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Biological soil crusts decrease erodibility by modifying inherent soil properties on the Loess Plateau, China

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ABSTRACT

Soil erosion and subsequent land degradation contributed to societal collapse in the past and are a leading cause of desertification in arid and semi-arid regions. Biological soil crusts (biocrusts) are ubiquitous living covers in many arid and semiarid ecosystems that have an important role in soil stabilization and erosion prevention. The "Grain for Green" ecological project improved vegetation recovery, and led to an extensive development of biocrusts across the Loess Plateau region in China, one of the most eroded regions in the world. The expansion of biocrusts was instrumental in reducing soil loss in a very large, severely eroded region of the Loess Plateau. We hypothesized that development of biocrusts would change soil organic matter (SOM) and soil particle size distribution (PSD), thereby reducing soil erodibility and soil loss. We sampled 56 sites that were passively revegetated grasslands on former croplands and 3 bare soil sites in the Loess Plateau region, and used the erosion productivity impact calculator (EPIC) model combined with simulated rainfall to test our assumption. The PSD and SOM content varied significantly among biocrust types and successional stages. The SOM content was 4 times higher in moss dominated biocrust and 1.5 times greater in cyanobacterially dominated biocrust than bare soil. More fine-particles (< 0.01 mm) and fewer coarse-particles (0.05–0.25 mm) were present in biocrusts than in bare soil. Modeled soil erodibility decreased significantly as biocrust biomass increased, mainly due to increase in SOM content, reducing the predicted soil loss by up to 90%. Finally, the prevalence of moss biocrust was a better predictor of soil erodibility than cyanobacteria in the Loess Plateau region. We conclude that biocrusts were a decisive factor for the initial reduction of soil erosion, which must be considered explicitly in models that aim to predict and manage soil loss on the Loess Plateau.

1. Introduction

Human-accelerated soil erosion is among the most pressing of environmental problems in many parts of the world, leading to the degradation of ecosystem function (Liu et al., 1999; Lal, 2001; Ludwig et al., 2006) and decreased agricultural productivity and sustainability (Zheng et al., 2004). Although the resistance of soil to water erosion depends in part on erosivity, topography, vegetation, and human activities (Morgan, 2005), the inherent properties of the soil, such as soil texture and soil organic matter (SOM) that influence soil erodibility, are also very important determinants. Soil erodibility defines the inherent resistance of soil to both detachment and transport by rainfall and runoff, commonly quantified measured by the soil erodibility factor (*K* value; Morgan, 2005). It is widely applied in models to predict soil erosion (Liu et al., 1999; Wang et al., 2001; Parysow et al., 2003), for example in the universal soil loss equation (USLE), revised universal soil loss equation (RUSLE2), water erosion prediction project (WEPP), and erosion productivity impact calculator (EPIC). Soil erodibility thus is an essential indicator for global land management. Soil particle size distribution (PSD) is the principal inherent soil property affecting

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erodibility. Larger particles are resistant to transport because of the greater force required to move them and fine particles are resistant to detachment because of their cohesiveness. Clay particles combine with organic matter to form soil aggregates, and the stability of these determines the resistance of the soil. The least resistant particles in size separates are silts and fine sands (Morgan, 2005). Another inherent soil property, SOM, influences soil erodibility due to its promotion of aggregate stability (Caravaca et al., 2001; Morgan, 2005). In addition, structure, permeability and salt content also influence soil erodibility (Parysow et al., 2003; Morgan, 2005; Bonilla and Johnson, 2012; Wang et al., 2013).

Stabilizing soil and preventing soil loss is the most important ecological function of biological soil crusts (biocrusts) in many ecoregions (Belnap and Lange, 2003; Eldridge and Leys, 2003; Belnap et al., 2009; Zhao and Xu, 2013). Biocrusts consist of microscopic (cyanobacteria, algae, fungi, and bacteria) and macroscopic (lichens, mosses) poikilohydric organisms that occur on or within the top few centimetres of the soil surface (Belnap et al., 2016). They also influence hydrology by determining soil surface structure and morphology (Eldridge et al., 2000; Belnap, 2006; Belnap et al., 2012), enhance soil fertility by fixing atmospheric carbon and nitrogen (Belnap, 2002, 2003; Zhao et al., 2010), and perform other functions. In one dryland region, biocrusts prevented soil loss from wind erosion even in the absence of vascular plants (Munson et al., 2011), and biocrust cover was the most important predictor of site stability (Belnap et al., 2009). Similarly, in regions experiencing water erosion, soil erosion may be decreased by 100% by well-developed biocrusts (Belnap et al., 2012; Zhao and Xu, 2013). In semiarid catchments, almost no erosion was measured in areas with biocrusts, in spite of the high runoff measured in these areas (Rodríguez-Caballero et al., 2014). In general, biocrusts exert protection against erosion that is proportional to their coverage of the soil surface, due to their ability to physically protect the erodible surface layers or through aggregate formation from their biomass (e.g., filamentous tissues). One plausible, but overlooked mechanism, is that biocrusts alter the inherent soil properties, leading to lower erodibility.

The Loess Plateau in China is one of the most severely eroded regions of the world. Preventing and controlling erosion is an urgent issue requiring resolution in the region (Fu et al., 2011). To solve this problem, the "Grain for Green" ecological project was implemented across a large portion of the Loess Plateau, in which farmers are compensated for taking land out of production and allowing passive vegetation recovery (Zhang et al., 2000). Cultivation on slopes steeper than 25° and grazing were both prohibited. The project is among the largest payment for ecosystem services programs ever undertaken. To a large degree, the program has been successful in drastically reducing sediment transport (Zheng, 2006; Chen et al., 2007; Wang et al., 2012; Wang and Zhuo, 2015). Biocrusts were a major, and unexpected, contributor to the reduction in erosion rates across the region in response to the cessation of disturbance (Ran et al., 2011; Zhao and Xu, 2013; Zhao et al., 2014). Natural recovery of biocrusts alongside grasses and shrubs was observed within a few years of implementation of the project and now cover up to 70% of the land area (Zhao et al., 2006a).

The change in land use brought about by the "Grain for Green" project, and the subsequent expansion of biocrusts, provides us an opportunity to determine the degree to which biocrusts regulate soil erosion in this ecoregion. Previous studies focus on the physical protection of soil from erosion provided by undisturbed biocrusts (Eldridge and Leys, 2003; Belnap et al., 2012; Zhao and Xu, 2013; Zhao et al., 2014), whereas we focused on biocrust-induced changes to inherent soil properties relevant to erodibility. We evaluated the influence of biocrusts on soil erodibility across the region using an extensive field survey in multiple watersheds, and rainfall simulation experiments. In addition to the protective value of undisturbed biocrust cover (Bowker et al., 2008), and their provision of surface roughness which slows overland flow (Rodríguez-Caballero et al., 2012), biocrusts can influence erodibility (as estimated by EPIC) through two mechanisms: accumulation of silt and clay (Xiao et al., 2007), and SOM (Zhao et al., 2006b,a; Xiao et al., 2007). Therefore, our study addressed three questions: (1) How do biocrust type and successional stage influence PSD and SOM in the Loess Plateau ecoregion? (2) Do changes in PSD and SOM translate into a corresponding effect on predicted soil erodibility? (3) Can these potential effects of biocrusts on erodibility result in less sediment yield? The results will demonstrate the degree of influence exerted by biocrusts on decreasing soil erodibility, protecting soil against erosion and governing soil loss on the Loess Plateau.

2. Materials and methods

We conducted a large scale field sampling campaign to estimate biocrusts contribution to soil erodibility, coupled with an experimental demonstration of soil stabilization by biocrusts using a state-of-the art rainfall simulator.

2.1. Study region

The study was conducted on passively revegetated grasslands on former croplands and rangelands of the Loess Plateau in the northern portion of Shaanxi province, China (Fig. 1). Mean altitude of the region is approximately 1200 m, but the topography varies locally in a complex of loessial hills and gullies. The region has a typical semiarid continental climate, with an average annual temperature of 8.8 °C. Mean monthly temperatures range from 22 °C in July to −7 °C in January. Mean annual accumulated temperatures above 0 and 10 °C are 3733 and 3283 °C, respectively. Mean annual precipitation is approximately 500 mm, 60% or more of which falls between July and September, typically in high-intensity and short-duration rainstorms (Zhang et al., 2011). Mean annual potential evapotranspiration is 1617 mm. The region experiences annual averages of 157 frost-free days and 2415 h of sunshine (Ansai Research Station, unpublished data, record period 1998–2015).

The soil is classified as a typical loessial soil, representing the most common soil type on the Loess Plateau. The average thickness of the loess parent material is approximately 50–80 m, with uniform soil texture of *Calciustepts*. The soil in this region is highly susceptible to erosion, with the erosion rate of over 10 000 t km^{-2} $year^{-1}$ before the "Grain for Green" ecoproject begun (Zhang et al., 2011).

Common vegetation in the region includes grasses such as *Bothriochloa ischaemum* (L.) Keng., *Stipa bungeana* Trin., *Artemisia capillaries* Thunb., and *Artemisia giraldii* Pamp., and shrubs such as *Cotoneaster horizontalis* Dcne., *Rosa xanthina* Lindl., *Rubus parvifolius* L., *Sophora davidii* (Franch.) Skeels., and *Artemisia sacrorum* Ledeb. The coverage of vegetation ranges from 20% to 70% where cropland was abandoned (Wang et al., 2011). *Achillea capillaries* Thunb. dominates initially and peaks in biomass between five to ten years after abandonment, while *Artemisia sacrorum* is the prime species after ten years of abandonment.

In the study area, cyanobacteria and mosses dominate the biocrust communities. Coverage of mosses may reach 80% on north-facing slopes in the Loess Plateau region (Zhao et al., 2014). Eight moss species, *Didymodon tectorum* (C. Mull.) Saito., *Didymodon vinealis* (Brid.) Zander., *Bryum argenteum* Hedw., *Bryum caespiticium* Hedw., *Bryum arcticum* (R. Brown) B.S.G., *Trichostomum crispulum* Bruch in F. A. Muell., *Crossidium squamiferum* (Viv.) Jur., and *Aloina rigida* (Hedw.) Limpr., have been identified in the