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Research paper

Relationships of the hydraulic flow characteristics with the transport of soil organic carbon and sediment loss in the Loess Plateau

L. Liu[a], Z.W. Li[a,b,*], X.F. Chang[a], X.D. Nie[a,b], C. Liu[a,b], H.B. Xiao[a], D.Y. Wang[b]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, CAS and MWR, Yangling, Shaanxi Province 712100, PR China
[b] College of Environmental Science and Engineering, Hunan University, Changsha 410082, PR China

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ABSTRACT

Erosive power is characterized by the hydraulic forces of moving water and determines the water transport capacity of soil organic carbon (SOC) and sediment. Understanding the relationships of hydraulic flow characteristics (flow velocity and depth, shear stress and stream power) with the transport of sediments and SOC will improve the understanding of the transport mechanism of sediment and SOC, which in turn will improve SOC prediction. To address this issue, two loess soils (one silt loam and one silty clay) were selected, and 32 simulated rainfall experiments were conducted in a 1 m by 5 m soil pan at a varying slopes (10°, 15°, 20°, and 25°) and two rainfall intensities (90 mm h^{-1} and 120 mm h^{-1}). The results showed that the flow velocities had significant positive linear relationships with the SOC concentrations ($P < 0.001$) under the rainfall intensity of 90 mm h^{-1} and that the flow velocities also had close relationships with the suspension transport of clay particles in the fine-textured soil and the rolling transport of light large aggregates in the coarse-textured soil. Under the rainfall intensity of 120 mm h^{-1}, the runoff depth was positively correlated with the SOC concentrations due to the suspension transport of the clay particles and was negatively correlated with the sediment concentration. The slope had a greater effect on the sediment and SOC loss of the coarse-textured soil than those of the fine-textured soil. Additionally, the stream power was a better descriptor of the sediment loss in the loess soils than shear stress. Overall, both the soil texture and rainfall intensity changed the relationships of the hydraulic flow characteristics with the sediment and SOC loss. Finally, the results of our study will provide important knowledge for improving or building hydraulic-based SOC and sediment loss models.

1. Introduction

Soil erosion always leads to a significant amount of soil organic matter loss (Lal, 2005; Schiettecatteet al., 2008a). The losses of soil and carbon (C) during erosion processes can deplete the fertility of agricultural land and influence atmospheric C circulation (Agata et al., 2015; Gregorich et al., 1998; Kuhn and Armstrong, 2012; Lal et al., 2004; Li et al., 2017; Ma et al., 2016; Williams et al., 1980). Soil erosion disturbs carbon-rich topsoil and preferentially removes soil organic carbon (SOC) from upslope sites, resulting in mineralization as well as the distribution and burial of SOC in depositional environments (Huang et al., 2017; Liu et al., 2017a; Ma et al., 2014; Wang et al., 2014b, 2010; Kuhn et al., 2009; Polyakov and Lal, 2004a). Gaining a better understanding of the removal of SOC due to soil erosion is an important part of elucidating the mechanisms of the SOC cycle (Li et al., 2016a; Liu et al., 2017b; Polyakov and Lal, 2004b). In fact, surface soil erosion is a complicated problem affected by many factors, e.g., microtopography, surface materials and flow characteristics (Fu, 1989). However, the hydraulic forces of moving water and soil types determine the extent of erosion and the transport mechanisms of sediment particles (Slattery and Bryan, 1992; Trout and Neibling, 1993). Flow depth, flow velocity and hydraulic parameters (shear stress, stream power, and unit stream power) are usually used to characterize the erosive power of overland flow determining sediment concentrations (Shih and Yang, 2009). Therefore, it is important to find an analytical solution for the mechanism by which SOC loss is controlled by hydraulic factors.

During the erosion process, if the rainfall energy is large enough and stable, the hydraulic factors, which vary with flow discharges and slope gradients (Schiettecatte et al., 2008b; Shen et al., 2016), control the amount of transported sediment particles (Kinnell, 2005; Shih and Yang, 2009). Previously, stream power was usually used as a measure of the erosive forces associated with the flowing waters for both interrill

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[*] Corresponding author at: State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Wate Conservation, CAS and MWR, Yangling, Shaanxi Province 712100, PR China.
E-mail address: lizw@hnu.edu.cn (Z.W. Li).

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Table 1
Selected properties of the original soils from Changwu and Suide.

Property*	Clay (%)	Fine silt (%)	Coarse silt (%)	Sand (%)	MWD (mm)	Bulk density (g cm^{-3})	$CaCO_3$ (g kg^{-1})	SOC (g kg $^{-1}$)	CEC (cmol$_c$ kg^{-1})	pH (in H_2O)
Suide	12.1	19.4	36.3	32.1	0.04	1.25	115.2	2.06	8.1	8.7
Changwu	21.2	38.0	31.3	9.5	0.28	1.20	81.1	6.36	12.4	8.3

MWD: mean weight diameter of aggregates after wet sieving; CEC: cation exchange capacity.
* Soil texture is classified on the basis of the USDA soil classification system.

and rill erosion (Kinnell, 2005; Nearing et al., 1997; Shi et al., 2012). However, flow velocity occasionally has a more significant relationship with sediment transports (Arjmand and Mahmoodabadi, 2015). Hydraulic parameters, e.g., flow velocity, flow depth, stream power and shear stress, are usually used to determine the sediment transport capacity of flow in physics-based erosion models, e.g., the Limburg Soil Erosion Model (LISEM) (De Roo et al., 1996), European Soil Erosion Model (EUROSEM) (Morgan et al., 1998) and Water Erosion Prediction Project (WEPP) (Nearing et al., 1989). SOC loss is mainly understood in term of soil loss (Palis et al., 1997). Although the hydraulic mechanism controlling soil loss has been widely researched (Pan and Shangguan, 2006; Slattery and Bryan, 1992), the relationships of various hydraulic flow characteristics with SOC loss have not been studied, and these relationships are essential for SOC loss prediction.

In previous studies, clay particles, silt particles and light aggregates were the first to be transported during erosion processes (Palis et al., 1997; Rodriguez et al., 2002). These clay and silt particles, which are easily the first to be transported, were strongly correlated with the SOC concentrations (Leifeld et al., 2005; Meersmans et al., 2008; Parton et al., 1987, 1993; Xu et al., 2015). In addition, Moss et al. (1979) noted that sediment particles of different sizes were broadly associated with particular sediment transport modes (e.g. suspended, saltating and contact (rolling) loads). In particular, clay was usually associated with suspension/saltation, whereas large aggregates were transported by rolling (Asadi et al., 2007). Thus, hydraulic forces and soil type determine the sediment transport and sediment size distribution and consequently influence SOC concentration. The SOC concentration related to the selective transport of the sediment, which is controlled by hydraulic factors, needs to be quantified to understand the effects of erosion on the SOC loss in loess soils.

The mechanism of the SOC loss through erosion is determined by three key factors: the distribution of the organic carbon pools in the soil aggregates, the kinetic energy of the rainfall and the structural stability of the soil (Martínez-Mena et al., 2012). For loess soils on the Loess Plateau, soil texture has a considerable effect on the sediment size distribution (Wang and Shi, 2015; Wang et al., 2014a). Hence, this study aimed (i) to analyze the relationships of the hydraulic flow characteristics (flow velocity, runoff depth, stream power and shear stress) with the sediment and SOC loss from the two different soil textures on the Loess Plateau of China and (ii) to determine how the hydraulic factors affect the SOC concentrations due to the selective transport of sediment particles during the erosion process.

2. Methods and materials

2.1. Experimental devices

Simulated rainfall experiments were conducted at the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau. The down sprinkler rainfall simulator system comprises three nozzles (Shen et al., 2015). The nozzles were placed 18 m above the ground to ensure that the raindrops created in the experiments were similar to natural raindrops. By adjusting the nozzle size and water pressure, rainfall intensities ranging from 30 mm h^{-1} to 350 mm h^{-1} were obtained. The soil pans were constructed with metal sheets measuring 5 m (length) × 1 m (width) × 0.5 m (depth). Each soil pan was electronically adjusted to the proper slope before each experiment. A metal runoff collector was placed at the end of the soil pan to collect the runoff (Shi et al., 2012). Tap water (electrical conductivity = 0.7 dS m^{-1}) was used in all experiments.

2.2. Experimental design

Two loess soil types were selected for this study, one from Suide (37°31′N, 110°16′E) and one from Changwu (35°12′N, 107°47′E), which are distributed in the north and south of the Loess Plateau, respectively. Both of these soil types were sampled from the topsoil (20 cm) of farmland that had been used to cultivate maize (*Zea mays* L.) for several decades. The samples were collected before crop cultivation, when no vegetation was planted in the farmland. The two soils were silt loam and silty clay. The Suide soil had a SOC content of 2.06 g kg^{-1}, whereas the Changwu soil had a SOC content of 6.36 k kg^{-1}. The properties of these soils are shown in Table 1. The climate of the study area is affected by the oceanic monsoon climate and belongs to the subhumid region (Wang and Xiao, 1993; Wei and Shao, 2007). Two rainfall intensities, 90 mm h^{-1} and 120 mm h^{-1}, which represent the typical rainfall intensities of strong storms in the subhumid climatic regions of China, were used in the experiments (Shi et al., 2012; Wang and Shi, 2015). Four typical slope gradients, 10°, 15°, 20°, and 25°, were selected for our study. The slope gradient of 25° is the steepest incline of slope in the region according to the classification of farmland slopes in the Loess Plateau (Comprehensive Scientific Expedition, 1990). A total of 16 treatments were conducted, with two repetitions of each experimental setup.

2.3. Experimental process

Before the experiments, all samples were passed through a 10-mm sieve and mixed thoroughly before being air dried to a 10% moisture content (gravimetric). Before packing the soil, a 10 cm-thick layer of coarse sand was added to the bottom of the experimental soil pan to maintain permeable conditions. Then, a fine gauze was placed on top of the layer of coarse sand. Afterwards, a 30-cm-thick soil layer was placed over the coarse sand layer in 5 cm increments. The Suide and Changwu soil plow layers in the soil pan were packed with bulk densities of 1.25 g cm^{-3} and 1.20 g cm^{-3}, respectively. Each layer was raked lightly to ensure the uniformity and continuity of the soil structure. Prior to performing the experiments, the simulated rainfall device was tested to ensure that it could attain the proper rainfall intensity. The soil surface of the experimental plot was exposed to accept rainfall evenly. During the rainfall process, the runoff and rill initiation times were recorded, and the runoff and soil loss were collected at the outlet once each minute. The rill locations and shapes were frequently measured with a millimeter-scale ruler at numerous points. The changes in sediment transport and soil surface conditions were both visually observed and recorded throughout the erosion process. A fluorescent dye method was used to measure the flow velocity (Gilley et al., 1990). The time for the tracer to travel from the injection point to a downslope point was measured visually. The surface velocity of the overland flow was obtained by dividing the travel distance by the travel time. The flow velocities were measured over a distance of 50 cm successively at four locations within the plot: 75–125, 175–225, 275–325, and 375–425 cm