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Natural recovery of moss-dominated biological soil crusts after surface soil removal and their long-term effects on soil water conditions in a semi-arid environment

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ABSTRACT

Biological soil crusts (BSCs) are extensively developed and commonly regarded as a kind of vegetation in desertification areas around the world. The natural recovery process of BSCs after disturbance and their long-term impacts on the soil water conditions are important but not well understood. In order to provide more insights into this problem, we set up two treatments including BSCs (natural BSCs without disturbance) and disturbed BSCs (the top 30 mm of surface soil, including the BSC layer, was severely disturbed and completely removed) in a semi-arid environment on the Loess Plateau of China. Over the succeeding years, the natural recovery process of BSCs was qualitatively described and the soil water content at 0–90 cm depth of the two treatments was consecutively monitored. The results showed the following: (1) it is possible to recover natural moss-dominated BSCs after severe disturbance under natural conditions, and the recovery process to BSC full-coverage took approximately three years; (2) the BSC disturbance greatly decreased soil water content by up to 18% and the effects gradually weakened with time; (3) the BSC disturbance decreased surface soil water content (0–70 cm) by up to 24% but increased deep soil water content (80–90 cm) by up to 13%; and (4) the BSC disturbance decreased soil water storage at 0–90 cm by 7.8 mm, 4.4 mm, 8.0 mm, and 4.9 mm in the second, third, fourth, and seventh years, respectively. We concluded that the BSC disturbance degraded soil water conditions in the three to four years following the disturbance. Therefore, the artificial destruction of natural moss-dominated BSCs in a semi-arid region on the Loess Plateau of China should not be recommended as a land management practice for the improvement of soil water conditions.

1. Introduction

Desertification and land degradation due to climate variability and human activities in arid and semi-arid regions are some of the greatest environmental challenges today (Helldén and Tottrup, 2008; Johnson et al., 2006; Thai et al., 2007; Verstraete et al., 2009). Throughout the world, desertification affects more than two billion people and the 36 million square kilometers of desertified land accounts for approximately 1/4 of the earth's surface area (Johnson et al., 2006; Thai et al., 2007). Owing to the extreme scarcity of water resources in such areas, the degradation of vascular plants and the irreversible rapid decrease in vegetative coverage become the most important characteristics of desertification (Asner and Heidebrecht, 2005). In some desertified areas (e.g., the Loess Plateau of China), vegetation covers approximately 5% of the area as a result of long-term shortages in precipitation, intense evaporation, and severe soil and water loss (Wang et al., 2008; Xin et al., 2008). However, in the open space between the sparse vegetation in such areas, biological soil crusts (BSCs), which are defined as the complex mosaic of soil, green algae, lichen, moss, micro-fungi, cyanobacteria, and other bacteria by Belnap and Lange (2003), are extensively developed and are widely distributed in hot, cool, and cold arid and semi-arid regions (Belnap and Lange, 2003). BSCs usually cover up to 40–100% of the open ground surface and become one of the most important components of vegetation and land cover in desertified areas (Clair et al., 1993; Xiao et al., 2011b).

The ecological functions of BSCs and their potential effects on desertification are attracting more attention, and recently, they have been recognized as a major influence on desert terrestrial ecosystems (Belnap, 2006; Bowker et al., 2011; Maestre et al., 2011; Tisdall et al., 2012). Some physical, chemical, and biological properties of surface soil, such as roughness, texture, porosity, absorptivity, color, organic matter, fertility, hydraulic parameters, biodiversity and activity are greatly influenced by BSCs (Chamizo et al., 2012; Duan et al., 2007; Eldridge and Leys, 2003; Fischer et al., 2010; Guo et al., 2008; Housman et al.,

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2006; Menon et al., 2011; Rodríguez-Caballero et al., 2012; Xiao et al., 2007; Zhao et al., 2010). Although there are some positive effects of BSCs on desert terrestrial ecosystems, including increasing soil carbon and nitrogen (Belnap et al., 2003; Chamizo et al., 2012; Green et al., 2008), improving soil stability against water and wind erosion (Bowker et al., 2008; Guo et al., 2008; Rodríguez-Caballero et al., 2012; Tisdall et al., 2012), increasing infiltration and reducing runoff and evaporation in semi-arid cool and cold regions (Belnap, 2006; Belnap et al., 2005; Xiao et al., 2011b; Zhang et al., 2008), the negative effects of BSCs have also been reported by many researchers. For example, BSCs smooth the soil surface and prevent plant seeds from penetrating the soil under natural conditions, and they make it difficult for seed roots to penetrate the surface soil (Beyschlag et al., 2008; Deines et al., 2007; Hawkes, 2004; Langhans et al., 2009; Li et al., 2005; Serpe et al., 2006; Su et al., 2007). For this reason, the quantity and diversity of the plant community is significantly decreased by the presence of BSCs (Green et al., 2008). In many cases, BSCs reduce water infiltration (e.g., in hyperarid and most warm arid and semi-arid regions (Coppola et al., 2011; Malam Issa et al., 2011)), increase water evaporation (Chamizo et al., 2013; Kidron and Tal, 2012), and ultimately, they degrade deep soil water conditions (Eldridge and Leys, 2003; Xiao et al., 2007), which are originally available for vascular plant growth.

To avoid the above negative effects of BSCs in a desertified area, scientists and land managers have suggested that BSCs should be artificially destroyed periodically by crushing the BSC layer or partly removing the BSC layer by hand or machinery (Belnap and Lange, 2003). Moreover, BSCs would also be severely disturbed as a side effect of the removal of physical crusts underneath BSCs, which are characterized by very limited infiltrability (Badorreck et al., 2013; Fox et al., 2004). It has reported that BSCs are highly sensitive to surface disturbance and soil burial, which are caused by unintentional acts from human trampling, livestock, off-road vehicles, and engineering activities (Belnap et al., 2003; Dojani et al., 2011; Green et al., 2008; Langhans et al., 2010; Read et al., 2011). The natural recovery process of BSCs after disturbance and their long-term ecological impacts on desertified ecosystems, especially on the soil water conditions that limit plant degradation and re-vegetation, are important but not well understood.

In this study, an experimental site with well-developed natural BSCs was selected in a semi-arid environment, representative of climate and desertification on the Loess Plateau of China; then two treatments including BSCs (natural BSCs without disturbance) and disturbed BSCs (the top 30 mm of surface soil, including the BSC layer, was severely disturbed and completely removed) were set up in 2005. After that, the natural recovery process of BSCs was qualitatively described, and the soil water content at 0–90 cm depth of the experimental plots with the BSCs and the disturbed BSCs was monitored from 2006 to 2011. Using the soil water content data, the long-term effects of BSC disturbance on soil water conditions were quantitatively determined between the BSCs and the disturbed BSCs. The objectives of this study were to answer the following questions. (1) Is it possible to recover moss-dominated BSCs after severe disturbance under natural conditions without any additional manipulation? How long does it take? (2) What are the impacts of BSC disturbance on soil water conditions in semi-arid environments? How long do these impacts last? (3) How do soil water conditions change during the recovery process of BSCs after disturbance? It was hoped that the results could give useful information about the optimal use of limited soil water resources and the management of BSCs in desertified area, and that the results could be helpful for re-vegetation in arid and semi-arid environments on the Loess Plateau of China.

2. Study area

The study was conducted in the Liudaogou watershed (38°46′–38°51′ N latitude and 110°21′–110°23′ E longitude, Fig. 1A) on the Loess Plateau of China. The average annual precipitation is 409 mm, and the precipitation from June to September accounts for 80% of the annual precipitation (Cha and Tang, 2000). The average annual potential evaporation is 1337 mm, which is more than three times the local precipitation. The annual mean temperature is 8.4 °C with the highest mean temperature of 23.7 °C in summer and the lowest mean temperature of −9.7 °C in winter. Drought followed by concentrated rainfall, sparse vegetation, loose soils, complex landform, and poor land use practices since the 17th century has resulted in severe soil erosion and water shortages resulting from runoff water losses (Cha and Tang, 2000; Xiao et al., 2011a). This region experiences the most serious soil erosion in the Loess Plateau and is the main source for coarse sediment in the Yellow River (Cha and Tang, 2000). Natural moss-dominated BSCs are extensively developed on fallow lands, shrub lands, and

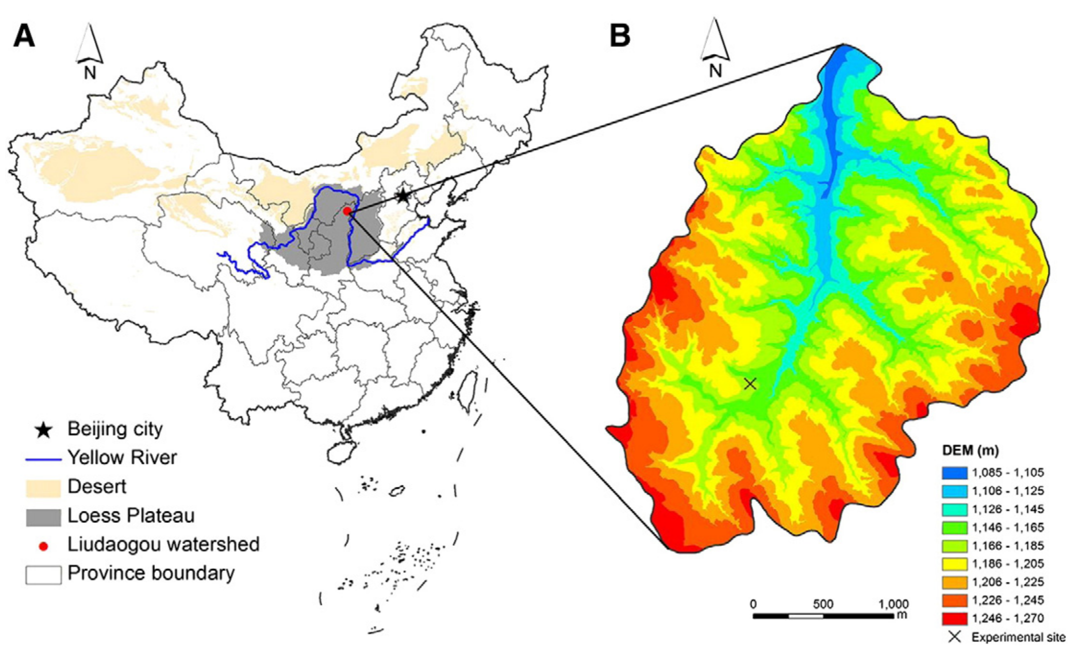

Fig. 1. Location of (A) the Liudaogou watershed on the Loess Plateau of China and (B) the experimental site in the watershed.