soil Physical Properties in the Hilly Loess Plateau Region China. Journal of Natural Resources 27:1316-1326

Jiang ZY , Li XY , Wei JQ, Chen HY, Li ZC, Liu L, Hu X (2018) Contrasting surface soil hydrology regulated by biological and physical soil crusts for patchy grass in the high-altitude alpine steppe ecosystem. Geoderma 326:201-209

Kidron GJ, Vonshak A (2012) The use of microbiotic crusts as biomarkers for ponding subsurface flow and soil moisture content and duration. Geoderma 181:56-64

Kidron GJ, Tal SY (2012) The effect of biocrusts on evaporation from sand dunes in the Negev Desert. Geoderma 179 104-112.

Lei WJ, Zhou XY (2019) Influence of biochar on migration of pesticide degradation product trichloro pyridinol in soil. Transactions of the Chinese Society of Agricultural Engineering 35:173-180

Li D, Yang B, Gao Z, Sun LX (2021) The effects of biomass ash on soil evaporation and cracking. Arab J Geosc 14:1-11

Li B, Zhang Z (2009) Species diversity of mosses crust and the effect in karst rocky
desertification control. Carsologica Sinica 28:55-60

Li Y, Piao S, Li LZ, Chen A, Wang X, Ciais P, Wang K (2018) Divergent hydrological response to large-scale afforestation and vegetation greening in China. J Sci Adv 4 https://doi.org/10.1126/sciadv.aar4182

Liu D, She D (2020) Combined effects of moss crusts and pine needles on evaporation of carbonate-derived laterite from karst mountainous lands. J Hydrol https://doi.org/10.1016/j.jhydrol.2020.124859

Liu M, Xu X, Wang D, Sun AY, Wang K (2016) Karst catchments exhibited higher degradation stress from climate change than the non-karst catchments in southwest China: An ecohydrological perspective. J Hydrol 535:173-180

Mager DM, Thomas AD (2011) Extracellular polysaccharides from cyanobacterial soil crusts: a review of their role in dryland soil processes. J Arid Environ 75:91-97

Meng X, Yuan W (2014) Can biochar couple with algae to deal with desertification? Journal of Sustainable Bioenergy Systems 4:194-198

Ni A, Chao ST, Shi KX, Xue PG, Bin S, Hilary II (2018) Effects of soil characteristics on moisture evaporation. Eng Geol 239:126-135

Poulsen TG, Cai W, Garg A (2020) Water evaporation from cracked soil under moist conditions as related to crack properties and near-surface wind speed. J Eur J Soil Sci 71:627-640

Swaffer BA, Holland KL (2015) Comparing ecophysiological traits and evapotranspiration of an invasive exotic Pinus halepensis in native woodland overlying a karst aquifer. Ecohydrology 8:230-242

Tang CS, Cui YJ, Shi B, Tang AM, Liu C (2011) Desiccation and cracking behaviour of clay layer from slurry state under wetting–drying cycles. Geoderma 166:111-118

Tang CS, Shi B, Liu C, Suo WB, Gao L (2011) Experimental characterization of shrinkage and desiccation cracking in thin clay layer. Appl Clay Sci 52:69–77

Thomas SC, Frye S, Gale N, Garmon M, Launchbury R, Machado N, Melamed S, Murray J, Petroff A, Winsborough C (2013) Biochar mitigates negative effects of salt additions on two herbaceous plant species. J Environ Manage 129:62-68

Wan Y, Wu C, Xue Q, Hui X (2019) Effects of plastic contamination on water evaporation and desiccation cracking in soil. Sci Total Environ 654:576-582

Wang C, Zhang ZY, Liu Y, Fan SM (2017) Geometric and fractal analysis of dynamic cracking patterns subjected to wetting-drying cycles. Soil Till Res 170:1-13

Wang T, Stewart CE, Sun C, Wang Y, Zheng J (2018) Effects of biochar addition on evaporation in the five typical Loess Plateau soils. Catena 162:29-39

Wang QX, Ju MC, Bu CF (2019) Effects of bacillus and a plant growth regulator for provenance propagation of moss biocrusts. Bulletin of Soil and Water Conservation 39:166-171

Wei ML, Zhang YM (2010) Effects of dehydration on photosynthetic pigment content
and chloroplast ultrastructure of Syntrichia caninervis in biological soil crusts. Journal of Desert Research 30:1311-1318

Wu K, Darcet D, Wang Q, Sornette D (2020) Generalized logistic growth modeling of the COVID-19 outbreak in 29 provinces in China and in the rest of the world.

Xiao B, Hu K, Ren T, Li B (2016) Moss-dominated biological soil crusts significantly influence soil moisture and temperature regimes in semiarid ecosystems. Geoderma 263:35-46

Xiao B, Sun F, Hu K, Kidron GJ (2019) Biocrusts reduce surface soil infiltrability and impede soil water infiltration under tension and ponding conditions in dryland ecosystem. Journal of Desert Research 30:1311-1318

Xiao B, Wang QH, Zhao YG, Shao MA (2011) Artificial culture of biological soil crusts and its effects on overland flow and infiltration under simulated rainfall. Appl Soil Ecol 48:11-17

Xiao B, Zhao YG, Shao MA (2010) Characteristics and numeric simulation of soil evaporation in biological soil crusts. J Arid Environ 74:121-130

Xiao B, Zhao Y, Wang Q, Li C (2015) Development of artificial moss-dominated biological soil crusts and their effects on runoff and soil water content in a semi-arid environment. J Arid Environ 117:75-83.

Xiao H, Xiong K, Zhang H, Zhang Q (2014) Research progress for karst rocky desertification control models China. Population Resources and Environment 163:330-334

Xie SQ, Gao LQ, Zhao YG, Guo YW (2019) Responses of runoff and soil loss from biological soil crustal slope to rainfall intensity under simulated rainfall. Chinese Journal of Applied Ecology 30:391-397

Yang J, Xu X, Liu M, Xu C, Zhang Y, Luo W, Zhang R, Lia X, Kiely G, Wang K (2017) Effects of “Grain for Green” program on soil hydrologic functions in karst landscapes southwestern China. Agr Ecosyst Environ 247:120-129

Yang YS, Bu CF, Gao GX (2012) Effect of biological soil crust on soil temperature in the Mu Us sand land. Arid Zone Res 29:352-359

Zhang J, Qun CHEN, Changfu YOU (2016) Biochar effect on water evaporation and hydraulic conductivity in sandy soil. Pedosphere 26:265-272

Zhang R, Xu X, Liu M, Zhang Y, Xu C, Yi R, Luo W (2018) Comparing evapotranspiration characteristics and environmental controls for three agroforestry ecosystems in a subtropical humid karst area. J Hydrol 563:1042-1050

Zhang Y, Gu K, Li J, Tang C, Shen Z, Shi B (2020) Effect of biochar on desiccation cracking characteristics of clayey soils. Geoderma 364

Zhao Y, Zhu Q, Li P, Zhao L, Wang L, Zheng X, Ma H (2014) Effects of artificially cultivated biological soil crusts on soil nutrients and biological activities in the Loess Plateau. J Arid Land 6:742-752

Zhou B, An H (2012) Research on problem of water resources security in guizhou and its strategic solutions. Research of Agricultural Modernization 33:19-24

Zong Y, Chen D, Lu S (2014) Impact of biochars on swell-shrinkage behavior
mechanical strength and surface cracking of clayey soil. J Plant Nutr Soil Sci 177:920-926
Table 1 Summary of previous studies contact with the effects of different types additive (organic and inorganic) in shallow soil on evaporation processes, surface cracks and soil temperature.

| Reference                  | Types of additives | Experimental designs                      | Scale                  | Soil thickness | Experimental methods                                                                 | Effect on Evaporation | Effect on Soil surface crack | Soil temperature | Soil          |
|----------------------------|--------------------|------------------------------------------|------------------------|----------------|---------------------------------------------------------------------------------------|------------------------|-----------------------------|------------------|---------------|
| Li et al., 2021            | Biomass ash        | Open plexiglass container                | 4 cm height × 18 cm diameter | 4 cm           | 1) Automatic weighing and photographing system investigated soil evaporation and crack 2) Digital image processing technology to identify crack | Evaporation might be decreased by increased resistance of water migration in soil | Biomass ash can effectively reduce soil surface crack | /                | Clay          |
| Zhang et al., 2020         | Biochar            | Square plexiglass container              | 20 × 20 × 1 cm          | 1 cm           | 1) High-precision (0.01g) electronic balance record the evaporation                    | Soil surface crack was inhibited by biochar of occupying soil shrinkage space | /                | Clay            |
| Wang et al., 2019          | Plastic film       | Copper tray                               | 3 cm height × 22 cm     | 3 cm           | 1) Oven at 60℃ measure soil water                                                    | Plastic film in soil might form covers to Plastic film in soil strengthens | /                | Clay            |
| Study              | Material                 | Diameter          | Height          | Width                     | Equipment                         | Method | Soil Type          |
|--------------------|--------------------------|-------------------|-----------------|---------------------------|-----------------------------------|--------|-------------------|
| Jiang et al., 2018 | Biocrust PVC cylinder    | 6 cm height × 6 cm diameter | 6 cm            |                           | High-precision (0.01g) electronic balance record the evaporation | 2) High-definition camera + Digital image processing technology (Matlab 2010b) inspect surface crack | / | Silt-loam          |
| Ni et al., 2018    | Quartzite Cylindrical evaporator | 0.7, 1.4, 2.1 and 2.8 cm height × 6.18 cm diameter | 0.7-2.8 cm      |                           | 1) High-precision electronic balance record the evaporation | / | /                |
| Wang et al., 2018  | Biochar PVC cylinder     | 10 cm height × 10 cm diameter | 10 cm           |                           | High-precision (0.01g) electronic balance record the evaporation | / | /                |
| Zribi et al., 2015 | Plastic, pine bark tray and wheat and microlysimeters | 29 cm × 19 cm × 5 cm × 10 cm | 5 cm × 10 cm    |                           | High-precision (0.01g) electronic balance record the evaporation | / | /                |
| Study                | Biocrust Type | Measurement Tools                          | Observations                                                                 |
|---------------------|---------------|--------------------------------------------|-----------------------------------------------------------------------------|
| Chamizo et al., 2012| Biocrust      | Polyvinyl chloride microlysimeters         | Straw height × 7.6 cm diameter, meteorological and experimental conditions and evaporation stage |
| Kidron et al., 2012 | Biocrust      | Petri dishes                              | Effect of different biocrusts on soil evaporation was not significant in the case of low water content |
| Xiao et al., 2010   | Biocrust      | PVC micro-lysimeters                       | High-biomass biocrust could retain more water to decrease evaporation      |
|                     |               |                                            | Effects of biocrust on evaporation were dependent on soil properties       |

- 1) Terrestrial laser scanner (Leica Scan Station 2) + software (SAGA 2.0.5) investigate soil surface roughness
- 2) High-precision (0.01g) electronic balance record the evaporation

- Biocrust increased soil subsurface temperature
- Biocrust decreased soil surface temperature
Table 2 Basic properties of carbonate-derived laterite, moss spore and biochar used in this study.

| Property                  | Unit     | Value               |
|---------------------------|----------|---------------------|
| Textural class            |          | Silt loam           |
| Organic matter content    | g kg⁻¹   | 51.60±0.33          |
| EC₁:₅                     | us cm⁻¹  | 232.22±14.35        |
| Soil                      |          |                     |
| Bulk density              | g cm⁻³   | 1.28-1.35           |
| pH                        |          | 5.56±0.15           |
| θ₀                        | g g⁻¹    | 0.15                |
| Clay (< 2 μm)             | %        | 1.25±0.36           |
| Silt (2-50 μm)            | %        | 77.48±0.51          |
| Sand (> 50 μm)            | %        | 21.28±0.82          |
| Moss spore                |          |                     |
| Main species              |          | Hypnum Hedw         |
| Manufacturer              |          | Cao Mu Ji Plant Research Center, China |
| Pyrolysis temperature     | °C       | 450-550             |
| Biochar                   |          |                     |
| EC₁:₅                     | us cm⁻¹  | 1149±31             |
| pH                        |          | 10.32±0.03          |
| Manufacturer              |          | Li Zhe Environmental Technology, China |

Textural class based on the USDA classification, θ₀: initial gravimetric soil water content, EC₁:₅: soil electrical conductivity of a 1:5 soil-to-water extra.
**Table 3** Equations for estimating growth of moss and soil evaporation loss.

| Treatment | Moss spore (g m\(^{-2}\)) | Biochar application (g m\(^{-3}\)) | Step: \( M_c = \frac{M}{1 + be^{-kt}} \) | Step: \( E_c = E_{c0}(aM_c + c) \) |
|-----------|-----------------------------|----------------------------------|----------------------------------|----------------------------------|
|           |                             |                                  | \( M \)   | \( b \)   | \( k \)   | RMSE   | \( R^2 \) | \( a \)   | \( c \)   | RMSE   | \( R^2 \) |
| B0M1      | 30                          | 0                                | 0.11    | 22.72    | 0.07    | 0.04    | 0.66    | -0.24    | 1.00    | 0.20    | 0.98    |
| B0M2      | 60                          | 0                                | 0.09    | 19.85    | 0.07    | 0.04    | 0.61    | -0.12    | 1.01    | 0.16    | 0.99    |
| B0M3      | 90                          | 0                                | 0.17    | 21.78    | 0.09    | 0.16    | 0.60    | -0.27    | 0.99    | 0.29    | 0.97    |
| B1M1      | 30                          | 100                              | 0.07    | 23.71    | 0.07    | 0.02    | 0.69    | 0.14     | 0.94    | 0.43    | 0.94    |
| B1M2      | 60                          | 100                              | 0.11    | 21.13    | 0.08    | 0.06    | 0.66    | -0.17    | 1.02    | 0.25    | 0.98    |
| B1M3      | 90                          | 100                              | 0.15    | 18.44    | 0.06    | 0.09    | 0.74    | -0.50    | 0.98    | 0.38    | 0.95    |
| B2M1      | 30                          | 400                              | 0.06    | 21.13    | 0.07    | 0.02    | 0.63    | -0.14    | 0.97    | 0.38    | 0.96    |
| B2M2      | 60                          | 400                              | 0.12    | 35.60    | 0.09    | 0.06    | 0.73    | -0.09    | 1.01    | 0.29    | 0.97    |
| B2M3      | 90                          | 400                              | 0.13    | 24.71    | 0.07    | 0.08    | 0.71    | -0.43    | 1.02    | 0.34    | 0.97    |
| B3M1      | 30                          | 700                              | 0.12    | 24.68    | 0.04    | 0.02    | 0.63    | 0.18     | 1.04    | 0.31    | 0.98    |
| B3M2      | 60                          | 700                              | 0.10    | 20.88    | 0.08    | 0.05    | 0.60    | 0.52     | 1.01    | 0.29    | 0.98    |
| B3M3      | 90                          | 700                              | 0.15    | 54.27    | 0.10    | 0.11    | 0.69    | 0.01     | 1.01    | 0.35    | 0.96    |

*Note:* \( E_{c0} \): evaporation of bare soil; \( E_c \): daily evaporation of soil under different moss cover; \( SWC_{mean} \): mean gravimetric soil water content; \( M_c \): moss coverage; \( M \): maximum moss coverage after growth; \( b \): time for mutation of growth rate; \( k \): growth rate corresponding to maximum moss coverage; \( t \): growth time; \( a \) and \( c \): evapotranspiration empirical coefficients considering mossy and biochar effects.
Table 4 Partial correlations between soil evaporation and environmental factors.

| Partial correlation | \( M_c \) (%) | \( R_c \) (%) | \( T_{soil\ surface} \) (℃) | \( SWC_{mean} \) | \( E \) (mm day\(^{-1}\)) |
|---------------------|---------------|---------------|-----------------------------|-----------------|-----------------|
| Biochar application (g cm\(^{-3}\)) | -0.11** | -0.22 | 0.01 | 0.07 | 0.01 |
| Moss spores (g m\(^{-2}\)) | 0.64** | -0.01 | 0.12* | 0.03 | 0.11* |
| \( SWC_{mean} \) (g g\(^{-1}\)) | 0.48** | -0.58** | 0.36** | / | 0.12* |
| \( M_c \) (%) | / | -0.13* | 0.11** | 0.48** | -0.22** |
| \( R_c \) (cm\(^2\) cm\(^{-2}\)) | -0.13* | / | 0.19** | -0.37** | 0.32** |
| \( T_{air} \) (℃) | -0.24** | 0.34** | 0.43** | -0.49** | 0.42** |
| \( RH_{mean} \) (-) | -0.33** | -0.18** | -0.16** | -0.13** | 0.09* |

\( SWC_{mean} \): mean soil water content at dry process; \( T_{soil\ surface} \): mean soil surface temperature in 12:00 (℃); \( T_{air} \): mean air temperature (℃); \( RH_{mean} \): mean atmospheric relative humidity; \( M_c \): coverage of moss (%); \( R_c \): mean soil surface crack ratio (%); \( E \): daily mean evaporation rate (mm day\(^{-1}\)); Significant at *P < 0.05, **P < 0.01.
Fig. 1 Soil collection site in Huaxi District, Guizhou Province, China (a), Landscape covered by moss in karst mountainous lands (b), an evaporation experiment in microlysimeter during six dry–wet cycles.
Fig. 2 Moss coverage versus time for different amounts of biochar application (B0, B1, B2 and B3) and moss spore (M1, M2 and M3) during six drying-wetting cycles. D-W1, D-W2, D-W3, D-W4, D-W5 and D-W6 represent the first, second, third, fourth, fifth, and sixth dry-wet cycle, respectively. Note that no growth of moss occurred in M0 treatments.
Fig. 3 Mean soil surface crack ratio versus dry-wet cycle for different amounts of moss spore (M0, M1, M2 and M3) and biochar application (B0, B1, B2 and B3).
Fig. 4 Mean soil surface crack ratio ($R_{cr}$) during the whole experimental duration for different amounts of moss spore (M0, M1, M2 and M3) and biochar application (B0, B1, B2 and B3).
Fig. 5 Relationships of mean soil surface crack ratio and moss coverage for each dry-wet cycle.
Fig. 6 Relative cumulative evaporation ($E_c/E_{c0}$, -) versus evaporation time for different amounts of moss spores (M0, M1, M2 and M3) and biochar applications (B0, B1, B2 and B3) during D-W1 and D-W6. Relative cumulative evaporation ($E_c/E_{c0}$, -) was calculated as the ratio of cumulative soil evaporation ($E_c$, mm) for all treatments to cumulative bare evaporation ($E_{c0}$, mm) for B0M0 treatment.
**Fig. 7** Relative cumulative evaporation ($E_c / E_{c0}$, -) versus moss coverage (%) for different biochar applications (B0, B1, B2 and B3) for all six dry-wet cycles. Relative cumulative evaporation ($E_c / E_{c0}$, -) was calculated as the ratio of cumulative soil evaporation ($E_c$, mm) for all treatments to cumulative bare evaporation ($E_{c0}$, mm) for B0M0 treatment.
Fig. 8 Difference between Soil surface temperature with moss and bare soil temperature ($T_{moss} - T_{bare-soil}$) at 12:00 versus moss spores for different biochar applications (B0, B1, B2 and B3) during the all dry-wet cycles.
Fig. 9 Schematic or mind map about the effects of initial moss spores amounts, moss coverage and biochar application on soil evaporation processes of carbonate-derived laterite during dry-wet cycles. Numbers adjacent to arrows are standardized path coefficients of the relationship. $R^2$ = the proportion of variance explained. P values are as follows: * < 0.05; ** < 0.01; *** < 0.001. Blue and red lines are positive and negative relationships, respectively.
Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementarydata2021.11.23.docx