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Contrasting surface soil hydrology regulated by biological and physical soil crusts for patchy grass in the high-altitude alpine steppe ecosystem

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ABSTRACT

How the presence of biological soil crusts (BSCs) and physical soil crusts (PSCs) regulates surface soil hydrological processes in the high-altitude alpine ecosystems is still a pressing scientific issue owing to a lack of convincing field observation data. This study highlights the interesting phenomenon whereby BSCs and PSCs are jointly distributed in opposite orientations under a canopy of patchy *Achnatherum splendens* grass on the alpine steppe of the Qinghai Lake watershed (Qinghai-Tibet Plateau, northwestern China). The vegetation characteristics (plant species, cover, and biomass) and soil properties (volumetric soil water content, hydraulic conductivity, temperature, salinity, and macroporosity) were investigated for BSCs zones, PSCs zones, and interpatch zones (IPZs) in the *A. splendens* patches (ASPs) system. The experimental results show that BSCs increased infiltration during wet periods by increasing significantly greater hydraulic conductivity and macroporosity ($p < 0.01$), and reduced soil evaporation by maintaining a lower soil temperature than PSCs and IPZs during dry periods. BSCs had an important role in improving water retention in ASPs and thereby provided highly favorable conditions for plant recruitment and survival. However, PSCs reduced the infiltration capacity of surface soils and were suspected of generating runoff after intense rainfall events, which might promote connectivity of the horizontal water flux for ASPs. PSCs had a negative effect on the vegetation community by creating a saline environment (e.g. 28-fold higher salinity than for BSC zones and IPZs at 5 cm depth) for other herbaceous plants. The predominant wind direction, canopy effects of *A. splendens* on local microclimate, and salt accumulation were identified as the main factors determining the opposite distribution of BSCs and PSCs. The results suggest that BSCs and PSCs play contrasting roles in soil hydrology in ASPs, and provide valuable insights for understanding the spatial distribution of soil crusts and vascular plants as well as their interactions in high-altitude alpine steppe ecosystems.

1. Introduction

Soil crusts, which act as a boundary between the biosphere and the atmosphere (West, 1990), are very common as ground cover in many arid and semiarid regions around the world (Belnap et al., 2001; Belnap, 2006). Soil crusts cover the uppermost surface of soils and can significantly impact multiple key ecosystem processes. These processes include local hydrological processes (Belnap, 2006; Kidron and Benenson, 2014; Faist et al., 2017), carbon cycling (Maestre et al., 2013), nutrient cycling (Li et al., 2008b; Maestre et al., 2011), soil physicochemical properties (Chamizo et al., 2012a; Concostrina-Zubiri et al., 2013), and desertification (Assouline et al., 2015), thereby playing a critical role in the structure and functions of the vegetation community (Eldridge et al., 2000). Soil crusts have also been considered as dryland ecosystem engineers that change the soil surface conditions and thus influence the habitat for other organisms (Chamizo et al., 2012a). They can modify soil surface features such as roughness, porosity, water retention, and aggregation, and play a major role in infiltration and surface runoff, evaporation, and soil moisture retention (Malam Issa et al., 2011; Rodríguez-Caballero et al., 2012; Chamizo

Abbreviations: BSCs, biological soil crusts; SBSCs, scalped biological soil crusts; PSCs, physical soil crusts; SPSCs, scalped physical soil crusts; ASPs, *A. splendens* patches; IPZs, interpatch zones; $K(h)$, unsaturated hydraulic conductivity

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et al., 2015; Faist et al., 2017). Vertical and horizontal water fluxes are then regulated by soil crusts, and water availability and redistribution as well as sediment and nutrient losses can be critically influenced in drylands (Chamizo et al., 2012b; Faist et al., 2017).

Soil crusts can be classified as biological soil crusts (BSCs) or abiotic (physical) soil crusts (PSCs) according to their morphology and genesis. Specifically, BSCs may be either microscopic (algae, bacteria, cyanobacterial, and fungi) or macroscopic (lichens and mosses) (Belnap et al., 2016). PSCs generally form either via consolidation of soil material due to rain impact or via the redistribution and accumulation of fine particles (e.g., silts or sands) during surface runoff processes (Ries and Hirt, 2008; Assouline et al., 2015). Although it has been acknowledged that soil crusts have a strong influence on hydrological processes, how they affect surface hydrological processes (e.g., water infiltration, runoff dynamics, and evaporation) has been a matter of debate (Belnap, 2006; Chamizo et al., 2012b). Consensus has been lacking on the hydrological effects of soil crusts because different conclusions (positive, negative, or neutral) have been reported by different groups. For example, many studies reported that BSCs can increase soil porosity and aggregate stability, and thus promote water infiltration (Deines et al., 2007; Malam Issa et al., 2011; Kidron and Benenson, 2014; Wei et al., 2015). By contrast, other researchers concluded that BSCs decreased water infiltration and could possibly reduce water availability for vascular plants, subsequently leading to vegetation degradation (Li et al., 2010; Xiao and Hu, 2017).

Patchy vegetation also commonly occurs worldwide and has been generally considered to provide "fertile islands" of water and nutrients accumulations in drylands (Wilcox et al., 2003; Ludwig et al., 2005; Juergens, 2013; Pennisi, 2015). Numerous studies have pointed out that vegetation patches trap surface flows and change the partitioning between surface runoff and infiltration by altering the soil environment via mechanisms such as BSC formation (Eldridge et al., 2000; Franz et al., 2011; McGrath et al., 2012). However, to the best of our knowledge, direct experimental evidence of the hydrological roles of soil crusts in vegetation patches is lacking, especially for alpine and arid ecosystems. The deep-rooted grass *Achnatherum splendens* grows around the saline Qinghai Lake on the northeastern Qinghai-Tibet Plateau in China. The landscape comprises two-phase mosaics consisting of tall *A. splendens* patches (ASPs) and intermediate patches of other short and low-growing grass species in the steppe ecosystem. The grassland dominated by *A. splendens* patches is a typical alpine and semiarid steppe ecosystem that plays a critical role in environmental protection and soil and water conservation in the Qinghai Lake watershed (Huai et al., 2008). An interesting and conspicuous phenomenon is that PSCs and BSCs are jointly distributed under the crowns of the ASPs, with the PSCs oriented in a southerly direction and the moss-dominated BSCs in a northerly direction (Fig. 1). The causes and ecological roles of these two different types of crusts in *A. splendens* patches are the main scientific issues addressed in this study.

The formation and ecological functions of soil crusts in arid and semiarid ecosystems have been extensively reported in the literatures (Maestre et al., 2011; Rodríguez-Caballero et al., 2012; Kidron and Benenson, 2014; Chamizo et al., 2017), particularly for the Tengger and Negev Deserts (Verrecchia et al., 1995; Li et al., 2002, 2005, 2008b; Kidron and Tal, 2012). However, the interactions between soil crusts and vascular plants are still difficult to clarify in terms of a single and uniform mechanism because the conclusions reached by different studies have significantly differed for different ecosystems with different soil crust types (Prasse and Bornkamm, 2000; Li et al., 2005). In particular, detailed experimental studies of the soil and hydrological properties of soil crusts in alpine and arid regions are rare (Belnap, 2006). Hence, our understanding of how BSCs and PSCs affect soil hydrology in alpine and arid *A. splendens* ecosystems is still in its infancy. To address these knowledge gaps, we conducted a series of investigations and experiments to clarify the relationship between soil crusts (BSCs and PSCs) and *A. splendens* patches in the alpine ecosystem. The study objectives were (1) to determine the roles of BSCs and PSCs in *A. splendens* patches by contrasting soil hydrological properties and vegetation responses and (2) to explore the reasons why BSCs and PSCs are oriented in opposite directions in *A. splendens* patches.

To the best of our knowledge, soil water and solar radiation are the primary factors controlling ecohydrological processes in *A. splendens* ecosystems (Zhang et al., 2016). Therefore, the ecohydrological roles of BSCs and PSCs for ASPs could be fully evaluated under various assumptions regarding water and temperature. More specifically, the hydrological roles of BSCs and PSCs for ASPs were identified by comparing differences in their effects on soil surface hydrological properties (e.g., bulk density, hydraulic conductivity, macroporosity, soil water content, salinity, temperature, and evaporation). In addition, the effects of *A. splendens* on rainfall redistribution (e.g., throughfall) in terms of plant morphology (e.g., crown, root distribution) and climatic factors were considered in a discussion of the causes of BSCs and PSCs. We hypothesized that (1) BSCs would increase the infiltration capacity and decrease evaporation, thereby increasing water retention in ASPs, but PSCs would have the opposite effect, and (2) interactions among climatic factors (e.g., precipitation, temperature, and wind), plant morphology, and soil properties would facilitate the formation of the two crust types.

2. Materials and methods

2.1. Study site

This study was conducted in the northern part of the *A. splendens* grassland (37°14′N, 100°14′E, Fig. 1), which is one of the most important ecosystems in the Qinghai Lake watershed (with an area of 29,661 km^2) on the Qinghai-Tibet Plateau in China (Huai et al., 2008). The mean annual temperature is 0.1 °C and the annual precipitation is 389.4 mm, with approximately 70%–80% occurring between July and October, according to the meteorological records from the National Weather Station in Gangcha County between 1982 and 2011, with 10 km away from study site (Zhang et al., 2016). The vegetation landscape primarily consists of a two-phase mosaic of tall *A. splendens* patches (ASPs, identified as the projecting area of the crown of *A. splendens* tussocks) and interpatch zones (IPZs, consisting of non-crusted bare soil, litter, cattle manure, and matrix vegetation dominated by *Stipa kryloovii*, *Stipa purpurea*, *Poa malaca Keng* and *Artemisia frigid Willd*). Interestingly, soils around each ASP were covered by two types of crust: BSCs and PSCs (Fig.1). BSCs (composed of a 5–25 mm thick layer of dark-colored mosses according to in-situ field investigations) are mainly distributed around the northern face of ASPs. The average organic content of the top-soil, including the crust and the first 5 cm of underlying soil, was 3.76% in BSCs. Soils on the south-facing side of ASPs are mainly covered by PSCs. The topography is relatively flat, with an elevation of approximately 3210 m. The zonal soils are mainly Calcic-orthic Aridisols according to the U.S. Soil Taxonomy, with a soil depth of 0.5–1 m. The soil texture at the study site is generally silt-loam, with a clay content of 2%–10%, silt content of 34%–56%, and sand content of 35%–60% (Jiang et al., 2016). Several studies have provided a good general description of the climatic, hydrological, and soil properties of this area (Hu et al., 2016; Jiang et al., 2016; Zhang et al., 2016; Jiang et al., 2017).

2.2. Vegetation investigation

Quadrats of 1 m × 1 m were used to investigate plant species richness, cover, aboveground biomass (AB), and root density of herbaceous plants for BSC zones, PSC zones, and IPZs, in July 2015. Six 1 m × 1 m quadrats were selected for each type of zone, so a total of 18 quadrats were defined. Species richness was defined as the total number of species in each quadrat. Plant cover within each quadrat was quantified using a gridded quadrat frame. AB was determined by clipping all living