Effect of biocrusts on profile distribution of soil water content and salinity at different stages of evaporation

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ABSTRACT

In this study, the effect of biocrusts on daily variations of evaporation in soils of an arid rangeland was investigated during 142 days. Temporal and spatial variations of soil water and solute content were analyzed in three times of 17, 50 and 103 days, and four depths of 10, 20, 30 cm and 40 cm in six columns (20 cm diameter × 50 cm height) containing biocrusts (43 cm saline soil + 5 cm biocrusts) and four columns filled with bare soil (48 cm saline soil) respectively. Temporal variation of evaporation rate was supposed as a 3-stages process. Results showed that stage 1 and stage 2 are not distinguishable. We further found that, compared to bare soil, the biocrusts retarded water evaporation from soil surface (24 vs. 30 mm and 34 vs. 44 mm after 17 and 50 days respectively), and reduced solute accumulation in top soil, especially in the stage 2 of evaporation process (5 vs. 8 dS/m and 13 vs. 20 dS/m after 17 and 50 days respectively). The effect of biocrusts on the evaporation rate at the stage 3 of evaporation was not significant (9 vs. 9 mm after 103 days). Reduction of evaporation by biocrusts resulted in less soil salinity within entire soil profile. The effects of biocrusts on evaporation reduction are attributed to i) the biocrusts create mats on the soil surface, and swelling of mats blocks the soil pores in wet condition, and ii) the large pores of biocrusts disrupt the hydraulic connectivity between topsoil and subsoil, which minimizes the capillary rise. Since major part of water is evaporated during stage 2, and is controlled by water flow within the soil and at the surface, so conservation of the BSCs would be important for preserving hydrological functions advantage such as reducing evaporation and enhancing water retention in the salt affected and dry soils.

1. Introduction

Water scarcity is a key limiting factor in arid environments, which constitutes more than 40% of the earth’s terrestrial surface (Warren, 2003; Belnap et al., 2016; Eldridge et al., 2020). In these environments, high evaporation is one of the important factors leading to soil water depletion, particularly where precipitation is very low (Chamizo et al., 2013b; Ding and Eldridge, 2020). Climate condition and soil hydraulic properties are important factors that control the soil evaporation rate (Xiao et al., 2010). Evaporation rate is also influenced by coverage of soil surface, especially vegetation cover, and other organic compounds such as biocrusts (BSCs) (Chamizo et al., 2013a). BSCs are complex communities of cyanobacteria, algae, fungi, lichens and mosses with soil particles, developing in first centimeters of the topsoil (Belnap et al., 2016). The BSCs create a living film on the soil surface and modify the inputs, losses, and transfer of material and energy between atmosphere and soil (Belnap et al., 2003, 2005, 2016). BSCs can influence many physical and hydrological properties of soil including surface micro-topography (Rodriguez-Caballero et al., 2012), porosity (Miralles Mellado et al., 2011), water absorption and retention (Chamizo et al., 2016; Eldridge et al., 2020), soil aggregation and stability (Belnap and Büdel, 2016; Chamizo et al., 2012b; Veluci et al., 2006), infiltration (Belnap, 2006; Chamizo et al., 2016) and evaporation (Chamizo et al., 2016; Benard et al., 2019). BSCs not only modify soil surface properties,
but also change many subsurface soil properties via affecting the hydrological characteristics (Belnap, 2006). Chamizo et al. (2016) reviewed the contradictory results of many researchers and concluded that the influence of BSCs on infiltration, runoff, and evaporation is complicated. Association of BSCs with soil particles and swelling of exopolysaccharides and physical structures such as thalli of lichens in BSCs can decrease evaporation through sealing the soil surface and clogging soil pores (Fischer et al., 2010; Chamizo et al., 2013a; Colica et al., 2014). However, in many cases, they can increase evaporation through reducing albedo coefficient, especially by dried mosses, which enhances soil surface roughness and evaporation surface area (Belnap et al., 2005; Chamizo et al., 2013a, 2016; Li et al., 2016). The effect of BSCs on soil evaporation depends on evaporation phase (Chamizo et al., 2019), it can highly influence accumulation of solute on the soil surface. This process can result in formation of saline boundary layer on the soil surface (Geng and Boufadel, 2015) which prevents plant establishment and degrades soil quality (Liu et al., 2013). However, there are some evidences that soil covered by BSCs is less prone to salinization compared to bare soil (Jiang et al., 2018; Kakeh et al., 2018, 2020). Although some researchers of found that the BSCs have a positive effects on most soil chemical properties such as soil pH (Concostrina-Zubiri et al., 2013), nutrient and carbon cycling (Chamizo et al., 2012b; García-Carmona et al., 2020), microelement availability (Bidwell et al., 2019; García-Carmona et al., 2020; Moreno-Jiménez et al., 2020), composition and concentration of soil solution (Abed et al., 2013; Jiang et al., 2018; Kakeh et al., 2020), but direct effects of BSCs on soil accumulation in natural arid and semi-arid environments have not been studied adequately (Liu et al., 2019). The objective of this study is to investigate the function of BSCs in i) daily variations of soil water evaporation as one of the key elements of water cycle in arid and semi-arid environments, and ii) temporal and spatial variations of solute and water in three specific times and four depths of soil profile. We hypothesized that BSCs would influence on soil solute and water dynamics through decreasing the evaporation rate.

2. Materials and methods

2.1. Study area and characteristics

Soil samples were collected from a soil with BSCs located in Qara Qir rangelands around Alagol Lake, Northern Iran (37°15’ and 37°23’ N and 54°33’ and 54°39’ E). The Qara Qir rangelands is a plateau with a general slope of 3-5% at an altitude of 15-47 m above sea level (Kakeh et al., 2018). In the study area, dominated by aeolian deposits of Holocene age (Rahimzadeh et al., 2019), the soil is classified as Coarse-loamy, mixed, superactive, thermic, Sodic Haplogypsids (Kakeh et al., 2018; United States Department of Agriculture, 2010). The mean annual temperature is 19.1 °C (−5.36 to 40 °C), and the mean annual precipitation is 273 mm. The highest rainfall occurs in January and February and the lowest in July and August. The annual potential evaporation is 1700 mm (Iranian Meteorological Organization, IRIMO). In the study area, dominant biocrusts are mosses (67.3%), and lichens (20.1%). Common lichens in the biocrust include Psora decipiens (Hedw.) Hoffm., Diploschistes diacapsis (Ach.) Lumbsch, Collemella tenax (Sw.) Ach, Fulgensia bracteata (Nyl.) Poelt, Squamaria cartilaginea (With.) P. James, Toninia sedifolia (Scop.) Timald and Calopla cauminii Savicz. Common mosses in the biocrusts include Tortula revoluta (Schimp.) G.Roth, Aloina bifrons (DeNot) Delgad, Aloina aloides (Schultz.) Kindb and Barbula trifaria (Kakeh et al., 2018).

2.2. Experimental design

To evaluate the effects of BSCs, core samples of BSCs along with 5 cm of the subsoil were collected as intact as possible (Fig. 1). BSCs samples along with adequate amount of adjacent bare soil were gently transferred to laboratory to perform evaporation simulation experiments. Initial soil water content (SWC) and electrical conductivity (EC) of soil was 9.4 (kg/kg × 100) and 18 (ds/m), respectively. To conduct experiment in a controlled condition, 10 plastic columns (20 cm diameter × 50 cm height) were prepared and packed as follows. 6 columns were filled up to 48 cm with about 14.5 kg (based on oven dry weight) of uniform saline soil collected from bare soil of the study area (Figs. 1b and 2b). 4 columns were filled up to 43 cm with about 12.2 kg of uniform saline soil and then, a layer of intact BSCs (with a thickness of 5 cm) was put on top of the soil columns (that considered as BSCs) to completely cover the soil profile (Figs. 1a and 2a). Two cm of top of the columns was left as buffer (Fig. 2a and b). Since preferential flow can curtail water redistribution within soil profile and, it can be induced by water ponding at soil surface (Clothier et al., 2008), so 1 L distilled water was sprayed gradually (Kidron and Tal., 2012; Wang et al., 2017) to each column in about 1 h until the water was completely distributed in the soil profile. Then, all the columns were put in an open place (outside the laboratory) to be exposed to climatic conditions. The daily evaporation was monitored by weighting the column using an electronic balance from 22 July to 11 December 2017, and one rainfall event (4.8 mm) was recorded during 4–5 October. Moreover, soil water and salt profile were determined three times during the experiment period, including 17 days (7 August), 50 days (10 September) and 103 days (1 November) after experiment onset in 2017. Soil sampling of columns at depths of 10 cm (D1), 20 cm (D2), 30 cm (D3) and 40 cm (D4) were performed via horizontal apertures created on sides of the plastic columns (Fig. 2a & b). After sampling, the boreholes were filled again with same saline soil and the openings were closed by glue to avoid air exchange. EC and SWC of the samples were measured in a 1:1 soil-water suspension (Rhoades, 1982) and using the gravimetric method (Gardner, 1965) respectively.

Thirty samples were taken from topsoil (0–5 cm) (15 samples for soil with BSCs and 15 samples for soil without BSCs) by the Kopecky’s rings (100 cm²) in order to determine the soil water characteristics curve (SWCC). The soil water content was measured at 14 matric suctions (h) of 0, 2, 4, 6, 8, 10, 20, 30, 50, 100, 250, 500, 1000, and 1500 kPa using the sand box apparatus and Richard’s pressure-membrane extractor (Ball and Hunter, 1988; Chen et al., 2010). Based on SWCC, the pore size distribution of the soil was determined by the method proposed by Ragab et al. (1982). Hydrus 1D software was used to model SWCC and also to simulate the soil salinity. The BSCs layer (5 cm) was considered as a layer with different hydraulic properties than below layer (43 cm) during simulation by Hydrus 1D. Whereas in soil without BSCs, just bare soil properties were considered in the simulation. The Van Genuchten (1980) model was used to express SWC and further simulate soil salinity:

\[ S_r = \left[1 + (\alpha h)^n\right]^{-\frac{1}{n}} \]
\[ S_r = \frac{(\theta_r - \theta)}{(\theta_{sat} - \theta_r)} \]

Where \( \theta (L^3 - L^3) \) is the soil water content, \( \theta_o (L^3 - L^3) \) and \( \theta_r (L^3 - L^3) \) are saturated and residual soil water content, respectively and \( S_r (-) \) is effective saturation. The parameters \( n \) and \( m \) are two fitting coefficients, \( \alpha (L^-1) \) is scale parameter and \( h (L) \) is the matrix suction.

The hydraulic characteristic of BSCs were represented in Table 1. Details of the physical and chemical properties of soils and BSCs are given in Kakeh et al. (2018) and Kakeh et al. (2020). To distinguish between different stages of evaporation process, the values of evaporation rate were calculated in 2 steps; i) fitting a power type model on experimental cumulative evaporation data and ii) calculating the derivative of obtained model.
2.3. Data analysis

Differences among the values were analyzed using one-way analysis of variance (ANOVA) and Duncan’s multiple range test. All statistical analyses were conducted using the R software (version 3.5.0). The level of significance was established at $P < 0.05$.

3. Results and discussion

3.1. Evaporation

Fig. 3 demonstrates the variation of evaporation rates for both BSCs and non-BSCs soils during 142 days. The evaporation rate from the initially wetted both soil types decreases with time and remains nearly constant after 68 days although the rainfall event enhances the evaporation rate slightly on 77th day (4–5 October). To better understand of the mechanisms of evaporation, the soil evaporation process is normally divided into three stages: the constant-rate (stage 1), the falling-rate (stage 2), and the low-rate (stage 3) stages (Xiao et al., 2011; Or and Lehmann, 2019). The first stage is not distinctive phase in this experiment. This gradual drop in the evaporation rate during stage1, is often associated with a high atmospheric demand (Shahraeeni et al., 2012). Despite of the indiscernible limit between stages 1 and 2, the boundary between stages 2 and 3 can be distinguished approximately on Fig. 3. Since the evaporation rate is slow and remains nearly constant after 83rd day (13 October), we suggest that 83rd day is the end of stage 2.

Fig. 4 shows the cumulative evaporation values in stage 2 (a) and stage 3(b) of evaporation process for the soils with and without BSCs. At the stage 2 (and 1) (22 July to 28 September 2017), the cumulative evaporation of the soil with BSCs was permanently lower than that of the soil without BSCs. However, at the stage 3 (13 October to 11 December), the effect of BSCs on the cumulative evaporation was not significant ($P < 0.05$). During stage 3, the restrictions for the evaporation rate are within the soil, and the soil surface or upper boundary layer is less important for the vapor exchange to the free water flow (Vanderborght et al., 2017).

In the stage 2 (and probably 1) with high evaporation rate, the soil with BSCs retains more water than the soil without BSCs, while the influence of the BSCs is not considerable at the stage 3 (Fig. 4 a & b). Researcher found that the falling rate stage (stage 2) is controlled by a combination of water flow within the soil and at the surface whereas, stage 3 is a vapor-diffusion stage without direct evaporation at the soil surface (i.g., see Mosthaf et al., 2014). Moreover, there are some evidences which show that BSCs decrease evaporation by coating the soil surface or enhance the infiltration rate (Chamizo et al., 2010). In the present study, reduced evaporation and soil moisture retained by BSCs can be partially attributed to lichen and mosses anchoring structures that create a cohesive mulch (mats) on the soil surface (Belnap, 2006; Chamizo et al., 2012a) blocking soil pores in wet conditions due to swelling of mats and consequently capping the soil surface (Fischer et al., 2010; Chamizo et al., 2012a, 2013a) especially in the first few days of the experiment. In addition, the abundance of large pores in BSCs prevents capillary rise which reduces salt accumulation at the soil surface in the evaporation dropping stage (moist condition). This can be also related to mosses, as a dominant element of BSCs coverage, which generate an insulated obstacle with air spaces and inhibit heating conduction and subsequently soil evaporation (Xiao et al., 2010).

In some cases, reduce in soil evaporation rate is also attributed to pore clogging by BSCs (Chamizo et al., 2016). Results demonstrate that the higher water-holding capacity of the soil with BSCs (Figs. 4 and 6).
does not necessarily increase the evaporation rate in the early phase of evaporation. The results obtained in the present study are in agreement with the finding of Chamizo et al. (2013a) and Zhang et al. (2016) who observed that the evaporation rate was lower in the soil covered by mosses than in the bare soil, despite of higher initial water content of the soil covered by mosses.

3.2. Salinity and water content

Fig. 5 shows the variations of soil salinity in terms of EC as a function of soil depth and time for the soils with and without BSCs during the evaporation experiment. Generally, EC was different among the columns with and without BSCs in all depths, and it was significantly higher in the soil without BSCs. For both soils with and without BSCs, the EC content increased with the increase of evaporation during the simulation time. Moreover, salinity was inclined to increase at the surface of the soil without BSCs, especially in a long time (i.e. 103 days). In other words, lack of BSCs at the soil surface conversed the trend of solute profile with time and resulted in accumulation of salt at the soil surface. The SWC was significantly higher in the columns with BSCs than in the columns without BSCs (Fig. 6). The SWC was significantly higher in columns with BSCs in D2 and D3 after 17 days and in D2, D3 and D4 after 50 days (Fig. 6). However, no significant difference was observed among the

### Table 1

<table>
<thead>
<tr>
<th>Surface type</th>
<th>( \theta_s ) (kg/kg)</th>
<th>( \theta_r ) (kg/kg)</th>
<th>( \alpha ) (1/cm)</th>
<th>( n )</th>
<th>( m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biocrusts</td>
<td>0.417</td>
<td>0.068</td>
<td>0.200</td>
<td>3.291</td>
<td>0.238</td>
</tr>
<tr>
<td>Bare soil</td>
<td>0.381</td>
<td>0.102</td>
<td>0.236</td>
<td>3.335</td>
<td>0.262</td>
</tr>
</tbody>
</table>

Fig. 2. Columns with BSCs (a) and columns without BSCs (b) for laboratory evaporation simulation.
soils with and without BSCs after 103 days in terms of SWC. Fig. 7 indicates the EC measured and modeled by HYDRUS-1D software in the soils with and without BSCs. The vertical salt movement pattern in the soil was simulated and analyzed through the modeling. The results showed that simulations of HYDRUS-1D were generally in line with the measured values, with an underestimate for both soils with BSCs and without them. However, the deviation between simulated and measured data was larger for the soil with BSCs, because the model predicted a two-layered soil that led to complexity of medium. In the soil without BSCs, due to homogeneity, the predicted values were closer to the measured values.

Accumulation of salts in the topsoil is more pronounced in the soil without BSCs due to higher homogeneity and subsequently pore connectivity. However, the spatial and temporal variations of soil salinity were reasonably predicted by Hydrus 1D, but the model underestimated all the experimental values particularly for the soil with BSCs, because the model predicted a two-layered soil that led to complexity of medium. In the soil without BSCs, due to homogeneity, the predicted values were closer to the measured values.

3.3. Pore size distribution

Fig. 8 demonstrates the cumulative pore size distribution as a
function of SWC in the soils with and without BSCs. The soil with BSCs has a higher total porosity and coarse pores (>10 μm) than the soil without BSCs, whereas the frequency of finer pores (<10 μm) is higher in the soil without BSCs than in the soil with BSCs. This can be attributed to higher amount of the stable coarse pores produced by structure formation. Therefore, porosity enhanced by the soil organic carbon produced by BSCs.

The exopolysaccharide exudation and organic carbon released from decay of biomasses lead to the flocculation of primary particles, develop of soil aggregates and subsequently large pores between aggregates (Belnap and Büdel, 2016; Faist et al., 2017). Moreover, decomposition of living roots and other elements of the BSCs can result in formation of the large pores and channels (Belnap et al., 2016).

These large pores (>10 μm) of BSCs can hold more water at lower matric suction (0–30 kPa) than soil without BSCs. The more frequency of fine pores (<10 μm) of non-BSCs soils can be attributed to percentage of clay particles (24.9%) than that of BSCs soils (11.5%). However large pores enhance the vertical water infiltration and saturated hydraulic conductivity but, they hinder the capillary rise and consequently upward movement of solutes (Hillel, 2005). Therefore, BSCs by creating large pores in soil surface facilitates water infiltration and inhabit water loss with evaporation.

4. Conclusion

The results indicated that biocrusted soil had a lower evaporation rate than bare soil in high evaporation demands. However, this effect was not significant at a low atmosphere demand. It was found that BSCs, as a natural soil surface coverage, largely influence evaporation process, leading to more water preservation in soil and less topsoil salinization, particularly in dry environments. More water and less solute content may provide a habitat for underground communities such as fungi, bacteria, protists and invertebrates. Considering the intensified land use and increased temperature and thereby evaporation in most areas, the important role of BSCs in preventing soil degradation when land-use practices and climate are undergoing rapid change would be accentuated. Evaporation and precipitation have a significant effect on BSCs community and stability. This emphasizes the need for an improved understanding of the reciprocal relationships among stability and function of BSCs, increase of temperature, evaporation, salinity, altered precipitation and their interactions. Instantaneous salinization of upper layer of the soil without BSCs indicates the damage of soil surface disturbance in a natural medium. Furthermore, establishment of BSCs on soil surface can be considered as a key approach for remediation of some degraded soils. Due to the complexity imposed by BSCs on soil profile characteristics, the solute and water content of soil predicted by Hydrus model may be deviated from experimental values, particularly in a long time, which can subsequently result in underestimation of soil degradation risks. This study only investigated the role of BSCs in soil hydrology and solute dynamics. Mechanical resistance, surface roughness, heat capacity and conduction, albedo coefficient and unsaturated hydraulic conductivity of BSCs should be further investigated to understand the mechanism of BSCs in soil and water preservation, especially in arid and semiarid areas. The results showed that the soil surface salinity rapidly increases in absence of BSCs. The results of this study can be used in future BSCs conservation investigations to reclaim ecosystem functions in arid and semi-arid lands. Moreover, conservation of the BSCs dominated by mosses and lichens is important for preserving hydrological functions advantage such as reducing evaporation and enhancing water retention in the salt affected soils. Because they help to recover the degraded soils where vegetation cover is sparse due to high levels of salinity. In addition to the remedial effect on soil hydrological properties, BSCs probably provide microenvironment for other soil organisms specially at saline soils, however this attribute should be reasonably investigated further. Therefore, we highlight the need to protect them to mitigate undesired effects of soil degradation driven by salinity in dryland ecosystems. Because of complex interaction between precipitation characteristics and BSCs functions in the soil hydrologic cycle and hence solute dynamics especially in arid and semi-arid lands, further studies are needed for scaling up findings at field and landscape levels.

CRediT authorship contribution statement

Jalil Kakeh: Data curation, Writing – original draft, preparation.

Declaration of competing interest

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

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