Catena 166 (2018) 192–199

Contents lists available at ScienceDirect

Catena

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

The effects of varied soil properties induced by natural grassland succession on the process of soil detachment

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ARTICLE INFO

Keywords:
Overland flow
Soil resistance
Stream power
Grassland
The Loess Plateau

ABSTRACT

The changes in soil properties caused by vegetation succession might have great effects on the process of soil detachment by overland flow. This study was carried out to quantify the effects of varied soil properties induced by natural grass succession on soil detachment capacity by overland flow and soil resistance to flowing water erosion on the Loess Plateau. 300 undisturbed soil samples (without roots) were collected from ten typical grasslands, and subjected to flow scouring under six shear stresses ranging from 4.98 to 16.37 pa. The results showed that the maximum soil detachment capacity (3.80 $\mathrm{kg\,m^{-2}\,s^{-1}}$) was found in *Astragalus melilotoides* Pall. grassland, where it was 49.0 times greater than that of the minimum found in *Poa sphondylodes* Trin. grassland. Soil properties induced by fibrous root herbage have strong effects on the process of soil detachment. In comparison to grasslands with tap root systems, grasslands with fibrous root herbage have lower soil detachment and rill erodibility by 84.6% and 84.3%, respectively, and critical shear stress which is higher by 15.2%. Stream power was a better parameter than velocity, shear stress or unit stream power for simulating soil detachment capacity. Soil cohesion, bulk density, organic matter and median soil grain size were the main factors affecting the process of soil detachment. Rill erodibility decreased with cohesion or clay content as an exponential or power function, and increased with the median soil grain size as an exponential function. A model was developed to estimate soil detachment capacity based on hydraulic parameters and soil properties on the Loess Plateau. The result was satisfactory and the performance of model was greatly improved in comparison to previous studies ($R^2 = 0.77$; NSE = 0.61; $p < 0.01$).

1. Introduction

Soil detachment process provides loose no-cohesion sediments for the following processes of sediment transport and deposition. Soil detachment is defined as the dislodgment of soil particles from the soil mass at a particular location on the soil surface by the erosive forces of rainfall and flow water (Govers et al., 1990; Zhang et al., 2002; Wang et al., 2014). Soil detachment capacity is the maximum soil detachment rate when sediment concentration of overland flow is zero (Nearing et al., 1991; Zhang et al., 2003). Rill erosion is a critical and common forms of erosion on hillslope. The detachment in rills is considered to be the most important process of sediment production on hillslopes and is mainly caused by overland flow (Owoputi and Stolte, 1995; Wang et al., 2014). Therefore, it is essential to quantify the factors which influence the process of soil detachment by overland flow under different conditions as well as the mechanisms by which they do.

As the driving force for soil detachment, hydraulic parameters of overland flow, such as flow discharge, slope gradient, flow velocity, shear stress, and stream power, affect the process of soil detachment significantly (Nearing et al., 1990; Zhang et al., 2002; Govers et al., 2007). Soil detachment capacity generally increases with flow discharge, slope gradient, flow depth or flow velocity as a linear or power function (Zhang et al., 2002). In process-based soil erosion models, shear stress, stream power, and unit stream power are used to simulate the process of soil detachment. Although the conclusions about which of these three factors is better to simulate the process of soil detachment are not consistent, all of these studies demonstrate that there is a significant power function relating soil detachment capacity and shear stress, stream power, or unit stream power (Nearing et al., 1999; Zhang et al., 2003).

Soil detachment is strongly affected by soil properties, no matter of soil type, texture, structure, physical or chemical properties. In generally, soil detachment capacity increases with silt content, the median soil grain size and soil moisture, but decreases with bulk density,

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https://doi.org/10.1016/j.catena.2018.04.007
Received 23 January 2018; Received in revised form 9 March 2018; Accepted 5 April 2018

cohesion, water stable aggregate, clay content and organic matter (Torri et al., 1998; Knapen et al., 2007; Zhang et al., 2008; De Baets and Poesen, 2010; Wang et al., 2013; Li et al., 2015). The measurement of soil detachment capacity is difficult and costly in terms of labor. Therefore, it is imperative to develop effective models to estimate soil detachment capacity based on some easily measured soil parameters. Torri et al. (1998) used soil bulk density, the median soil grain size, cohesion, and clay content to establish an equation to simulate soil detachment capacity by overland flow. This equation was revised by Zhang et al. (2008) and Li et al. (2015) when it was applied on the Loess Plateau. The results seemed satisfactory when some of the coefficients were modified.

Soil properties changed significantly after a series of vegetation restoration projects were conducted on the Loess Plateau since the 1970s, especially the implement of “grain for green” project in 1999 (Chen et al., 2007). Many studies confirmed that soil properties improved greatly after the implementation of these projects. As the duration of the restoration period increased, soil bulk density decreased while clay content, water stable aggregate, and organic matter content increased (Fu et al., 2000; Wang et al., 2011). Furthermore, some other studies implied that land-use type and plant species had more important effects on soil properties (Wang et al., 2004; Jiao et al., 2012). Wang et al. (2014) showed that water stable aggregate of top-soil layer (0 to 20 cm) was much greater in abandoned farmland than that in the forest land. Even in natural succession grasslands, soil anti-erodibility factors (such as water stable aggregate, bulk density and ratio of soil structure dispersion) were not continuing to improve as expected with restoration age, but were mainly affected by plant species, root types and soil condition controlled by the former pioneer species (Jiao et al., 2008).

Soil detachment capacity by overland flow is a key parameter for determining soil resistance to flowing water erosion in the process-based erosion models. Significant advances have been made in the past several decades to quantify the relationship between soil detachment capacity, and flow hydraulic parameters and soil properties. However, the effects of changes in soil properties caused by plant species, root types and vegetation succession on the process of soil detachment are still unclear and need to be further quantified. Grass is the main vegetation type on the Loess Plateau. After the implement of “grain for green” project, many farmlands were abandoned and the natural vegetation succession began. Consequently, the grassland grew rapidly, reaching an area of 2.6×10^5 km^2 by the end of 2010, which accounted for 41.7% of the total area of the Loess Plateau (Li et al., 2016). For the natural succession of grassland, the top communities or species are commonly considered as *Bothriochloa ischcemum* (Linn.) Keng, *Stipa bungeana* Trin. and *Artemisia vestita* Wall. ex Bess. in the hilly and gully region of the Loess Plateau (Jiao et al., 2012). During the process of succession, the communities or dominate species and their root types are greatly different due to the differences in seed bank, succession pathway, slope aspect, temperature and illumination, even when the restoration time is the same. Moreover, the effects of plant root type or structure (tap root system or fibrous root system) on soil properties also different. Hence the effects of natural grassland on the process of soil detachment cannot be generalized during the different stages of vegetation succession. Therefore, ten typical grasslands with different root types representing different succession stages were selected with the aim of investigating the effects of soil properties induced by natural grassland succession on soil detachment capacity and soil resistance to flowing water erosion (rill erodibility and critical shear stress) and developing a model to simulate soil detachment capacity of grassland based on hydraulic parameters and measurable soil properties on the Loess Plateau.

2. Materials and methods

2.1. Study area

This study was conducted at Zhifanggou, a small watershed with a drainage area of 8.27 km^2 (N36°46′28″to N36°46′42″, E109°13′03″to E109°16′46″; the altitude ranged from 1010 to 1431 m). The watershed is located in Ansai County in the middle of the Loess Plateau, which is a typical loess hilly and gully region. The climate is warm temperate and belongs to a transition from semi-humid to semi-arid. The mean annual temperature is 8.8 °C, and the mean annual precipitation is 505 mm which mainly concentrated between July and September. The soil has a typical silt loam texture. The natural vegetation is forest steppe zone and is the ecotone of warm-temperate deciduous broad-leaved forest zone and steppe zone. Soil erosion in this area is serious caused by intense human activities.

2.2. Grassland selections

The communities of grassland were quite different during the different natural succession stages, whether in time or space. Ten typical grasslands were selected to represent the common types of natural succession grass on the Loess Plateau. For five of them, the dominate species have tap root systems. For other five of them, the dominate species have fibrous root systems. All selected grasslands were used as farmland originally and underwent a natural succession since it was abandoned. It was assumed that the grassland was uniform in slope and soil type. Information about the ten selected grasslands, such as coordinates, elevation, soil type, and vegetation characteristics are shown in Table 1.

2.3. Soil sampling for soil detachment capacity measurement and soil properties testing

The undisturbed soil samples were taken from the top-soil layer for each grassland with the steel ring of 9.8 cm in inside diameter and of 5 cm in height. The bare soil surface was selected before sampling. Taking into account that the plant roots would affect soil properties, the horizontal distance from steel ring to plant stem was controlled in the range of 10 to 15 cm to make sure that the effects of root itself on soil detachment were excluded. In this way, even where the soil sample contains some plant roots, they are distributed at least 2 cm below soil surface. The details of the sampling processes are the same as in previous studies and can be found in Zhang et al. (2009). Meanwhile, mixed soil from within the depth of 0 to 5 cm from the soil surface around each sample was collected to test soil moisture and further used to calculate the dry soil weight for each soil sample. In addition, around each soil detachment sample, cohesion (Eijkelkamp pocket vane tester) and bulk density (steel ring with 5 cm in height and 5 cm in diameter) of the top soil layer (0 to 5 cm) were tested. Soil samples of organic matter (mixed soil) and soil particle size distribution (sand, silt and clay content, median soil grain size; mixed soil) of the top soil layer (0 to 5 cm) were collected for lab analysis. Finally, 30 soil samples were collected for each grassland and 300 samples in total were taken from ten grasslands for soil detachment capacity measurement and soil properties testing, respectively. The mean values of cohesion, bulk density, soil organic matter and soil particle size distribution for each grassland are shown in Table 2.

2.4. Determination of hydraulic parameters and soil detachment capacity

A hydraulic flume 4 m in length and 0.35 m in width was used to measure soil detachment capacity by overland flow. Six combinations of slope (17.5% to 43.6%) and flow discharge (0.004 to 0.007 m^2 s^{-1}) were designed to obtain different shear stresses (Table 3). Under each combination of slope and flow discharge, the flow surface velocity was