Effects of incorporated plant litter on soil resistance to flowing water erosion in the Loess Plateau of China

Long Sun a,b, Guang-hui Zhang a,c,* , Fa Liu c , Li-li Luan c

a State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100 China
b University of Chinese Academy of Sciences, Beijing 100049 China
c School of Geography, Beijing Normal University, Beijing 100875 China

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Plant litter can be incorporated into top soil via different approaches, which probably influence soil erosion processes controlled by overland flow. However, few studies have been conducted to quantify the effects of incorporated plant litter on the soil detachment process by overland flow. This study was performed to investigate the effects of incorporated litter rate on soil detachment capacity and soil resistance to flowing water erosion using undisturbed soil samples taken from 16 plots (three plant litter species by five incorporation rates, and one bare control) and were subjected to six different flow shear stresses in the Loess Plateau. The results showed that soil detachment capacity decreased exponentially with incorporated plant litter rate. A threshold of 0.35 kg m⁻² of litter needed to be incorporated to provide protection of soil from overland flow erosion. The effects of litter incorporation rate on soil detachment capacity was not significant when the incorporation rate was greater than 0.35 kg m⁻². Rill erodibility also decreased exponentially with the incorporated plant litter rate. The shape of plant litter fragments was hypothesised to account for the variations in the effects of different incorporated litter species on soil detachment capacity and rill erodibility. A distinguishable increasing linear trend was observed between critical shear stress and litter incorporated rate, but with a weak correlation. Critical shear stress also increased with incorporated rate and was related to soil cohesion.

* Corresponding author. State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, China. Tel.: +86 13671086156; fax: +86 10 58806955.
E-mail address: ghzhang@bnu.edu.cn (G.-h. Zhang).
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1. Introduction

Great efforts have been made in the past several decades to restore vegetation in order to reduce soil and water losses in the Loess Plateau (Chen, Huang, Gong, Fu, & Huang, 2007). The Grain for Green Project was implemented in 1999 to control soil erosion and improve the ecological environment. More Great efforts have been made in the past several decades to restore vegetation in order to reduce soil and water losses in the Great efforts have been made in the past several decades to restore vegetation in order to reduce soil and water losses in the Loess Plateau. The litter coverage ranged from 0% to 100%. Furthermore, as rills develop, the potential changes in near soil surface characteristics on soil detachment by overland flow and revealed that plant litter-stems contributed to 30% of the reduction in soil detachment capacity in a seven year natural succession grassland in the Loess Plateau. Sun et al. (under review) quantified the effects of litter cover on soil detachment capacity by overland flow in the Loess Plateau. The litter coverage ranged from 0% to 100% with five different classes. The results showed that soil detachment capacity was affected significantly by litter coverage and increased with litter coverage, since litter cover prevented soil from raindrop impacted consolidation. When litter cover exceeded 50%, the effects of different litter covers were relative stable. No difference was detected between three different litter species (black locust, sea buckthorn, and green bristle grass).

Besides the litter cover on the soil surface, it can also be incorporated into topsoil under natural circumstances through three processes: soil splash, sediment deposition and soil animal activities (Geddes & Dunkerley, 1999; Laossi, Ginot, & Noguera, Blouin, & Noguera, 2001; Wilson, Xu, Chen, Liu, & Romkens, 2003). Singer, Matsuda, and Blackard (1981) and McGregor, Bengtson, and Mutchler (1988) showed that increases in surface straw cover could remarkably reduce soil loss. Benkobi, Trlica, and Smith (1993) detected a close correlation between soil loss and amounts of surface litter cover. Generally, soil loss decreased with surface litter or residue cover as an exponential function (Cogo, Moldenhauer, & Foster, 1984). Wang, Zhang, Zhang, et al. (2014) investigated the effects of near soil surface characteristics on soil detachment by overland flow and revealed that plant litter-stems contributed to 30% of the reduction in soil detachment capacity in a seven year natural succession grassland in the Loess Plateau. Sun et al. (under review) quantified the effects of litter cover on soil detachment capacity by overland flow in the Loess Plateau. The litter coverage ranged from 0% to 100% with five different classes. The results showed that soil detachment capacity was affected significantly by litter coverage and increased with litter coverage, since litter cover prevented soil from raindrop impacted consolidation. When litter cover exceeded 50%, the effects of different litter covers were relative stable. No difference was detected between three different litter species (black locust, sea buckthorn, green bristle grass).

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surface litter often falls into rills and forms mini-debris dams where sediment is trapped and deposited (Pannkuk & Robichaud, 2003; Wilson et al., 2008). Furthermore, when raindrops directly disturb soil surfaces covered with very shallow overland flow, plant litter retards the water flow which accelerates sediment deposition (Moss, Walker, & Hutka, 1979). All these three sub-processes related to sediment deposition can result in the mixture of topsoil with plant litter (Fig. 1b). Thirdly, soil animals, like several species of earthworms, can incorporate the fragments of plant litter into soil (Laossi et al., 2010; Ma et al., 2014). Tsukamoto (1991) documented that Lumbricus terrestris draw fresh litter into their burrows. Anecic earthworms fragment plant litter and incorporate it into the soil where it can subsequently be ingested by endogeic earthworms (Laossi et al., 2010). Generally, plant litter can be fragmented and translocated into mineral soil horizons (Foote & Grogan, 2010; Ma et al., 2014).

Nevertheless, reports or studies about the amount of plant litter incorporated into soil are very few. To our knowledge, the only reported rates of incorporated plant litter into topsoil (0–5 cm) caused by sediment deposition ranged from 0.10 to 0.28 kg m⁻² in the Japanese cypress stands (Tsukamoto, 1991). In fact, the distribution of plant litter in topsoil is more extensive than the general presumption, especially in the vegetation restoration land in the Loess Plateau (Fig. 1). Li, Zhang, Geng, and Wang (2015) found that litter density in top 5 cm soil layer varied from 0.07 to 1.08 kg m⁻² with a mean of 0.32 kg m⁻² in a 90 m long and 40 m wide ephemeral gully developed hillslope covered with black locust (Robinia pseudacacia L.) in Zhifanggou small watershed in the Loess Plateau.

The incorporated plant litter (just like buried crop residue) probably has great influences on erosion processes, particularly on soil detachment by overland flow. In recent years, many studies have been performed to quantify the effects of incorporated crop residue on soil erosion processes (Chen, Monero, Lobb, Tessier, & Cavers, 2004; Franti, Foster, & Monke, 1996; Giménez & Govers, 2008). It is well known that crop materials incorporated into topsoil can reduce the erosive runoff energy and increase the topsoil erosion resistance to flowing water (Brown, Foster, & Beasley, 1989; Giménez & Govers, 2008; Van Liew & Saxton, 1983; Zeleke, Grevers, Si, Mermut, & Beyene, 2004), which vary with climate, topography, soil properties, crop type, incorporated rate and depth, and biological properties of crop residue (Brown, West, Beasley, & Foster, 1990; Franti, Foster, & Monke, 1996; Van Liew & Saxton, 1983; Wilson et al., 2008). Both soil detachment rate and rill erodibility decreased exponentially with the incorporated rates of crop residue (Nearing, Foster, Lane, & Finkner, 1989; Renard, Foster, Weesies, McCool, & Yoder, 1997).

Compared with crop residue, the potential effects of incorporated plant litter on the soil detachment process are poorly quantified. The quantitative relationships between incorporated-litter rates and soil detachment capacity, rill erodibility, and critical shear stress are unclear. Meanwhile, the differences in the effects of different incorporated-litter species on soil erosion remain unknown. Therefore, the objectives of this study were to quantify the effects of plant litter rates incorporated into topsoil on soil detachment capacity by overland flow and soil resistance (rill erodibility and critical shear stress) to flowing water erosion and to identify the differences in soil detachment capacity and erosion resistance between different incorporated plant litter species in the Loess Plateau of China.

2. Materials and methods

2.1. Site description

The experiment was conducted 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 and has a semi-arid, continental climate with an annual mean temperature of 8.8 °C. The annual precipitation is between 297 mm and 645 mm with a mean of 505 mm. More than 70% precipitation falls during June to September as short heavy storms. The region has a
typical silt loam loess-derived soil. The principal land uses are cropland, orchard, shrub land, woodland, grassland, and wasteland. The major plant species are *R. pseudoacacia*, *Hippophae rhamnoides*, *Caragana Korshinskii*, *Artemisia capillaries*, and *Lespedeza davurica*.

The sampling field is a 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 organic matter content was 0.76%. The initial macro-aggregates (>0.25 mm) was 75.3% and the water stable aggregates (>0.25 mm) was 25.1%.

### 2.2 Experimental treatments

The surface existing residue was removed before tillage. The remaining residue within the top 10 cm soil layer was completely eliminated manually during the processes of tillage and plot preparation. The field was tilled twice with a rototiller (the tillage depth ranged from 25 to 34 cm) to homogenise the soil properties in early May, 2014, and left open to natural environmental conditions until November. The field was then divided into 16 plots (15 for litter incorporation and one for control) with a length of 3 m and width of 1.5 m. Plant litter of *R. pseudoacacia* Linn. (Black locust, abbr. BL), *H. 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 litter of black locust and sea buckthorn consisted of leaves and a few twigs. But the litter of green bristle grass was mainly stalks and a few leaves and only this litter was chopped to a mean length of 3 cm. Prior to incorporation, the plant litter was air dried for 48 h in early November, 2014. The plots were ploughed again to incorporate plant litter into top 10 cm soil layer. The incorporated rates were 0.10, 0.35, 0.60, and 0.56, respectively. But the litter of green bristle grass was chopped to a mean length of 3 cm. Prior to incorporation, the plant litter was air dried for 48 h in early November, 2014. The cumulative rainfall period (Fig. 2). Then the soil sampling for detachment capacity measurement was started.

### 2.3 Soil detachment capacity measurement

Soil sampling procedure was the same for all 16 plots. The detailed information of soil sample collection and preparation can be found in the previous study of Zhang, Liu, Liu, He, and Nearing (2003). The main outlines are described briefly. Soil samples were collected from the top 5 cm soil layer using a circular steel ring with a 10.0 cm in diameter and a 5.0 cm in depth (Zhang, Tang, & Zhang, 2009; Zhang et al., 2003). The steel ring was slowly pushed into the soil, then excavated and cut carefully across the bottom rim of the sampler. Both ends of the ring were covered by cotton cloth to prevent disturbance during transport (Zhang et al., 2003). Thirty samples were collected from each plot and weighed as soon as possible.

Simultaneously, for each plot, soil moisture and bulk density of top 5.0 cm soil layer were measured by oven dry method using steel ring (100 cm³) for six replicates. The mean soil water content was used to calculate the original dry mass of soil sample. Soil cohesion was measured by a pocket torque (Durham Geo-enterprises, Inc., UK) for twelve replicates at the near saturated soil surface, wetted by a light sprayer (Zhang et al., 2009).

Soil detachment was measured in a 4.0 m long, 0.35 m wide flume (Zhang et al., 2003). Soil collected from the experimental field was air-dried and sieved (2 mm). The sieved soil was glued on the surface of the flume bed to simulate the natural hydraulic roughness of the test soil samples (Zhang et al., 2003, 2009). The flow discharge was controlled by a series of valves. The surface maximum flow velocity was measured by the fluorescent dye technique (Zhang et al., 2003) for ten replications when the flow became stable. Then the mean value was adjusted by a reduction coefficient of 0.8 to obtain the mean flow velocity (Abrahams, Parsons, & Luk, 1986). Flow depth was calculated as:

\[
S_f = \sum \frac{p_i l_i w_i h_i}{V_i} \tag{1}
\]

where the \(i\) is the different components (e.g. leaves, twigs), \(p_i\) is the ratio of volume of a specific component to total volume of the plant litter, \(l_i\) is the length of the \(i\)th litter fragment (mm), \(w_i\) is the width of the \(i\)th litter fragment (mm), \(h_i\) is the height of the \(i\)th litter fragment (mm), and \(V_i\) is the volume of the \(i\)th litter fragment measured by water displacing volumetric method (mm³). For each litter species, \(S_f\) was calculated for twenty replications and the mean was used to represent the geometry for that litter species. The computed \(S_f\) for black locust, sea buckthorn and green bristle grass were 0.14, 0.22, and 0.56, respectively.

All prepared plots were left free to open natural environmental conditions until April, 2015. The cumulative rainfall was 41.2 mm and the mean temperature was 0.2 °C during this period (Fig. 2).
\[ h = \frac{Q}{Bv} \]  
(2)

where \( h \) is the flow depth (m), \( Q \) is the flow discharge (m\(^3\) s\(^{-1}\)), \( B \) is the width of flume (m), and \( v \) is the mean flow velocity (m s\(^{-1}\)). The flow shear stress was calculated as (Zhang et al., 2003):

\[ \tau = \rho ghS \]  
(3)

where \( \tau \) is the flow shear stress (Pa), \( \rho \) is the water mass density (kg m\(^{-3}\)), \( g \) is the gravitational acceleration (m s\(^{-2}\)), \( h \) is the depth of flow (m), and \( S \) is the sine of flume bed slope gradient (m m\(^{-1}\)). In this study, six combinations of flow rate and slope gradient were applied to obtain six different flow shear stresses ranging from 5.7 to 17.8 Pa.

Prior to the test, soil samples were wetted-up in containers with a water level of 1 cm below the top soil surface for 8 h and drained for 12 h. Then the soil sample was inserted into a hole (located 0.5 m above the lower end of flume) on the flume bed and subjected to scouring under designed flow shear stress (Zhang et al., 2003). The test was ceased when the scouring depth of soil sample was approximately 2 cm (Knapen, Poese, & De Baets, 2007; Zhang et al., 2003). Then the scoured sample was oven dried at 105°C for 24 h and weighed to calculate the final dry soil mass (Li, Zhang, Geng, & Wang, 2015; Wang, Zhang, Shi, et al., 2014). The plant litter washed away from the sample during the process of scouring was collected using fine mesh plastic nets at the flume outlet, and then was oven dried at 65°C for 24 h (Austin & Ballaré, 2010; Rodushkin, Ruth, & Huhtasara, 1999) and weighed. Soil detachment capacity (\( D_s \), kg m\(^{-2}\) s\(^{-1}\)) was calculated as (Zhang et al., 2003, 2009):

\[ D_s = \frac{M_s - M_f - M_l}{tA} \]  
(4)

where \( M_s \) is the original dry mass of soil sample (kg), \( M_f \) is the final dry soil mass after scouring (kg), \( M_l \) is the dry mass of plant litter fragments washed away during the test (kg), \( A \) is the cross-sectional area of soil sample (m\(^2\)), and \( t \) is the test duration (s). Soil detachment capacity was tested for five replicates under each flow shear stress and the mean was considered as the measured soil detachment capacity for that flow shear stress. Altogether, 480 samples were tested for three plant species and one control plot. The relative soil detachment capacity (\( RD_s \)) was calculated as the ratio of the absolute soil detachment capacity of different litter incorporated treatments to the absolute soil detachment capacity of control.

Rill erodibility and critical shear stress were used to reflect soil resistance to flowing water erosion (Knapen et al., 2007). They were estimated from the linear regression between the measured soil detachment capacity and flow shear stress described by Water Erosion Prediction Project (WEPP) model (Nearing et al., 1989):

\[ D_s = K_r (\tau - \tau_c) \]  
(5)

where \( K_r \) is the rill erodibility (s m\(^{-1}\)), and \( \tau_c \) is the critical shear stress (Pa). The relative rill erodibility (\( RK_r \)) was computed as the ratio of the absolute rill erodibility of different litter incorporated treatments to the absolute rill erodibility of control.

### 2.4 Data analysis

Paired t-tests were utilised to detect significant differences in soil detachment capacity, rill erodibility, and critical shear stress between different incorporation rates of each litter species and between different species of plant litter. Pearson correlation was used to analyse the relationships between incorporated litter rates and \( D_s \), \( K_r \), and \( \tau_c \). The simple regression method was utilised to analyse the relationship between incorporated litter rate and \( RD_s \), \( RK_r \), and \( \tau_c \), and the relationship between \( \tau_c \) and soil cohesion. The performance of the regression results was evaluated by the coefficient of determination (\( R^2 \)) and the coefficient of Nash-Sutcliffe model efficiency (NSE). All statistical analyses were performed using IBM SPSS Statistics (version 19.0, SPSS Inc., Chicago, IL).

### 3 Results and discussion

#### 3.1 Effects of litter incorporation rates on soil detachment capacity

Soil detachment capacity by overland flow was significantly influenced by litter incorporation for all three types of litter (Fig. 3). The measured \( D_s \) of control was generally greater than those of litter incorporated treatments (Fig. 3). However, the upper quartiles of the box at incorporation rate of 0.10 kg m\(^{-2}\) for black locust and sea buckthorn and the lower quartile of the box at incorporation rate of 0.10 kg m\(^{-2}\) for green bristle grass were slightly greater than that of the control. A possible explanation was that the litter incorporation may have partly protected the surface soil and hampered the process of soil surface crusting and consolidation induced by raindrop impact, thus resulting in a greater soil strength for the control. Meanwhile, the enlargement of the soil erosion resistance due to litter incorporation could not be compensated for by the changes in soil strength.

Soil detachment capacities of the different litter species showed a similar decreasing trend with litter incorporation rates. Significant differences between incorporation rates and the control were detected for all three species (Fig. 3). The mean detachment capacities of different incorporation rates varied from 1.41 to 2.51 kg m\(^{-2}\) s\(^{-1}\), 1.20 to 2.43 kg m\(^{-2}\) s\(^{-1}\), and 1.06 to 2.40 kg m\(^{-2}\) s\(^{-1}\) with the means of 1.78, 1.67, and 1.57 kg m\(^{-2}\) s\(^{-1}\) for black locust, sea buckthorn, and green bristle, respectively. The mean detachment capacities were of the same magnitude as those measured from cropland in the Loess Plateau by Yu, Zhang, Geng, and Sun (2014). The relative soil detachment capacities ranged from 0.52 to 0.92, 0.44 to 0.89, and 0.39 to 0.88 for black locust, sea buckthorn, and green bristle. Compared with the control, soil detachment capacities for the greatest incorporation rate of black locust, sea buckthorn and green bristle grass were reduced by 48%, 56% and 61%.
For all three litter species, soil detachment capacity was not significantly greater than the control for the 0.10 kg m$^{-2}$ incorporation rate. However, they differed significantly when the incorporated litter rate increased from 0.10 to 0.35 kg m$^{-2}$. No statistical difference was detected among incorporation rates above 0.35 kg m$^{-2}$ for all three litter species (Fig. 3). This result implied that the effect of litter incorporation rate on soil detachment capacity was similar when the incorporation rate was greater than 0.35 kg m$^{-2}$. In other words, a threshold value of litter incorporation rate of between 0.10 and 0.35 kg m$^{-2}$ existed to protect soil effectively from detachment by overland flow. Importantly, plant litter incorporation effect in situ is the sum of mechanical and biological components, and the reduction in soil detachment capacity with time after litter incorporation is considered a function of the biological decomposition rate (Brown et al., 1990). In this study the plant litter could be considered as undecomposed or having only decomposed at a very low rate since the temperature was quite low (Fig. 2). The decomposition rate would accelerate for warm and rainy summer in the Loess Plateau. Therefore, the threshold rate of litter incorporation to prevent soil effectively from detachment by overland flow probably changes with the climatic cycle.

The relative mean soil detachment capacity decreased exponentially with the incorporated litter rate for all three plant species (Fig. 4). The exponents for black locust, sea buckthorn, and green bristle grass were $-0.737$, $-0.841$, and $-0.961$. Van Liew and Saxton (1983) among others (Brown et al., 1989, 1990) found that the variation in the regression exponent was closely related to litter type, decomposition rate, and soil properties. In current study, the decomposition rate was very low and soil properties were homogenised. Hence, the difference in regression exponent was probably derived from the plant litter species, including its shape and mechanical properties. This implication could be confirmed by the similar trend between regression exponents and shape complexity factors of three litter species.

### 3.2. Rill erodibility as influenced by litter incorporation rate

The rill erodibilities under different litter incorporation rates of three litter species, regressed using the measured soil detachment capacity and flow shear stress, are shown in Table 1. Correlation between rill erodibility and litter incorporation rate was significant for all three litter species and the Pearson correlation coefficients for black locust, sea buckthorn, and green bristle were $-0.97$ ($p = 0.006$), $-0.95$ ($p = 0.014$), and $-0.99$ ($p = 0.002$), respectively. For green
bristle grass, rill erodibility varied from 0.15 s m\(^{-1}\) at the incorporation rate of 1.10 kg m\(^{-2}\) to 0.35 s m\(^{-1}\) for control treatment. While for black locust and sea buckthorn the minimum \(K_r\) were 0.19 and 0.17 s m\(^{-1}\). Compared with the control, rill erodibilities reduced by 47%, 50% and 59% for black locust, sea buckthorn and green bristle grass when the litter incorporation rate was greatest. Rill erodibility (0.35 s m\(^{-1}\)) of control (no litter incorporation) in this study was lower than the measured rill erodibilities (greater than 0.5 s m\(^{-1}\)) just after tillage operation in the study of Yu, Zhang, Geng, and Li (2014). This difference was probably contributed to by the processes of soil consolidation and surface crust development in this study during the standing period (Knappen et al., 2008). Rill erodibilities at the highest incorporation rate for three litter species ranged from 0.15 to 0.19 s m\(^{-1}\), which were similar to rill erodibilities measured from the undisturbed soils in the Loess Plateau (Li et al., 2015; Zhang, Liu, Tang, & Zhang, 2008).

The relative rill erodibility (\(R_k\)) varied from 0.53 to 0.89, 0.50 to 0.86, and 0.41 to 0.84 for black locust, sea buckthorn and green bristle grass, respectively. The \(R_k\) decreased as an exponential function with litter incorporation rate for all three litter species and the coefficients of determination (\(r^2\)) were greater than 0.90 (Fig. 5). The negative exponential relationship between rill erodibility and incorporated litter rate, i.e. rill erodibility adjustment factor, is consistent with the results of residue incorporation (Alberts et al., 1995; Brown et al., 1989) and inter-rill erosion under surface straw cover (McGregor et al., 1988). The regression exponents (BL: –0.569, SB: –0.629, GBG: –0.803) were of the same magnitude as those documented in the literature (Alberts et al., 1995; Brown et al., 1989). Nevertheless, they were obviously greater than the recommended exponent (–0.4) for incorporated residue in WEPP model (Alberts et al., 1995) and the exponents (ranged from –0.116 to –0.227) reported by Brown et al. (1989) for silt loam soil incorporated with cornstalk residue. This difference was probably caused by the differences in climate, soil, and litter or residue species as well as their distribution within soil profile, which were closely related to litter or residue decomposition (Brown et al., 1989, 1990; Debevec, 1984; Van Liew & Saxton, 1983). This implication was partially confirmed by the close correlation between the regression exponents of relative rill erodibility and \(S_I\) of three litter species.

### 3.3 Relationship between critical shear stress and incorporation rates

The fitted critical shear stresses under different incorporation rates for three litter species are shown in Table 1 and ranged from 3.79 Pa (incorporation rate of 0.10 kg m\(^{-2}\) for sea buckthorn) to 5.10 Pa (incorporation rate of 0.85 kg m\(^{-2}\) for black locust). Generally, critical shear stress increased with the litter incorporated rate (Fig. 6). This result is in accordance with the result of a previous study (Léonard & Richard, 2004). Compared to rill erodibility, the relationship between litter incorporation rate and critical shear stress was more closely related to the critical shear stress.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Incorporation rates (kg m(^{-2}))</th>
<th>Regression equation</th>
<th>(K_r) (s m(^{-1}))</th>
<th>(\tau_c) (Pa)</th>
<th>(R^2)</th>
<th>NSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0</td>
<td>(D_c = 0.3520 - 1.4453)</td>
<td>0.35</td>
<td>4.11</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Black locust</td>
<td>0.10</td>
<td>(D_c = 0.3131 - 1.2008)</td>
<td>0.31</td>
<td>3.84</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>(D_c = 0.2630 - 1.2284)</td>
<td>0.26</td>
<td>4.67</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>(D_c = 0.2415 - 1.1748)</td>
<td>0.24</td>
<td>4.87</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>0.85</td>
<td>(D_c = 0.2057 - 1.0487)</td>
<td>0.21</td>
<td>5.10</td>
<td>0.89</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>1.10</td>
<td>(D_c = 0.1862 - 0.7952)</td>
<td>0.19</td>
<td>4.27</td>
<td>0.91</td>
<td>0.91</td>
</tr>
<tr>
<td>Sea buckthorn</td>
<td>0.10</td>
<td>(D_c = 0.3013 - 1.1417)</td>
<td>0.30</td>
<td>3.79</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>(D_c = 0.2437 - 1.1798)</td>
<td>0.24</td>
<td>4.84</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>(D_c = 0.2216 - 0.9993)</td>
<td>0.22</td>
<td>4.51</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>0.85</td>
<td>(D_c = 0.1913 - 0.8899)</td>
<td>0.19</td>
<td>4.65</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>1.10</td>
<td>(D_c = 0.1749 - 0.8729)</td>
<td>0.17</td>
<td>4.99</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>Green bristle grass</td>
<td>0.10</td>
<td>(D_c = 0.2973 - 1.1277)</td>
<td>0.30</td>
<td>3.79</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>(D_c = 0.2212 - 0.9556)</td>
<td>0.22</td>
<td>4.33</td>
<td>0.89</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>(D_c = 0.1833 - 0.7083)</td>
<td>0.18</td>
<td>3.86</td>
<td>0.93</td>
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</tr>
<tr>
<td></td>
<td>0.85</td>
<td>(D_c = 0.1758 - 0.8144)</td>
<td>0.18</td>
<td>4.63</td>
<td>0.96</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>1.10</td>
<td>(D_c = 0.1451 - 0.6546)</td>
<td>0.15</td>
<td>4.51</td>
<td>0.92</td>
<td>0.92</td>
</tr>
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</table>
incorporated rate and critical shear stress was weak, especially for black locust ($r^2 = 0.27$). This difference was partially caused by the random roughness of the soil surface affected by incorporated plant litter, and was also related to the interference induced by plant litter in the process of soil sealing and crusting (Alberts et al., 1995; Knapen et al., 2007).

The minimum critical shear stress occurred at the incorporation rate of 0.10 kg m$^{-2}$ rather than control treatment which might be attributed to the incorporated litter inhibiting the processes of crusting and consolidation (Knapen et al., 2007).

Soil cohesion was considered as a satisfactory soil property to reflect critical shear stress (Knapen et al., 2007; Léonard & Richard, 2004). As shown in Fig. 7, a distinguishable linear trend was showed between critical shear stress and soil cohesion. This result is consistent with the result of Knapen et al. (2007). However, none of the relationships were significant (BL: $r^2 = 0.56$, $p = 0.086$; SB: $r^2 = 0.62$, $p = 0.063$; GBG: $r^2 = 0.61$, $p = 0.068$), which suggests that the critical shear stress-soil cohesion relationship was not suitable for soil incorporated with plant litter. The non-significant relationship was similar to the result derived from the soil surface covered with residue (Knapen et al., 2007), and implies that plant litter incorporation was similar to residue cover in terms of response.

4. Conclusions

This study was performed to investigate the effects of incorporated plant litter on soil detachment capacity by overland flow and soil resistance to flowing water erosion using undisturbed samples collected from sixteen plots (a control and fifteen combinations of three plant litter species and five incorporation rates) in the Loess Plateau of China. The results showed that soil detachment capacity decreased exponentially with incorporated plant litter rate. No significant difference was detected between the effects of different incorporation rates on soil detachment capacity when the incorporation rates were above 0.35 kg m$^{-2}$, thus a threshold of litter incorporation of no greater than 0.35 kg m$^{-2}$ was observed. The incorporated litter of green bristle grass was more effective than that of black locust at preventing soil from detachment by overland flow. Rill erodibility also decreased with incorporated plant litter rate exponentially. Shape complexity factor of plant litter could partially explain the variations in the effects of incorporated litter on soil detachment capacity and rill erodibility. Critical shear stress increased with litter incorporation rate for all three litter species. However, only a weak relationship was detected between critical shear stress and soil cohesion. The results were helpful for understanding the erosion mechanism under vegetation recovery conditions and for evaluating the benefit of soil and water conservation of vegetation succession in the Loess Plateau. Further studies are needed to investigate the temporal variations in the effects of litter incorporation on soil erosion process by overland flow in the Loess Plateau.

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References


