Journal of Arid Environments 117 (2015) 75–83

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Development of artificial moss-dominated biological soil crusts and their effects on runoff and soil water content in a semi-arid environment

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A R T I C L E I N F O

Article history:
Received 6 May 2014
Received in revised form
12 February 2015
Accepted 19 February 2015
Available online 25 February 2015

Keywords:
Biocrust
Soil moisture
Soil water regime
Soil and water conservation
Loess Plateau in China
Semi-arid region

A B S T R A C T

Artificial biological soil crusts (hereafter 'crusts') are promising candidates for the control of soil and water loss in semi-arid ecosystems. However, their hydrological functions have not yet been sufficiently investigated. In this study, runoff plots were constructed in a semi-arid environment on the Loess Plateau of China, and moss-dominated crusts were later artificially cultured. The effects of the artificial crusts on runoff and soil water content (0–90 cm) over eight years (2005–2012) were determined, depending on the differences between the artificial crusts and no crusts. The results showed that (1) artificial moss-dominated crusts primarily developed after two years and fully formed after four years in the semi-arid environment; (2) artificial crusts reduced runoff by 27% in total in the first three years after the inoculation; (3) artificial crusts decreased soil water content, and this effect increased linearly with time; and (4) artificial crusts increased water content in the upper 20 cm of soils but reduced water content in deeper (>30 cm) soils. The results indicate that it is feasible to artificially culture moss-dominated crusts in semi-arid regions. However, artificial crusts only slightly improved surface soil water conditions and greatly impaired deeper soil water conditions.

1. Introduction

Vegetation degradation and desertification due to climate change and human activities in arid and semi-arid regions represent two of the most significant global environmental problems of our time (Verstraete et al., 2009). It has been reported that vegetation covers only approximately 5% of some desertified areas (e.g., the Loess Plateau in China) as a result of long-term scarce precipitation, intensive evaporation, and major soil and water losses (Wang et al., 2008). However, biological soil crusts (crusts) cover 40–100% of the open ground surface in these regions and represent one of the most important components of vegetation and land cover (St Clair et al., 1993; Xiao et al., 2011b). The filaments and rhizoids of the living components of crusts weave through the top few millimeters of soil and bind loose soil particles together, forming a special matrix layer on the original soil surface (Belnap and Lange, 2003; Tisdall et al., 2012). It has been reported that the physical, chemical, and biological properties of surface soil, such as its roughness, texture, porosity, absorptivity, color, organic matter content, fertility, hydraulic parameters, biodiversity and activity, are greatly influenced by crusts at multiple scales (e.g., Zhao et al., 2010; Menon et al., 2011; Chamizo et al., 2012b). Crusts have ultimately been recognized as a component that exerts a major influence on arid and semi-arid ecosystems (Belnap, 2006; Maestre et al., 2011).

Due to the important functions of crusts in arid and semi-arid ecosystems, mainly including stabilizing soil surface and conserving soil and water (Belnap and Lange, 2003), it is expected that crusts could eventually be artificially cultured and propagated to control soil and water loss, which could lead to desertification (Wei, 2005). A number of studies have been conducted to test the feasibility of artificially culturing different types of crusts under laboratory or field conditions in different climate regions. For example, Chen et al. (2006) reported that the algal-dominated

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http://dx.doi.org/10.1016/j.jaridenv.2015.02.017
0140-1963/

crusts formed in a short time and could resist the erosion of wind and rainfall for 22 days after inoculation in Inner Mongolia, China; Wang et al. (2009) assessed the feasibility of crust formation via cyanobacteria inoculation in desert areas in Inner Mongolia, China; Tian et al. (2005) found that the moss-dominated crusts completely covered soil surface after one month inoculation in Tengger Desert, China; Xiao et al. (2011b) confirmed that the moss-dominated crusts almost completely covered soil surface after about 10 months in the laboratory using a natural crust inoculum from the Loess Plateau, China. Although the studies affirmed that it was feasible to artificially grow algae-, cyanobacteria-, or moss-dominated crusts through inoculation, the ecological functions of these artificial crusts in arid and semi-arid ecosystems are not clear. Artificial crusts possibly have very different functions, compared to natural crusts, due to their fast growth rates under human-made favorable conditions (e.g., moisture, light, and nutrients), although they are similar in appearance (e.g., density, height, and color) and even in species composition (Dojani et al., 2011; Xiao et al., 2011b). Owing to the scarcity and importance of water in arid and semi-arid ecosystems, the hydrological functions of artificial crusts, for example in changing runoff generation and soil moisture regimes, are especially important, however, rarely investigated. Furthermore, research on the hydrological functions of natural crusts globally has led to contradictory conclusions, indicating that the influence of natural crusts on infiltration and evaporation is positive (Zhang et al., 2008; Xiao et al., 2011b), negative (Xiao et al., 2007; Kidron and Tal, 2012), or neutral (Xiao et al., 2010; Chamizo et al., 2012a).

We hypothesized that moss-dominated crusts could be artificially cultured in semi-arid environments, and that these artificial crusts could significantly influence runoff generation and soil water content. Based on these hypotheses, we constructed runoff plots in a semi-arid environment on the Loess Plateau of China, and moss-dominated crusts were then artificially cultured. The coverage of artificial crusts was then measured continuously, and the runoff and soil water content (0–90 cm) in the plots with and without artificial crusts monitored over eight years. The objectives of this study were to (1) describe the development of the artificial crusts from zero to full coverage; (2) determine the effects of the artificial crusts on runoff; and (3) assess the influences of the artificial crusts on soil water content at different soil depths. This study could be useful to understand the hydrological functions of artificial crusts and their potential for soil and water conservation, in semi-arid regions.

2. Materials and methods

2.1. Study site description

The study was carried out in the Liudaogou watershed (38°46′–38°51′ N, 110°21′–110°23′ E) located in north of the Loess Plateau, China. The average annual precipitation and potential evaporation are 409 and 1337 mm, respectively (Xiao et al., 2011a). 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 (Xiao et al., 2011a). Natural moss-dominated crusts are extensively developed in this watershed, with coverages reaching to 70–80% (Xiao et al., 2010). The soil at the study site was a loess soil (Los-Orthic-Entisol), and it presented a clayey texture, with 10% sand, 35% silt, and 55% clay. The field capacity, saturated water content, and saturated hydraulic conductivity were 0.37 $cm^3\ cm^{-3}$, 0.43 $cm^3\ cm^{-3}$, and 11.5 cm h^{-1}, respectively. The topsoil pH, organic matter, available nitrogen, and phosphorus contents were 8.8, 0.36%, 20.8 mg kg^{-1}, and 5.2 mg kg^{-1}, respectively.

2.2. Experimental design

Three independent variables were considered: soil cover (two levels: artificial crusts and no crusts), time (covering a total of 25 field campaigns conducted after the inoculation of crusts), and soil depth (covering 0–90 cm at 10 cm intervals). According to the experimental design, two treatments (artificial crusts and no crusts, defined as control) with three replications were set up, and corresponding six hydraulically isolated plots (5.0 m length and 3.0 m width with a V-shaped runoff collection area) with 14% slope gradient were constructed. The top 10 cm of soil in the plots was first plowed, after which the carbonate nodules were removed, and clods of soil greater than 10 mm were sieved out and broken into pieces. Finally, the soil surface was smoothed to produce an even northwest-facing slope.

2.3. Artificial propagation of crusts

The natural crusts collected from the local environments were air dried in the dark, and then crushed with a grinding machine with a 2 mm mesh screen. These collected natural crusts were dominated by *Bryum arcticum* (R. Brown) B.S.G. and *Didymodon vinealis* (Brid.) Zander. On the pretreated soil surface in the plots, the crushed natural crusts were mixed with fine soil (1:4 in mass) and distributed uniformly at a rate of 1.25 kg m^{-2} air-dried matter on August 4, 2005. The soil surface was then immediately irrigated with a sprinkler that could generate very fine and gentle water drops. The irrigation took several minutes, as determined by the wetness of the surface soil (sufficiently wet but without surface runoff). The irrigation was repeated every 3–5 days and lasted until the end of May in 2006, when well-developed artificial crusts had initially formed. During this period, 20 g of KH_2PO_4 fertilizer was dissolved in water and sprinkled evenly over the soil surface on September 12, 2005 and June 17, 2006, respectively. Dichlorvos ($C_4H_7Cl_2O_4P$) was applied to kill mole crickets (*Scapteriscus borellia* Giglio-Tos) on July 1, 2006 because soil disturbance by these animals was observed, which could result in serious damage to the artificial crusts. These management practices ceased after July, 2006, except for manual weeding, which was performed at regular intervals and lasted until the end of the experiment. The plots with and without artificial crusts were all managed in an identical manner, with respect to irrigation, fertilization, and application of pesticides for soil animals and weed control.

2.4. Measurements

Before the experiment, the topsoil (10 cm) in the plots was sampled and its physiochemical properties were tested. During the experiment, the measurements mainly addressed three parameters over eight years from 2005 to 2012: the coverage of artificial crusts, runoff, and soil water content at different depths. These parameters were measured using the following methods. (1) Photographs of the soil surface were taken at more than five sites in each plot using a digital camera (C2500L, OLYMPUS in Japan), and the coverage of artificial crusts was then calculated from the pictures via supervised classification in ERDAS IMAGINE 8.7 (Xiao et al., 2011b, 2014). (2) The runoff volume (V) from the plots was measured after each rainfall event and then converted to the runoff depth (D) using following equation.

$$D = V/[S \times \cos(arctan\theta)] \quad (1)$$

In this equation, D is the runoff depth, in mm; V is the runoff volume collected from the plots, in L; S is the area of the plot, in m^2; θ is the slope gradient of the plot, in %. (3) Three plastic tubes were