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Temporal variation in soil resistance to flowing water erosion for soil incorporated with plant litters in the Loess Plateau of China

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ABSTRACT

Plant litter can be incorporated into topsoil under natural circumstances by soil splash, sediment deposition, and soil-dwelling animal activities. The incorporated litter can change the mechanical properties of soil and the decomposition of the incorporated litter can improve soil structural stability. Those changes likely influence soil detachment process by overland flow. This study was undertaken to quantify the effects of incorporated plant litters into topsoil on the temporal variation in soil resistance to detachment by overland flow using natural soil samples collected from four different plots (one control and three litter incorporation treatments) and then scoured under six different flow shear stresses in a hydraulic flume. The experiment started from April 19 to October 5, 2015 for 10 times at approximately 20 days sampling intervals. Soil properties and environmental parameters were also measured at each sampling time to explain the temporal variations in rill erodibility and critical shear stress. The results showed that the incorporated plant litter was effective to enhance soil resistance to flowing water erosion. Compared to bare soil, rill erodibilities of litter incorporated soils of black locust, sea buckthorn, and green bristle grass decreased by 24.3%, 33.5%, and 34.8%. The temporal variations in rill erodibility of bare and litter incorporated soils were similar. Rill erodibility decreased significantly over time as an exponential function for both bare and litter incorporated soils. The relative rill erodibility of three litter incorporated soils increased over time as a power function. The fitted critical shear stress increased exponentially over time. The temporal variations in rill erodibility could be explained by the temporal variations in soil consolidation, water stable aggregate, and litter decomposition. Rill erodibility could be well estimated by soil bulk density, water stable aggregate, and litter mass density ($r^2 = 0.92$).

1. Introduction

Soil erosion involves the processes of soil detachment, sediment transport, and deposition. Soil detachment, defined as the soil particles being separated from the soil matrix at a particular location on the soil surface by erosive agents (Zhang et al., 2003), determines the amount of sediment that is potentially transferred to water bodies (Li et al., 2015c). Soil detachment capacity (D_c) and soil resistance to flowing water erosion (reflected by rill erodibility (K_r) and critical shear stress (τ_c)) are important input parameters for many process-based soil erosion models, such as the Water Erosion Prediction Project (WEPP) model (Nearing et al., 1989). Soil detachment process by overland flow is susceptible to soil physical properties (e.g. soil texture, bulk density, water stable aggregate, soil cohesion) and the plant materials incorporated into topsoil, such as plant roots, crop residue, and plant litter (Brown et al., 1989; Knapen et al., 2007a; Li et al., 2015a; Wang et al., 2014; Zhang et al., 2014).

As an important component of near soil surface characteristics, apart from covering on soil surface, plant litter usually can be incorporated into topsoil under natural circumstance through three different approaches: soil splash, sediment deposition and soil animal activities (Geddes and Dunkerley, 1999; Laossi et al., 2010; Tsukamoto, 1991; Wilson et al., 2008). Soil particles are splashed by raindrops wrapping litter up by adhesive force and lead to a large amount of plant litter coated with soil particles after rainfall. Plant litter and detached soil particles can be transported downslope and deposited together in low areas (Tsukamoto, 1991). The deposited litter can form mini-dam in rills, which traps and deposits sediment to facilitate the mixture (Pannkuk and Robichaud, 2003; Wilson et al., 2008). Plant litter can also be partly translocated to topsoil by soil animals, like earthworms and soil-dwelling insects (Laossi et al., 2010; Ma et al., 2014).

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Generally, plant litter can be incorporated into topsoil before fully fragmented (Tsukamoto, 1991; Li et al., 2015a). The incorporated rate changes with climatic conditions and vegetation communities. Tsukamoto (1991) reported that the rates of plant litter incorporated into topsoil (0–5 cm) caused by sediment deposition ranged from 0.10 to 0.28 kg m^{-2} in the Japanese cypress stands. Li et al. (2015a) found that the incorporating rates of plant litter into 0–5 cm topsoil varied from 0.07 to 1.08 kg m^{-2} with a mean of 0.32 kg m^{-2} at a 90 m long and 40 m wide ephemeral gully developed hillslope covered with black locust (*Robinia pseudoacacia* L.) in Zhifanggou small watershed of the Loess Plateau.

The incorporated plant litter can influence soil properties related to soil detachment by overland flow such as increase in soil aggregate stability, soil organic matter, and decrease in soil bulk density (Kladivko and Unger, 1994; Mandal et al., 2004). Similar to the effect of buried crop residue in situ by conservation field management on soil properties, the incorporated litter can change soil structural stability thus modify soil resistance to detachment by overland flow. More importantly, the incorporated litter also affects soil properties greatly by releasing fragmented organic substance to soil mass through mineralization and humification processes (Durán et al., 2004; Ma et al., 2014). Morachan et al. (1972) found that the size of wet aggregate increased progressively with increased residue addition. Black (1973) reported a significant increase in soil aggregate and a significant decrease in bulk density with increasing incorporated residue levels. Bhagat and Verma (1991) conducted a field experiment for 5 years and proved that water stable aggregates and soil bulk density under litter incorporation treatment were significantly higher and lower than those of control. Some other studies (Ghuman and Sur, 2001; Kladivko and Unger, 1994) also observed a distinguishable decrease in soil bulk density after litter incorporation.

The effects of incorporated litter on soil properties change with time. Immediately after incorporation, the mechanical effect of litter on enhancing soil stability is at its maximum. Then, the litter decomposes and its rate is controlled by soil temperature and moisture conditions (Brown et al., 1989). After a period of decomposition, the incorporated litter may still offer some mechanical resistance to flowing water erosion. But the interactive effects of the mechanical resistance and litter decomposition on soil properties may produce uncertain alteration in soil erosion (Brown et al., 1989; Franti, 1987; Knapen et al., 2007a). Brown et al. (1990) studied rill erosion after incorporation of crop residue and pointed out that natural soil consolidation over time likely masked the effect of residue incorporation on topsoil resistance. However, Zeleke et al. (2004) revealed that soil cohesion at the 5 cm depth reduced compared to control after three (annual) residue incorporations. Therefore, it is essential to investigate the temporal variation in the effects of incorporated litter on soil properties and soil detachment by overland flow under different conditions.

Soil detachment process by overland flow (or rill erosion) is affected considerable by the plant litter incorporation. Van Liew and Saxton (1983) found that residue incorporation could significantly increase soil resistance to flowing water erosion and reduce rill erosion rate. A recent study conducted by Knapen et al. (2007a) demonstrated that the decomposition of incorporated residue could enhance the stability of topsoil, which was closely related to the litter biomass loss by decomposition. But the correlation was weak and thus more additional experiments under controlled conditions were required to define the exact relationships between incorporated plant materials and soil resistance to flowing water erosion. A more recent study was carried out by Li et al. (2015a) at a hillslope covered with approximately 20-year black locust (*Robinia pseudoacacia* L.) in the Loess Plateau. Their results revealed that the mass density of incorporated litter had significantly positive influence on reducing soil detachment capacity by overland flow for 0–5 cm topsoil. However, the temporal variation in the effects of incorporated litter decomposition on soil detachment process by overland flow is still unknown.

Great efforts have been paid to restore vegetation and reduce soil and water losses in the Loess Plateau of China (Chen et al., 2007). For example, the Grain for Green Project was implemented in 1999 in the Loess Plateau. As a result, >2 million ha of steep slope croplands have been converted to woodland or grassland in the past several years (Chang et al., 2011; Deng et al., 2014). A rapid accumulation of plant litter always occurs after the cropland is newly converted to woodland or grassland (Clark et al., 2001; Olson, 1963). It is supported by the facts of abundant plant litter accumulation following vegetation restoration in the Loess Plateau (An et al., 2013; Ma et al., 2014). Consequently, extensive undecomposed or partly decomposed plant litters are incorporated into topsoil in this region (Li et al., 2015a).

As mentioned above, the plant litter incorporated into topsoil and its decomposition over time likely have great influence on soil detachment process by overland flow and its temporal variation. Nevertheless, few studies have been conducted to investigate the potential effects of incorporated plant litter on the temporal variation in soil detachment by overland flow. Therefore, the objectives of this study were to quantify the temporal variations in soil resistance to flowing water erosion of topsoil incorporated with three different plant litters and to identify the factors influencing these variations in the Loess Plateau of China.

2. Materials and methods

2.1. Study area and sampling site

The experiments were performed at the Ansai field station (109°18′51″E, 36°51′15″N) of the Institute of Soil and Water Conservation, Chinese Academy of Sciences. It is located in a typical loess-hilly region with a typical silt loam loess-derived soil. The climate is a semi-arid, continental with a mean annual temperature of 8.8 °C and precipitation of 505 mm >70% of precipitation falls during June to September (summer months) as heavy storms with short duration. The principal land uses are cropland, orchard, shrub land, woodland, grassland, and wasteland. The major vegetation species are *Robinia pseudoacacia* Linn., *Pinus tabulaeformis* Carr., *Hippophae rhamnoides* Linn., *Caragana korshinskii*, *Astragalus adsurgens*, and *Artemisia capillaries*.

The sampling field is a 21 year-old man-made level terrace and the elevation is 1290 m. It was fallowed for one year before the experiment was performed. The soil is a typical silt loam with 12.6% clay, 60.6% silt, and 26.8% sand. The field was tilled twice with a rototiller (the tillage depth ranged from 25 to 34 cm) to homogenize soil properties in early May 2014, and was left open to natural environmental conditions until November. Then the field was divided into 4 plots (3 for litter incorporation and 1 for control as baseline) with a length of 12 m and a width of 3 m. Plant litters of *Robinia pseudoacacia* Linn. (Black locust, abbr. BL), *Hippophae rhamnoides* Linn. (Sea buckthorn, abbr. SB), and *Setaria viridis* (*L.*) Beauv. (Green bristle grass, abbr. GBG) were collected from a nearby small watershed (Zhifanggou). The litters of black locust and sea buckthorn were consisted of leaves and a few twigs with a mean length of approximately 3 cm. But the litter of green bristle grass was mainly stalks and a few leaves and thus it was chopped to the same length with other two litters. Prior to incorporation, the plant litters were air-dried to constant mass. The plots were plowed again to incorporate plant litter into 0–5 cm topsoil layer with a rate of 0.35 kg m^{-2} for all three plant litters based on the field investigation in Zhifanggou small watershed by Li et al. (2015a). Then the plots were raked by hands to make a relatively smooth, uniform soil surface. All prepared plots were left free to open natural environmental conditions until April 2015.

2.2. Soil sampling

Undisturbed topsoil samples were collected from all four plots for 10 times during the whole experimental period, from April 19, 2015 to October 5, 2015 at approximately 20 days sampling intervals. For each