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

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\textbf{A R T I C L E I N F O}

\textbf{Keywords:}
Overland flow
Soil resistance
Stream power
Grassland
The Loess Plateau

\textbf{A B S T R A C T}

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 kg m\textsuperscript{-2} s\textsuperscript{-1}) was found in Astragalus mellilotoides Pall. grassland, where it was 49.0 times greater than that of the minimum found in Poo 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,
cohesion, water stable aggregate, clay content and organic matter (Torri et al., 1998; Kaapen 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-erosibility 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 ischecemum (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′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
tested within the interval of 2 m at the distance of 0.6 m from the flume outlet by using a fluorescent dye method (KMSO₄). During the velocity test, 10 evenly distributed points were selected at the flume cross section and 3 times were tested at each point. The flow mean velocity then was calculated by multiplying by a reduction factor (Luk and Merz, 1992). The flow depth (h, m), shear stress (τ, Pa), stream power (α, kg m⁻²) and unit stream power (ρ, m s⁻¹) were calculated using Eq. (1), (2), (3) and Eq. (4), respectively.

\[
h = \frac{Q}{vB} \quad (1)
\]

\[
τ = ρghS \quad (2)
\]

\[
ω = τv \quad (3)
\]

\[
p = S\overline{v} \quad (4)
\]

where Q is the flow discharge (m³ s⁻¹), v is the mean flow velocity (m s⁻¹), and B is the flume width (B = 0.35 m), ρ is the density of water (kg m⁻³), g is the constant of gravity (m s⁻²), and S is the sine of the slope (m⁻¹).

For each desired combination of slope and flow discharge, soil samples were set into a hole (10 cm in diameter) in the flume bed at the distance of 0.6 m from the flume outlet to determine soil detachment capacities. Five samples were tested under each shear stress and the mean was used for further analysis. In total, 300 soil samples were tested. To eliminate the effects of the soil moisture on the soil detachment measurement, all the collected samples were wetted for 8 h (with a constant water level of 4.5 cm below the soil surface to allow for a slow capillary rise) and then were taken out to drain before scouring (De Baets and Poesen, 2010; Wang and Zhang, 2017). The test time (varied from 1.41 to 204.93 s) was controlled by the scouring depth (2 cm) for each soil sample to reduce the potential effects of ring rim on experimental results (Nearing et al., 1991; Zhang et al., 2002). Soil
The dry weight of soil sample after scouring (kg), shear stress (Nearing et al., 1989):

\[ \text{shear stress} = \frac{W_e - W_i}{A \times t} \]  

(5)

where \( W_e \) is the dry weight of soil sample before scouring (kg), \( W_i \) is the dry weight of soil sample after scouring (kg), \( A \) is the scouring area \((m^2)\), and \( t \) is the scouring time \((s)\).

Soil resistance, reflected by rill erodibility \( (K_e) \) and critical shear stress \( (\tau_c) \), was calculated based on the equation in Water Erosion Prediction Project (WEPP) model (Eq. (6)). Rill erodibility and critical shear stress are the slope and the intercept on the x axis of the regression line between the measured soil detachment capacity and flow shear stress (Nearing et al., 1989):

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

(6)

2.5. Statistical analysis

Curve estimation was used to find the better relationships between soil detachment capacity and hydraulic parameters. The partial correlation was used to analyze the correlation coefficient between soil detachment capacity and soil properties. The stepwise regression was used to detect the main factors of hydraulic parameters and soil properties affecting soil detachment capacity. Linear regression was used to calculate the soil resistance. The performance fitness was evaluated by \( R^2 \) and Nash–Sutcliffe efficiency (NSE). All analyses were made using SPSS 22.0 software (IBM SPSS Statistics., 2013) and Origin Pro 8.0 software (OriginLab Corp., 2008).

3. Results

3.1. Changes in soil properties induced by natural grassland succession

Soil properties induced by natural grassland succession vary greatly based on differences in vegetation characteristics (Jiao et al., 2008). In this study, the aboveground biomass (ranged from 2.02 to 31.93 g), root distribution depth (18.23 to 35.00 cm) and underground biomass (ranged from 0.33 to 9.47 g) showed a wide range of variation between the ten typical grasslands and caused a significant variation in soil properties (Table 1 and Table 2). The maximum soil cohesion (4.6 KPa) was found in Artemisia vestita Wall. ex Bess., and was 3.8 times greater than that of the minimum, which was found in Leymus secalinus (Georgi) Tzvel. The differences in soil properties were also found among ten tested grasslands with different plant root types. For five grasslands with tap root systems, the mean soil cohesion, bulk density, and sand content were between 3% and 6% lower than that of the other five grasslands with fibrous root systems, while mean silt content, clay content, median soil grain size, and soil organic matter increased by between 3% and 54% in grasslands with tap root systems, compared to that of grasslands with fibrous root systems. These results confirm that differences in vegetation characteristics, including plant species, biomass, and root type have great effects on soil properties, and hence affect the process of soil detachment.

3.2. Variation of soil detachment capacity under ten natural grasslands

Soil detachment capacity showed significant differences between the ten tested grasslands. The mean soil detachment capacity ranged from 0.01 to 14.21 kg m\(^{-2}\) s\(^{-1}\), with a mean of 1.04 kg m\(^{-2}\) s\(^{-1}\) (Fig.1). The maximum mean soil detachment capacity of the ten grasslands was found in Astragalus melilotoides Pall., where it was 3.80 kg m\(^{-2}\) s\(^{-1}\). Correspondingly, the minimum mean soil detachment capacity was occurred in Poa sphondylodes Trin., where it was 0.08 kg m\(^{-2}\) s\(^{-1}\). The maximum soil detachment capacity was 49.0 times greater than that of the minimum, which demonstrated a great difference in soil detachment capacity caused by the herbage species.

The great difference in soil detachment capacity was also found between the different herbage root types of the ten tested grasslands. For the five herbage grasslands with tap root system, the ratio of the minimum, which was found in Leymus secalinus (Georgi) Tzvel. The differences in soil properties were also found among ten tested grasslands with different plant root types. For five grasslands with tap root systems, the mean soil cohesion, bulk density, and sand content were between 3% and 6% lower than that of the other five grasslands with fibrous root systems, while mean silt content, clay content, median soil grain size, and soil organic matter increased by between 3% and 54% in grasslands with tap root systems, compared to that of grasslands with fibrous root systems. These results confirm that differences in vegetation characteristics, including plant species, biomass, and root type have great effects on soil properties, and hence affect the process of soil detachment.

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The great difference in soil detachment capacity was also found between the different herbage root types of the ten tested grasslands. For the five herbage grasslands with tap root system, the ratio of the
maximum mean soil detachment capacity (Arachis melleoloides Pall.) to the minimum (Lespedeza davurica (Laxm.) Schindl.) was 36.6. However, for other five herbage grasslands with fibrous root systems, the corresponding value was only 5.7 (Säpa bungeana Trin. in maximum and Poa sphenoidales Trin. in minimum). Moreover, for the five herbage grasslands with tap root systems, their soil mean detachment capacity was 1.81 kg m⁻² s⁻¹ (ranging from 0.01 to 14.21 kg m⁻² s⁻¹), while the mean soil detachment capacity of the five herbage grasslands with fibrous root systems was 0.28 kg m⁻² s⁻¹ (ranging from 0.03 to 1.87 kg m⁻² s⁻¹), which was 84.6% less than that of the grasslands with tap root systems. This result indicated that fibrous root systems are much more effective than tap root system at improving soil properties and enhancing soil resistance to flowing water erosion.

4. Discussions

4.1. The effects of hydraulic parameters on the process of soil detachment

Hydraulic factors, such as flow velocity (v, m s⁻¹), shear stress (τ, Pa), stream power (ω, kg s⁻³), and unit stream power (p, m s⁻¹), influence soil detachment capacity greatly (Zhang et al., 2002). In this study, the measured soil detachment capacity of each grassland increased with flow velocity, shear stress, stream power and unit stream power. Soil detachment capacity could be expressed as a series of power functions of flow velocity (Table 4; Fig. 2), shear stress (Table 4; Fig. 3), stream power (Table 4; Fig. 4), and unit stream power (Table 4; Fig. 5), respectively. Generally, soil detachment capacity by overland flow was better simulated by stream power (R² ranged from 0.78 to 0.98 with mean of 0.90) than by velocity (R² ranged from 0.66 to 0.96 with mean of 0.85), shear stress (R² ranged from 0.75 to 0.99 with mean of 0.87), or unit stream power (R² ranged from 0.59 to 0.94 with mean of 0.78).

Some previous studies have also indicated that soil detachment capacity by overland flow was better simulated by stream power with a power function (Nearing et al., 1999; Zhang et al., 2002). The fitted equations of undisturbed bare soil (with 43% of rock fragments) reported by Nearing et al. (1999) and disturbed bare soil (static compression with a bulk density of 1.2 g cm⁻³) reported by Zhang et al. (2002) were compared with the results of this study. The predicted results were quite different. Soil detachment capacity estimated by equation of disturbed bare soil (Zhang et al., 2002) increased quickly with stream power, while the estimated results by equation of undisturbed bare soil (Nearing et al., 1999) increased slowly with stream power compared to the data of this study (Table 4; Fig. 6). For the undisturbed bare soil mixed with rock fragments, the low soil detachment capacity was partially due to the 43% of soil mass replaced by rock fragments. The mixed rock fragments would dissipate the kinetic energy of the flowing water, and enhance the stability of the soil mass. For the disturbed bare soil, the stability of soil was destroyed during the process of static compression and made the soil more easier to detach, although the soil bulk density was almost the same with this study (the mean soil bulk density of this study was 1.21 g cm⁻³).

4.2. The effects of soil properties on the process of soil detachment

The growth of herbage can improve the properties of top soil layer, and hence affect the process of soil detachment. In this study, soil properties, such as cohesion, bulk density, organic matter content, soil particle size distribution (clay, silt and sand content) and the median soil grain size were significantly correlated with soil detachment capacity (positively or negatively; p < 0.05; Table 5). Soil detachment capacity increased with sand content and the median soil grain size, while it decreased with soil cohesion, bulk density, organic matter, silt content, and clay contents. In general, soil mass with high sand content was easily scoured by flowing water because of its low cohesiveness, while high clay content and soil organic matter would enhance the stability of the soil mass and reduce the soil detachment capacity. The increase in soil bulk density would increase the compactibility and soil

Table 4

<table>
<thead>
<tr>
<th>Site code</th>
<th>Velocity (v, m s⁻¹)</th>
<th>Shear stress (τ, Pa)</th>
<th>Stream power (ω, kg s⁻³)</th>
<th>Unit stream power (p, m s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equation R²</td>
<td>Equation R²</td>
<td>Equation R²</td>
<td>Equation R²</td>
</tr>
<tr>
<td>HH</td>
<td>Dv = 0.75v0.4032</td>
<td>Dτ = 0.058v0.507</td>
<td>Dx = 0.127τ0.219</td>
<td>Dy = 10.53τ1.410</td>
</tr>
<tr>
<td>HQ</td>
<td>Dv = 1.02v0.671</td>
<td></td>
<td>Dτ = 0.031v0.71</td>
<td>Dp = 12.43τ1.478</td>
</tr>
<tr>
<td>AH</td>
<td>Dv = 0.023v0.878</td>
<td></td>
<td>Dτ = 0.002v0.981</td>
<td>Dp = 0.29τ0.374</td>
</tr>
<tr>
<td>TGH</td>
<td>Dv = 0.022v0.826</td>
<td></td>
<td>Dτ = 0.003v0.981</td>
<td>Dp = 0.33τ0.764</td>
</tr>
<tr>
<td>HZZ</td>
<td>Dv = 0.039v0.752</td>
<td></td>
<td>Dτ = 0.005v0.861</td>
<td>Dp = 0.19τ0.769</td>
</tr>
<tr>
<td>ZSH</td>
<td>Dv = 0.018v0.93</td>
<td></td>
<td>Dτ = 0.002v0.821</td>
<td>Dp = 0.20τ0.988</td>
</tr>
<tr>
<td>CMC</td>
<td>Dv = 0.096v0.362</td>
<td></td>
<td>Dτ = 0.004v0.89</td>
<td>Dp = 1.52τ0.344</td>
</tr>
<tr>
<td>BC</td>
<td>Dv = 0.06v0.50</td>
<td></td>
<td>Dτ = 0.002v0.95</td>
<td>Dp = 1.04τ0.420</td>
</tr>
<tr>
<td>YZC</td>
<td>Dv = 0.028v0.423</td>
<td></td>
<td>Dτ = 0.001v0.92</td>
<td>Dp = 0.41τ0.44</td>
</tr>
<tr>
<td>BYC</td>
<td>Dv = 0.029v0.464</td>
<td></td>
<td>Dτ = 0.006v0.836</td>
<td>Dp = 0.24τ0.996</td>
</tr>
<tr>
<td>Ten grasslands</td>
<td>Dv = 0.21v0.869</td>
<td>Dτ = 0.018v0.698</td>
<td>Dτ = 0.031v0.239</td>
<td>Dp = 2.71τ0.425</td>
</tr>
</tbody>
</table>

Note: HH, HQ, AH, TGH and HZZ are Artemisia capillaris Thunb., Arachis melleoloides Pall., Artemisia argyi Lev. et Vant., Artemisia vestita Wall. ex Bess., and Lespedeza davurica (Laxm.) Schindl., respectively. ZSH, CMC, BC, YZC and BYC are Poa sphenoidales Trin., Säpa bungeana Trin., Leymus secalinus (Georgii) Tzvel., Cleistogenes squarrosa (Trin.) Keng, and Bothriochloa isechinum (Linn.) Keng, respectively.
cohesion of the soil mass, thereby resulting in a low erosion rate (Wang et al., 2014).

It is imperative to develop an effective model to simulate or estimate soil detachment capacity based on easily measured parameters, such as hydraulic parameters and soil properties. Torri et al. (1998) assumed that soil grains were spherical, and developed an equation by using stream power and soil properties to estimate soil detachment capacity as follows:

\[ D_{c} = \delta_{s}D_{50}\omega C^{1.5} \]  


(7)

where \( \delta_{s} \) is the bulk density (kg m\(^{-3}\)), \( D_{50} \) is the median soil grain size (\( \mu m \)), \( C \) is the function of clay content (%), \( \tau_{s} \) is the soil cohesion (Pa). Then Ciampalini and Torri (1998) optimized it by nonlinear technique and revised it to:

\[ D_{c} = \frac{\delta_{s}D_{50}\omega C}{1.5} \]  


(8)

\[
D_{c} = 0.38\frac{\delta_{s}D_{50}\omega}{\tau_{s}} \exp \left[ 6.4 \frac{C}{D_{50}} + 7.1S - 1.3 \left( \frac{\delta_{s} - \rho}{\rho} \right) \right]
\]  


(9)

Although the simulated results by Eq. (9) (\( R^2 = 0.47; \) NSE = 0.47) and Eq. (10) (\( R^2 = 0.78; \) NSE = 0.53) were significant, notable scatter appeared and many values of soil detachment capacity were underestimated (Fig. 7). Moreover, the effects of soil organic matter on soil detachment capacity were not considered in the above equations, which would great affect the performances of those equations. Hence, the stream power and all the tested soil properties were considered to develop a model to estimate soil detachment capacity by overland flow:
4.3. The effects of soil properties on soil resistance to flowing water erosion

The fitted rill erodibility \( (K_r) \) and critical shear stress \( (\tau_c) \) reflected soil resistance to flowing water erosion and were calculated through the linear regression between the measured soil detachment capacity and flow shear stress based on the WEPP Model (Eq. (6), Nearing et al., 1989). Soil properties were commonly considered having significant influences on soil resistance. In this study, rill erodibility and critical shear stress varied significantly among ten grasslands, and their mean values were 0.152 s m\(^{-1}\) and 3.3 Pa. (Table 6). Rill erodibility was

\[
K_r = 4.220 \exp(-0.002COH) \\
R^2 = 0.89; p < 0.01
\]

\[(11)\]

where \( \text{COH} \) is the soil cohesion (KPa), \( BD \) is the soil bulk density \( (\text{g cm}^{-3}) \), and \( \text{SOM} \) is the soil organic matter \( (\text{g kg}^{-1}) \). Compared to Eq. (9) and Eq. (10), the performance of Eq. (11) was improved greatly \( (R^2 = 0.78; \text{NSE} = 0.61; p < 0.01; \text{Fig. 8}) \).

Table 5

<table>
<thead>
<tr>
<th>Cohesion</th>
<th>Bulk density</th>
<th>Soil organic matter</th>
<th>Sand content</th>
<th>Silt content</th>
<th>Clay content</th>
<th>Median soil grain size</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.667**</td>
<td>-0.351**</td>
<td>-0.516**</td>
<td>0.564**</td>
<td>-0.575**</td>
<td>-0.616**</td>
<td>0.599**</td>
</tr>
</tbody>
</table>

Note: \( n = 60 \).

** \( p < 0.01 \).

Table 6

Fitted rill erodibility and critical shear stress for ten grasslands.

<table>
<thead>
<tr>
<th>Sites</th>
<th>Tap root system</th>
<th>Sites</th>
<th>Fibrous root system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rill erodibility</td>
<td>Critical shear stress</td>
<td>Rill erodibility</td>
</tr>
<tr>
<td></td>
<td>( (\text{s m}^{-1}) )</td>
<td>( (\text{Pa}) )</td>
<td>( (\text{s m}^{-1}) )</td>
</tr>
<tr>
<td>HH</td>
<td>0.5806</td>
<td>3.9061</td>
<td>ZSH</td>
</tr>
<tr>
<td>HQ</td>
<td>0.6906</td>
<td>4.1720</td>
<td>CMC</td>
</tr>
<tr>
<td>AH</td>
<td>0.0140</td>
<td>1.7769</td>
<td>BC</td>
</tr>
<tr>
<td>TGH</td>
<td>0.0199</td>
<td>4.2471</td>
<td>YZC</td>
</tr>
<tr>
<td>HZZ</td>
<td>0.0111</td>
<td>1.1303</td>
<td>BYC</td>
</tr>
</tbody>
</table>

Note: HH, HQ, AH, TGH and HZZ are \( \text{Artemisia capillaris} \) Thunb., \( \text{Artemisia melilotoides} \) Pall., \( \text{Artemisia argyi} \) Levl. et Vant., \( \text{Artemisia vestita} \) Wall. ex Bess., and \( \text{Lespedeza davurica} \) (Laxm.) Schindl., respectively. ZSH, CMC, BC, YZC and BYC are \( \text{Poa sphenoides} \) Trin., \( \text{Stipa bungeana} \) Trin., \( \text{Leymus secalinus} \) (Georgi) Tzvel., \( \text{Cleistogenes squarrosa} \) (Trin.) Keng, and \( \text{Bothriochloa ischchemum} \) (Linn.) Keng, respectively.
closely related to soil cohesion, clay content, and the median soil grain size. It decreased with soil cohesion (exponential function, $R^2 = 0.89$; Fig. 9) and clay content (power function, $R^2 = 0.34$; Fig. 10), and increased with the increase of soil cohesion and clay content, soil mass became more stable, which made the soil hard to be scoured by flowing water and thus reduced rill erodibility. Conversely, with the increase of the median soil grain size, soil became looser and more easily detached, and rill erodibility increased. However, no significant relationships were found between soil properties and critical shear stress. Further studies are needed to quantify the effects of plant root type and its characteristics on the process of soil detachment.

Acknowledgments

Financial assistance for this work was provided by the National Natural Science Foundation of China (41530858 and 41771555), National Key Research and Development Plan (2016YFC0501703), the Innovative Talents Promotion Plan in Shaanxi Province (2017KJXX-88). We thank the members of the Ansai Research Station of Soil and Water Conservation, the Chinese Academy of Sciences and the Ministry of Water Resources for their technical assistance.

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Fig. 11. Rill erodibility as an exponential function of median soil grain size.

The changing of soil properties induced by vegetation succession greatly affected the process of soil detachment. Soil properties changed greatly with the difference in plant species and resulted in great differences in the process of soil detachment among the ten selected grasslands. The maximum value of bare soil detachment capacity was found in *Astragalus melilotoides* Pall. grassland, where it was 3.80 kg m$^{-2}$ s$^{-1}$, and it was 49.0 times greater than that of the minimum value, which was found in *Poa sphondylodes* Trin. grassland. Moreover, soil properties induced by fibrous root herbage have strong effects on the process of soil detachment. Compared to grasslands having tap root systems, soil detachment capacity and rill erodibility was reduced by 84.6% and 84.3%, while critical shear stress was increased by 15.2%. Although soil detachment capacity increased with the increases of median soil grain size as an exponential function, while no significant relationship was found between soil properties and critical shear stress. Further studies are needed to quantify the effects of plant root type and its characteristics on the process of soil detachment.

5. Conclusions

The changing of soil properties induced by vegetation succession greatly affected the process of soil detachment. Soil properties changed greatly with the difference in plant species and resulted in great differences in the process of soil detachment among the ten selected grasslands. The maximum value of bare soil detachment capacity was found in *Astragalus melilotoides* Pall. grassland, where it was 3.80 kg m$^{-2}$ s$^{-1}$, and it was 49.0 times greater than that of the minimum value, which was found in *Poa sphondylodes* Trin. grassland. Moreover, soil properties induced by fibrous root herbage have strong effects on the process of soil detachment. Compared to grasslands having tap root systems, soil detachment capacity and rill erodibility was reduced by 84.6% and 84.3%, while critical shear stress was increased by 15.2%. Although soil detachment capacity increased with the increases of median soil grain size as an exponential function, while no significant relationship was found between soil properties and critical shear stress. Further studies are needed to quantify the effects of plant root type and its characteristics on the process of soil detachment.

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