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Impact of cornstalk buffer strip on hillslope soil erosion and its hydrodynamic understanding

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ABSTRACT

Soil erosion is still a serious concern on the Loess Plateau of China. Cornstalk buffer strips are not commonly utilized for erosion control on the Loess Plateau, and there is little hydrodynamic understanding of this soil erosion control practice. A simulated rainfall experiment was designed to investigate how a cornstalk buffer strip affected soil erosion and to enhance the hydrodynamic understanding of this method. Large loessial soil beds (10 m-long, and 3 m-wide) with slope gradient of 20° were subjected to three successive simulated rainfall events with intensities of 100 mm h^{-1} for each experimental run. The rainfall events were conducted by a down sprinkler rainfall simulator system. Two treatments (with and without a cornstalk buffer strip) were tested in the following four runs: 1) without cornstalk buffer strip, 2) with cornstalk buffer strip in the third rain event, 3) with cornstalk buffer strip in the second rain event, 4) with continuous cornstalk buffer strip in all three successive rainfall events. In treatments with buffer, a 1 m-width cornstalk buffer strip was applied. The results showed that, compared with the run without cornstalk buffer strip, the run with continuous cornstalk buffer strip in three successive rainfall events reduced sediment yield by 29.1% while the other two runs with cornstalk buffer strip in a single event only reduced sediment yield by 2.0%–9.1%, and early buffer run had a larger reduction in soil erosion than late buffer run. The runoff-sediment relationship coefficients revealed that cornstalk buffer decreased the sediment concentration and increased the runoff threshold required for soil erosion initiation. Moreover, the buffer strip increased sheet flow velocity in interrill areas, while it decreased concentrated flow velocity in rills. This promoted a shift of rill flow to subcritical laminar flow which reduced sediment yield. Cornstalk buffer strip also increased the critical hydrodynamic forces required for the initiation of soil erosion.

1. Introduction

Mulches, e.g. straw, stalk, leaves, or plastic film, are often used to protect the soil surface from raindrop (splash) erosion and runoff detachment during the critical period of plant establishment (Smets et al., 2008). Many field and laboratory studies, focusing on the impact of mulches on water erosion, have been conducted in a wide range of environmental and topographic conditions (Kamara, 1986; Brown et al., 1989; Bradford and Huang, 1994; Döring et al., 2005; Mulumba and Lal, 2008; Wilson et al., 2008; Jordán et al., 2010; Shi et al., 2013; Montenegro et al., 2013; Prosdocimi et al., 2016a,b). Lal (1976) reported that organic mulches reduce soil loss by reducing raindrop impact, increasing surface storage and infiltration, decreasing runoff velocity, and improving soil qualities (soil structure, soil porosity and biological activity). Mulumba and Lal (2008) used a long term field plot to study the effects of mulching on soil physical properties and determined an optimum mulching rate for increasing soil porosity, available water capacity, soil moisture retention and aggregate stability which was meaningful for reducing soil erosion by water. Based on a 3-year experiment, Jordán et al. (2010) found that mulch helped to improve the soil physical properties and to reduce runoff coefficient and sediment yield, with an optimum rate of mulch application under semi-arid conditions in southern Spain set to 5 Mg ha^{-1} yr^{-1}. By conducting an intermittent simulated rainfall, Montenegro et al. (2013) found that residue cover strongly affected infiltration, soil moisture, runoff and erosion. Prosdocimi et al. (2016a,b) conducted an experiment testing the effects of barely straw mulching on soil erosion on vineyards in eastern Spain and concluded that straw mulch was very effective in reducing soil particle detachment and surface runoff, and this benefit was achieved immediately after the application of the straw.

Cornstalk, as one kind of typical organic mulch, can greatly reduce water erosion (Gilley et al., 1986; Wen et al., 2014). Cornstalk retention in fields is also important for promoting physical, chemical, and biological attributes of healthy soil in agricultural systems (Turmel et al.,

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2015). The term buffer strip here implies to a strip of vegetation that acts as a filter for sediment and attached nutrients and pollutants (Barling and Moore, 1994; Hussein et al., 2007). Xu et al. (2015a) applied a cornstalk buffer strip using the whole plant cornstalk after harvest, which proved to be more efficient in erosion control than clipped short cornstalks applied in the simulated gully. It also served to shorten the slope length for runoff convergence and intercepted the sediment from upslope.

Soil erosion by water is a process of detachment and transport of soil particles by rainfall and runoff. Flow detachment is often described by energy-based approaches and linked to the soil surface condition (Guo et al., 2013; Shen et al., 2016). Flow hydrodynamics are related to particle detachment and sediment transport. It is of great significance to evaluate the hydrodynamic characteristics of runoff on hillslopes with organic mulches. Gilley and Kottwitz (1995) measured the Darcy-Weisbach roughness coefficients for surfaces with different kinds of crop residues under controlled laboratory conditions. They found that smaller diameter residue materials did influence hydraulic resistance when they substantially increased the total volume of resistance elements. Cassol et al. (2004) conducted a laboratory study to test the impact of crop residue on flow hydraulic conditions on sandy clay loam soil. They proposed that, due to the increase in the viscous forces from the physical interference of residue on runoff, soil surface residue cover caused an increase in water flow depth and hydraulic roughness which decreased the mean flow velocity, thus contributing to a reduction in interrill soil detachment and transport rate. Xu et al. (2015a,b) examined rill flow characteristics by conducting an indoor experiment with and without cornstalk buffer strip. Their results showed that rill flow velocity was decreased and rill flow energy was consumed after it went through the cornstalk buffer strip.

Shear stress, unit stream power, and unit energy of cross section are basic hydrodynamic parameters used to evaluate soil detachment rates and characterize critical conditions required to initiate soil erosion (Nearing et al., 1997; An et al., 2012; Reichert and Norton, 2013; Zhang et al., 2015). Although hydrodynamic understanding of soil erosion has received more attention lately, the hydrodynamic characteristics associated with organic mulches are still unclear and need more quantification and understandings.

The Loess Plateau is well known for its serious soil erosion caused by concentrated annual precipitation with intensive rainfall, steep slopes, less vegetation cover, and highly erodible silty soils (Cai, 2001). Although the Grain for Green Project (conversion steep slope farmlands to permanent vegetation cover), which is a national ecological project, has greatly increased the vegetation cover in this region, there are still large areas of farmlands needed for the food security on the Loess Plateau (Zhao et al., 2013; Chen et al., 2015). Corn (*Zea mays* L.) is one of the most common crops grown on the Loess Plateau in order to produce a large amount of grain necessary for local people. As one kind of by-product, cornstalks are often utilized as biofuel or animal feed, which may contribute to air pollution (Li et al., 2002). Cornstalks are also pulverized and left on farmland to increase soil organic matter, but this method is not easy to implement on steep slopes of the Loess Plateau. So, it may be environmentally-friendly and sustainable to set up cornstalk buffer strips on loessial hillslopes for soil erosion control.

Rainfall simulations have been recognized as an important method for water erosion research (Cerdà, 1998). Rainfall simulation is considered by several studies as a rapid and efficient method to study erosion, which can be better controlled than natural rainfalls (Cerdà, 1997; Iserloh et al., 2013a; Prosdocimi et al., 2016a,b). It has been widely used to assess the impact of several factors on soil erosion, such as slope, soil type, soil moisture, aggregate stability, surface structure, and vegetation cover on soil erosion processes (Arnaez et al., 2007; Blavet et al., 2009; Iserloh et al., 2012; Lassu et al., 2015; Marzen et al., 2015; Xiao et al., 2015). Field rainfall simulation experiments are often carried out with small portable rainfall simulators (Iserloh et al., 2012, 2013b; León et al., 2013; Rodrigo Comino et al., 2015, 2016a,b,c). While laboratory-based rainfall simulations are often conducted with fixed rainfall simulator systems that can provide special requirements for laboratory environments that enable a large range of hydrologic, pedologic, and surface treatment conditions (de Lima and Singh, 2002; de Lima et al., 2003; Zhang et al., 2010; Shen et al., 2015; Li et al., 2016).

The main goals of this research performed under laboratory conditions were to: a) quantify the reduction of soil erosion induced by a cornstalk buffer strip; b) determine the relationship between runoff and sediment yield on the hillslope; c) enhance the hydrodynamic understanding of cornstalk buffer effects on hillslope soil erosion processes.

2. Materials and methods

2.1. Experimental materials

2.1.1. Rainfall simulator system

The experiments were carried out using a rainfall simulator under laboratory conditions in the rainfall simulation laboratory of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Yangling City, Shaanxi Province, China. A down sprinkler rainfall simulator system was used (He et al., 2014). This rainfall simulator system consists of three sets of nozzles in which the rainfall intensity can be set to the range from 30 to 350 mm h^{-1} by adjusting the nozzle size and water pressure. The nozzle type used in this study is SP (1.9 cm) type developed by the Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources. The nozzles were installed 18 m above the ground as this height was enough for the majority raindrops to reach terminal velocity. Spatial distribution of rainfall and its intensity was measured using 10 rows and 3 columns of equally spaced rain gauges. The spatial uniformity of the simulated rainfall was controlled to above 90%. When rainfall intensity was set to 100 mm h^{-1}, the simulated raindrop diameters were 0.2 to 3.1 mm with 85.7% (±2.4%) of raindrop diameters less than 1.0 mm as calibrated by the stain method (Cerdà et al., 1997; Wang et al., 2015). Prior to the experiments, calibration of rainfall intensity was carried out in order that the tested rainfall intensity reached the requirement.

2.1.2. Soil bed

A 10-m long, 3-m wide and 0.5-m deep soil pan with many drainage holes (2 cm aperture) at the bottom was used in the experiments. The soil pan can be inclined to the slope gradient from 0 to 30° with adjustment steps of 0.5°. A runoff collector was installed on the soil pan outlet and used to collect the sediment and runoff samples during the rainfall simulation. In this study, the soil pan was set to 20° which was the average slope gradient for rill erosion development on farmland of the Loess Plateau.

The soil used in this study was loessial soil (fine-silty and mixed), classified as a *Calcic Cambisols* (USDA NRCS, 1999). Tested soils were collected from the top layer (20 cm) in the Ap horizon of a well-drained farmland site (tilled by hand) in Ansai County (36°45′N, 109°11′E), Yan'an City, Shaanxi Province, which is located in the hilly-gullied region of the Loess Plateau in northwest China. The soil texture was 28.3% sand (>50 μm), 58.1% silt (50–2 μm), 13.6% clay content (<2 μm) determined by pipette method according to USDA soil classification system. Soil organic matter was 5.9 g kg^{-1} determined by the potassium dichromate oxidation-external heating method. The pH in water was 7.95, measured with a 1:2.5 solid-to-water ratio on a weight basis. Prior to the experiment, the soil was air-dried at 25 °C, and then, big clods were broken by hand into subangular-blocky clods less than 4 cm in size, but was not sieved and ground to keep the in-situ soil aggregation fabric.

Soil water content was tested to calculate the soil amount needed for packing the soil pan. The lowest 10 cm of soil pan was filled with sand to allow free drainage of excess water. A highly permeable cloth was spread on the sand surface to separate the sand layer from the soil