Effects of Near Soil Surface Characteristics on Soil Detachment by Overland Flow in a Natural Succession Grassland

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Vegetation restoration probably has great effects on the process of soil detachment. This study was conducted to investigate the effects of near soil surface characteristics on soil detachment by overland flow in a 7-yr restored natural grassland. Four treatments were designed to characterize the effects of dead roots, live roots, biological soil crusts (BSCs), and plant litter-stems in succession. For comparison, an undisturbed bare Loess soil was used as a baseline. The testing area (1.0 m in length and 0.1 m in width) of each treatment was subjected to flow scouring under five different shear stresses ranging from 6 to 13 Pa. The results showed that near soil surface properties of plant litter-stem, BSCs, and plant roots enhanced the resistance of soil to water detachment significantly. With these factors subsequently superimposed, soil detachment capacity decreased progressively. Taken together, the 7-yr restored natural grassland would decrease soil detachment capacity by 98.9% compared with the bare Loess soil, in which plant litter-stem, BSCs, and total roots contributed to 30.3, 14.9, and 53.7%, respectively. Furthermore, for the total root effects, chemical bonding of root exudates accounted for 14.7% while physical binding of root systems accounted for 39.0%. Results also indicated that BSCs were unable to protect the soil from detachment when the shear stress was greater than 11 Pa, and tended to accelerate soil erosion. This paper developed an equation for adjusting WEPP's rill erodibility for use in natural succession grassland in the Loess Plateau of China, and the result seemed satisfactory with the Nash-Sutcliffe efficiency (NSE) coefficients ranging from 0.28 to 0.77. Further studies are needed to detect the dynamics of near soil surface characteristics with succession age of grassland in the Loess Plateau.

Abbreviations: BSC, biological soil crust; CR, contribution rate; NSE, Nash-Sutcliffe efficiency; RDC, reduction of detachment capacity; WEPP, Water Erosion Prediction Project.

Soil detachment was defined by Govers et al. (1990) as the dislodgment of soil particles from the soil mass at a particular location on the soil surface by the erosive forces of rainfall or surface flow of water. Soil detachment by overland flow, such as rill erosion, is generally considered as the most important process of sediment production and contributes greatly to total soil loss (Poesen et al., 2003). It occurs when the effect of flowing water exceeds the certain threshold of soil resistance (Knapen et al., 2007), which implies that the erosive forces of overland flow and the resistance of the topsoil mass are two factors influencing soil detachment in rills.

Overland flow is the external driving force for rill formation and development. Both laboratory and field experiments have found that hydraulic parameters of flowing water were closely related to the process of soil detachment by overland

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flow (Govers et al., 1990; Nearing et al., 1999; Poesen et al., 2003; Zhang et al., 2003; Knapen et al., 2007). Some hydraulic parameters (i.e., slope gradient, flow discharge, and velocity) which can be measured directly were positively correlated with soil detachment capacity as power functions. Other parameters, calculated by the above measured hydraulic parameters, such as shear stress, stream power or unit stream power, were also used as soil detachment predictors.

The near soil surface characteristics, including both aboveground and underground factors, had great effects on soil detachment by overland flow. The effects of aboveground factors on soil detachment mainly are caused by plant litter, BSCs, surface roughness, and soil properties (Nicolau et al., 1996; Zavala et al., 2009; Xiao et al., 2011), while the effects of underground factors probably related to the inherent traits of soil mass (i.e., soil type, soil texture, and soil physicochemical properties) and the plant roots system (De Baets et al., 2006, 2007, 2008; Gyssels et al., 2005; Zhang et al., 2008, 2009). Both above and underground characteristics influence the resistance of soil to flowing water, and hence impact the process of soil detachment by overland flow.

For aboveground characteristics, the effects of BSCs (as a complex mosaic of soil) on soil erosion are complex. Some studies showed that BSCs increased infiltration by increasing soil porosity, enhancing aggregate stability, and improving soil physical structure, and hence decreased overland flow and erosive force and soil detachment rate (Greene et al., 1990; Zhang and Liu, 2005). Nevertheless, some other studies found that dried BSCs reduced infiltration due to the increased water repellency and swelling of crust when the sheathed material imbibed water, which would create an impermeable seal, and increased surface runoff and soil detachment capacity by flowing water (Verrecchia et al., 1995; Al-Qinna and Abu-Awwad, 1998). The plant litter and its decomposed residue would enhance the resistance of soil to rill erosion by increasing the soil surface roughness and reducing the flow velocity. The combination of plant litter and plant stems formed a series of small dam, which would greatly enhance the effects of vegetation litter on reducing flow velocity and dissipating the energy of flowing water (Nicolau et al., 1996; Zavala et al., 2009).

For underground characteristics, the soil resistance to detachment by overland flow is affected by almost all soil properties (Nachtergaele and Poesen, 2002; Knapen et al., 2007). The influences of soil physicochemical properties (i.e., soil texture, bulk density, porosity, cohesion, water content, aggregate stability, and organic matter content) on soil detachment by flowing water acted via two pathways. The first one was related to erosive force. The hydraulic conditions of overland flow would be changed due to the effects of soil physicochemical properties by changes in the capacity of infiltration (Jiao et al., 2011). For example, the infiltrability of the soil increased and the amount of overland flow reduced as soil porosity increased. The second pathway was the resistance of soil mass to flowing water, which depended on soil physicochemical properties. As aggregate stability and soil organic matter content increased, the stability of the soil mass increased, and soil resistance to flowing water was enhanced (Zhang et al., 2008, 2009). Soil detachment by overland flow was greatly influenced by plant root systems. Detachment rate declined as exponential functions with root density (Mamo and Bubenzer, 2001a, 2001b; Gyssels et al., 2005; De Baets et al., 2006, 2007, 2008; Wynn and Mostaghimi, 2007). The resistance of soil to water offered by plant root systems received more attention over the last decades. The effects of plant roots were closely related to the root architecture. Some results indicated that the ability of plant roots to increase the resistance of soil to flowing water erosion mainly depended on the number of lateral roots <1 mm in diameter (Li et al., 1991; De Baets et al., 2007) and that fibrous root systems reduced soil detachment rates to a greater extent than tap root systems (Wischmeier, 1975; De Baets et al., 2007). Specifically, effects of root systems on increasing soil resistance to water erosion could be attributed to exudates-bonding effect and physically binding effect. For the bonding effect of plant roots, soil particles were adhered firmly to the root surfaces by root exudates, which enhanced the soil stability and increased the resistance of soil to be detached (De Baets et al., 2008). For the binding effect of plant roots, soil structure became stable due to the plant roots interspersed in the soil during growth and physically bound the soil mass, and hence reduced the soil detachment capacity by overland flow (De Baets et al., 2007).

The Loess Plateau, located in Northwest China, attracts worldwide attention for its severe soil erosion (ranging from 5000 to 10000 Mg km^{-2} yr^{-1}; Zhang and Liu, 2005; Fu et al., 2011). The irrational land use and low vegetation cover were considered as the key driving force for such serious soil erosion (Zheng, 2006; Fu et al., 2011). The average soil detachment from cropland was 2 to 13 times greater than that of forest land, shrub land, and grassland (Zhang et al., 2008). The results indicated that cropland was the principal sediment source in this region due to the intense disturbance produced by farming activities (Zhang et al., 2009). To control soil erosion, an important countermeasure of “Grain for Green” project was launched in the Loess Plateau in 1999. A large number of steep croplands (>15°) have been converted to grassland and forested land (Fu et al., 2011). The adjustments in land use certainly caused changes in the near soil surface characteristics, which probably have great influence on soil detachment by overland flow. Although the effects of litter, BSCs, and plant roots on soil erosion were investigated independently under different conditions, the relative contributions of these factors in reducing soil detachment by overland flow in a naturally recovered grassland system are still unknown. The mechanisms of these factors affecting the process of soil detachment by overland flow are not yet fully understood. The aims of this study were to: (i) investigate the effects of near soil surface characteristics on soil detachment by overland flow, (ii) quantify their contributions in reducing soil detachment, and (iii) develop an equation for adjusting WEPP’s rill erodibility for use in a natural succession grassland in the Loess Plateau of China.

MATERIALS AND METHODS

Site Description

The study was performed in a 7-yr natural succession grassland (109.312726°E, 36.852148°N; Elevation ranged from 1291.7 to 1296.5 m) located in the Dun mountain, the Ansai Soil and Water Conservation Station of Chinese Academy of Science and Ministry of Water Resources, which belongs to the Loess Hilly region. The study area was used as farmland and abandoned 7 yr ago and vegetation underwent a natural succession. The site has a silt loam Loessial soil and is north facing with slope gradient varying from 20.9 to 24.4%. Perennial *Artemisia Capillaris* was the dominant species, along with the other supporting species including *Lespedeza davurica (Laxm.) Schindl.*, *Artemisia Giraldii Pamp.*, and *Heteropappus altaicus (Willd.) Novopokr*. The cover ranged from 50 to 60% and the root mass density was approximately 3.58 kg m^{-3}. The slope, soil, roughness and vegetation were relatively homogeneous on the site. Soil particle distribution was 15.9% clay, 61.7% silt, and 22.3% sand. The aggregates were composed of 52.6% macro-aggregates (>0.25 mm) and 47.4% micro-aggregates ($\leq$0.25 mm). The water stable aggregates (>0.25 mm) were 29.6%. The bulk density, soil cohesion, and organic matter content were 1100 kg m^{-3}, 7231 Pa, and 11.3 g kg^{-1}, respectively. The soil surface was covered with plant litter (0.13 kg m^{-2} in biomass) and BSCs, composed largely of cyanophytes (*Microcolus vaginatus*, 70 ± 5% in cover) together with some moss (*Barbula tectorum C. Muell.*, 8 ± 2% in cover).

Table 1. The near soil surface characteristics of each treatment participated in the process of soil detachment capacity by overland flow.

Treatment	Surface or subsurface factors	Treatment Effects
T_0	Undisturbed Loess soil	Baseline condition
T_1	Undisturbed soil with dead root	Root physical binding
T_2	Undisturbed soil with live root	Total roots effect, including chemical bonding of root exudates and physical binding
T_3	Undisturbed soil with live root and biological soil crusts (BSCs)	Total roots effect plus BSCs effect
T_4	7-years-old grassland	Total grassland effect, including plant litter-stem effect and all the above

Experimental Treatments

Five treatments (Expressed as T_0, T_1, T_2, T_3, and T_4) were designed based on the potential effects of near soil surface characteristics of vegetation restoration on soil detachment by overland flow. The bare loess soil (The top soil layer of 0 to 40 cm was removed and just kept the undisturbed loess soil without plant roots) of T_0 was used as the baseline. For the T_1, an atomizing pesticide (glyphosate, 30% agent, Monsanto, St. Louis, MO) was sprayed to kill all vegetation with a hand sprayer. The plant was found dead 1 wk later and plant roots no longer exuded. The chemical bonding effect of root exudates to soil was assumed to disappear in the rhizosphere in the following 3 wk (Staddon et al., 2003). Totally, after 4 wk, the plant roots were dead but un-decomposed, and believed to have only physical binding effect on the soil mass. Before the experiment was conducted, herbage above the ground was clipped near the soil surface by a scissors and plant litter was removed using a brush. The BSCs were removed carefully, and the disturbed loose soil particles on the soil surface were brushed slightly by a soft brush. Compared with the baseline T_0, T_1 only had the dead root effect, that is, the physical binding. For the T_2, herbage, plant litter, and BSC at or above the ground were removed as described in T_1 before testing. Since no pesticide was sprayed, plant roots were alive and exerted both chemical bonding and physical binding effects, representing the live root effect. For the T_3, herbage and plant litter above the ground were removed, and both live plant roots and BSCs remained. As such, the effect of BSC was induced in T_3 compared with T_2. For the T_4, the 7-yr-old grassland was used without any measures to quantify the total effects of near soil characteristics of idle grassland on the process of soil detachment by overland flow. The effect of plant litter and stems were introduced in T_4 compared with T_3. To minimize the differences in near soil surface characteristics, the experimental site was quartered along the slope aspect and each treatment was conducted in all four subsites. The near soil surface factors of each treatment that operated in the process of soil detachment by overland flow are listed in Table 1.

Experimental Facilities

The experimental facilities were composed of five parts: (1) water storage system, (2) discharge adjusting system, (3) flume system, (4) testing area, and (5) collecting system (Fig. 1). Clean water (salinity is 478.5 mg L^{-1}; Gravimetric method) supplied by the water storage system flowed into the discharge adjusting system for adjustment to any designed flow rate. The clean flowing water was stabilized in the flume system before soil detachment occurred in the testing area. Finally, the runoff and sediment were collected by the collecting system.

Water storage system. Four interconnected steel barrels (0.6 m in diameter and 1.5 m in height) were used for storing clean water. One steel barrel with three outlets (0.03 m in diameter, welded equidistantly at a 0.05-m distance to the bottom of the barrel) was used as the main water source and placed in the center (Fig. 1). The other three barrels that have only one outlet were connected to the main barrel by rubber tubes (0.03 m in diameter). A valve and a hydrant (0.07 m in diameter) were welded together at the bottom of the main barrel (0.05 m distance to the bottom) to provide clean water for the discharge system by a fire hose. Four tripods (0.3 m in height) were used to support the four barrels. The water flowed to the discharge adjusting system under gravity and the flow rate was controlled by the installed valve.

Discharge adjusting system. It consisted of a constant-water-level-barrel (0.8 m in diameter, 1.2 m in height). To keep a constant water level in the barrel, an overflow port was welded in the barrel at the 1 m height to drain excess water. Five drainage outlets (0.03 m in diameter) were welded at a 0.02-m distance

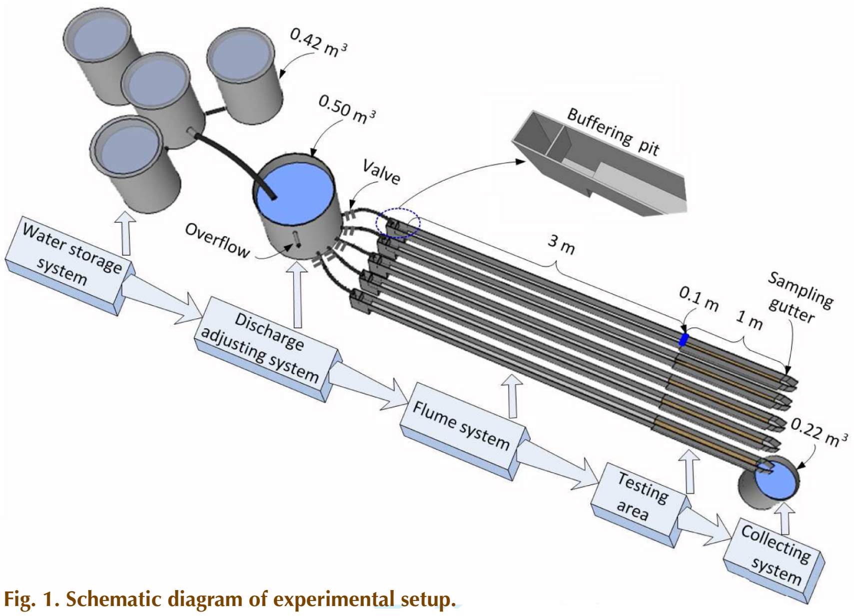

Fig. 1. Schematic diagram of experimental setup.

to the bottom of the barrel, and two cupreous spherical valves were welded at each drainage outlet. The inside spherical valves (near the barrel) of the five outlets were fixed after the discharge was adjusted to one of the designed values of 0.2, 0.3, 0.4, 0.5, and 0.6 L s^{-1}, respectively. The outside valves were fully opened or closed only to turn water on or off. Each of five outlets was connected with a 1-m long rubber tube to make sure the water flowed into the flume system smoothly. The altitude difference between the valves and outlet (rubber tubes) was kept constant (0.25 m) to avoid the potential effects on flow discharge. For each test, the flow rate was measured five times with a graduate cylinder after scouring and the mean value was used as actual flow rate.

Flume system. It consisted of a buffering pit (0.2 m in length, 0.1 m in width, and 0.3 m in height) and a flume (3 m in length, 0.1 m in width, and 0.15 m in height). The buffering pit dissipated the flow energy and the flow emerged smoothly and uniformly into the flume. The flume was installed on the land surface at the same slope gradient as of the tested area. A 5-mm layer of the testing Loessial soil (sieved by 0.25 m mesh screen) was glued to the flume bed surface to simulate the grain roughness of the testing area. The flow velocity was measured ten times by the dye method (Luk and Merz, 1992) within the last 2 m of the flume and modified according to the flow regime to obtain the mean velocity.

Testing area. For each treatment, two steel plates (1.05 m long, 0.2 m in height) were aligned to the outside of the flume and driven 0.05 m into soil. The 0.05 m overlap between the steel plates and flume was fixed with screws. The steel plates were flush with the top of the flume and were parallel to each other. The inside seam between the steel plate and flume was sealed off with glass cement (neutral multipurpose sealant). To minimize the disturbance of the test area, plant litter under the steel plate was cleaned and soil was sprinkled. The outside of the steel plate was filled with soil and tamped lightly to ensure seamless contact between steel plate and soil. Before scouring, the slope gradient was measured and the surface soil in the testing area was wetted to saturation to ensure the same initial soil water content for each test. The runoff and sediment during the first 3 to 6 s after scouring were not collected to minimize the effects of disturbance during installation. The test stopped when the scouring depth reached 2 to 3 cm (Nearing et al., 1991; Zhang et al., 2002, 2003) and the scouring duration was recorded.

Collecting system. Before the experiment started, the inside seam between the sampling gutter and steel plate was sealed off with glass cement, and the outside was filled with soil and tamped. The runoff and sediment were collected in a steel barrel (0.6 m in diameter and 0.8 m in height). After the scouring, the collected runoff and sediment were clarified. The sediment was taken back to experiment station for drying (105°C, 24 h) and weighed.

Hydrological Parameters and Soil Detachment Capacity Measurement

Five flow rates (0.2, 0.3, 0.4, 0.5, and 0.6 L s^{-1}) were designed for each treatment and four replicates were performed for each discharge. For all 100 tests, slope gradient ranged from 20.9 to 24.4% and the differences in elevation between the entrance and the outlet of the test section varied from 0.22 to 0.26 m. The measured flow rate (Q, L s^{-1}), the unit width flow discharge (q, $m^2\ s^{-1}$), the mean velocity (v, m s^{-1}), and the scouring duration (t, s) ranged from 0.18 to 0.67 L s^{-1}, 1.8 to 6.7 $\times 10^{-3}$ $m^2\ s^{-1}$, 0.91 to 1.50 m s^{-1}, and 26.72 to 358.00 s, respectively. The water depth (h, m; Eq. [1]) changed from 3 to 6 mm. The ratios of flume width to flow depth ranged from 18.7 to 30.3 and the side wall effects could be neglected (Webel and Schatzmann, 1984; Knapen et al., 2007). The flow shear stress (τ, Pa; Eq. [2]) varied from 6.08 to 13.25 Pa. The soil detachment capacity (D_C, kg $m^{-2}\ s^{-1}$) was calculated according to Eq. [3].

$$h=\frac{Q}{vB} \qquad [1]$$

where B is the flume width (B = 0.1 m);

$$\tau=\rho ghS \qquad [2]$$

where ρ is the water density (kg m^{-3}), g is the gravity acceleration (m s^{-2}), s is the sine of slope (m m^{-1}).

$$D_C=\frac{W}{tA} \qquad [3]$$

where w is the dry weight of sediment collected during scouring (kg), A is the scouring area (A = 0.1 m^2), and t is the collection time (s). For a given flow discharge of each treatment, the averaged shear stress and soil detachment capacity were used in analysis.

The Reduction of Detachment Capacity and Contribution Rate

The topography was uniform and near soil surface characteristics (including herbage, BSC, and plant litter) were relatively homogeneous in the study area. The reduction of soil detachment capacity (RDC) caused by plant roots (including root bonding effect and binding effects), BSC, plant litter-stem, and total grassland would be calculated by Eq. [4] to [9], and their contribution rates (CR) to soil detachment could be computed by Eq. [10].

$$\mathrm{RDC}_{\text{Root-binding}} = D_{\text{C-T0}} - D_{\text{C-T1}} \qquad [4]$$

$$\mathrm{RDC}_{\text{Root-bonding}} = D_{\text{C-T1}} - D_{\text{C-T2}} \qquad [5]$$

$$\mathrm{RDC}_{\text{Total-root}} = D_{\text{C-T0}} - D_{\text{C-T2}} \qquad [6]$$

$$\mathrm{RDC}_{\text{BSCs}} = D_{\text{C-T2}} \text{-} D_{\text{C-T3}} \qquad [7]$$

$$\mathrm{RDC}_{\text{Litter-stem}} = D_{\text{C-T3}} - D_{\text{C-T4}} \qquad [8]$$

$$\mathrm{RDC}_{\text{Grassland}} = D_{\text{C-T0}} - D_{\text{C-T4}} \qquad [9]$$

where $\mathrm{RDC}_{\text{Root-binding}}$ is the reduction of soil detachment capacity by the dead roots (kg m^{-2} s^{-1}), $\mathrm{RDC}_{\text{Root-bonding}}$ is the reduction of soil detachment capacity by live root exudates (kg m^{-2} s^{-1}), $\mathrm{RDC}_{\text{Total-root}}$ is the reduction of soil detachment capacity under live plant roots (kg m^{-2} s^{-1}), $\mathrm{RDC}_{\text{BSCs}}$ is the reduction of soil detachment capacity by BSCs (kg m^{-2} s^{-1}), $\mathrm{RDC}_{\text{Litter-stem}}$ is the reduction of soil detachment capacity by plant litter and stem (kg m^{-2} s^{-1}), and $\mathrm{RDC}_{\text{Grassland}}$ is the reduction of soil detachment capacity by 7-yr-old grassland (kg m^{-2} s^{-1}). The $D_{\text{C-T0}}$, $D_{\text{C-T1}}$, $D_{\text{C-T2}}$, $D_{\text{C-T3}}$, and $D_{\text{C-T4}}$ were the soil detachment capacity of T_0, T_1, T_2, T_3, and T_4 (kg m^{-2} s^{-1}), respectively.

$$CR_i = \frac{E_i}{\sum E_i} \times E_{Grassland} \qquad [10]$$

where CR_i is the contribution rate of each factor i (litter-stem, BSCs, root-bonding, and root-binding, respectively) in reducing soil detachment capacity (%). $E_{\text{Grassland}}$ is the effect of 7-yr-old grassland on reducing soil detachment (%; Eq. [11]), and E_i is the effect of factor i on reducing soil detachment (%; Eq. [12] to [15]).

$$E_{\text{Grassland}} = \frac{\mathrm{RDC}_{\text{Grassland}}}{D_{\text{C-T0}}} 100\% \qquad [11]$$

$$E_{\text{Litter-stem}} = \frac{\mathrm{RDC}_{\text{Litter-stem}}}{D_{\text{C-T3}}} 100\% \qquad [12]$$

$$E_{\text{BSCs}} = \frac{\mathrm{RDC}_{\text{BSCs}}}{D_{C-T2}} 100\% \qquad [13]$$

$$E_{\text{Root-bonding}} = \frac{\mathrm{RDC}_{\text{Root-bonding}}}{D_{\text{C-T1}}} 100\% \qquad [14]$$

$$E_{\text{Root-binding}} = \frac{\mathrm{RDC}_{\text{Root-binding}}}{D_{\text{C-T0}}} 100\% \qquad [15]$$

Note that $\mathrm{CR}_{\text{Root-bonding}} + \mathrm{CR}_{\text{Root-Binding}} = \mathrm{CR}_{\text{Total-root}}$ and $\mathrm{CR}_{\text{Litter-stem}} + \mathrm{CR}_{\text{BSCs}} + \mathrm{CR}_{\text{Total-root}} = E_{\text{Grassland}}$.

Soil Erodibility and Critical Shear Stress

Soil detachment in rills occurs when flow shear stress exceeds the critical shear stress of the soil and when sediment load is less than sediment transport capacity (Nearing et al., 1989). Soil erodibility (K_r) and critical shear stress (τ_C) were estimated for each land use as the slope and intercept on the x axis of a linear regression line between soil detachment capacity (D_C) and shear stress (τ) as described in the WEPP (Water Erosion Prediction Project) model (Nearing et al., 1989) as follow:

$$D_C = K_r(\tau - \tau_C) \qquad [16]$$

Hence the detachment capacity of T_0 would be estimated as follows:

$$D_{C-T0} = K_{r-T0}(\tau - \tau_{c-T0}) \qquad [17]$$

where the $K_{r\text{-}T0}$ and $\tau_{C\text{-}T0}$ were the baseline erodibility and the critical shear stress of the Loess soil in the check T_0 treatment. For the same soil (Loess soil) was used in this study, its critical shear stress was assumed to be the same for all treatments and equal to that of the Loess soil (Control site, T_0). The soil detachment capacity of 7-yr-old grassland ($D_{\text{C-Grassland}}$) could be expressed as follows:

$$D_{C-Grassland} = C_{T1}C_{T2}C_{T3}C_{T4}K_{r-T0}(\tau - \tau_{c-T0}) \qquad [18]$$

where C_{T1} ($C_{T1} = K_{r\text{-}T1}/K_{r\text{-}T0}$), C_{T2} ($C_{T2} = K_{r\text{-}T2}/K_{r\text{-}T1}$), C_{T3} ($C_{T3} = K_{r\text{-}T3}/K_{r\text{-}T2}$), and C_{T4} ($C_{T4} = K_{r\text{-}T4}/K_{r\text{-}T3}$) were correction coefficients of each treatment factor (T_1 to T_4) for the effects of dead root, live root, BSC, and plant litter-stem; and $K_{r\text{-}T1}$, $K_{r\text{-}T2}$, $K_{r\text{-}T3}$ and $K_{r\text{-}T4}$ were rill erodibilities of each treatment (T_1 to T_4).

Statistical Analysis

The differences of soil detachment capacity among treatments were analyzed using a method of multiple comparisons, which was also used for all surface and subsurface factors, and for both RDC and CR. Relationships between soil detachment capacity and shear stress of each treatment were analyzed and simulated with a method of linear regression, and their determination coefficients or significance coefficients were used to evaluate the performance of the goodness of fitness. All analyses were made using the SPSS 17.0 software (SPSS Inc.,

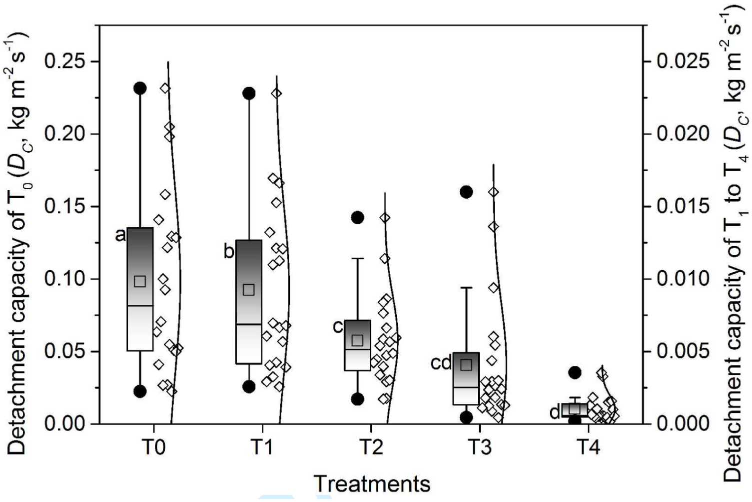

Fig. 2. Variations of soil detachment capacity of each treatment. The curved lines in the right side of each box were the distribution curve. The same letter means that differences are not significant at $p < 0.05$; T_1 is the dead root effect, T_2 is the live root effect, T_3 is live root and biological soil crusts effect, and T_4 is the total grassland effect.

2008) and all graphical displays were done with the Origin Pro 8.0 software (OriginLab Corp., 2008).

RESULTS AND DISCUSSION

Soil detachment capacities of each treatment varied significantly with overland flow in the 7-yr-old grassland, ranging from 0.002 to 0.232 kg m^{-2} s^{-1} (Fig. 2, $p < 0.05$). The bare Loessial soil was used as the baseline of soil detachment, and its soil detachment capacities were generally higher and were 10.7 to 94.3 times of other treatments. Near soil surface characteristics of plant roots, BSCs, and plant litter-stem had great effects on the process of soil detachment and enhanced the ability of soil to resist flowing water scouring. The mean values of soil detachment capacity of dead roots (T_1) and live roots (T_2) were 90.6 and 94.2% less than that of Loess soil (T_0), respectively (Fig. 3). Meanwhile, with other factors of BSCs and plant litter-stem successively superimposed (corresponding to the treatments from T_3 and T_4), mean values of soil detachment capacity of T_3 and T_4 were 95.9 and 98.9% less than that of the loess soil, respectively (Fig. 3).

Reductions of detachment capacity caused by plant litter-stem, BSCs, and plant roots were quite different (Fig. 4) since their effects on the process of soil detachment capacity were not the same. In this study, mean values of RDC for each factor were calculated and varied from 0.002 to 0.093 kg m^{-2} s^{-1} (Eq. [4] to [8], Fig. 4). Litter-stem and their decomposed residue would enhance the soil resistance to rill erosion mainly by increasing the surface roughness and reducing the flow velocity. The combination of litter and plant stem, which formed a series of grille during the detachment process, greatly enhanced their effects on reducing flow velocity and thus dissipating the kinetic energy and shearing force of flowing water. The BSCs was one of the main near soil surface characteristics and covered about 70% of the land surface in the Loess Plateau (Zhao et al., 2006). The BSC protected soil surface well from detachment by overland flow. The sheath of filamentous cyanophytes would bind and bond soil particles which had enough integrity to be removed and appeared to reduce soil erosion (Dabney et al., 1993; Zhao et al., 2006; Xiao et al., 2011). Also, the biological crust increased surface roughness and reduced the flowing water power (Xiao et al., 2011). In general, plant roots enhanced the resistance of soil to water erosion though their binding and bonding effects. The plant root nets would bind and connect the soil mass and make the soil structure more stable (binding effects, which is the treatment of dead root in this study), and the root exudates would adhere to soil particles in the rhizosphere closely though

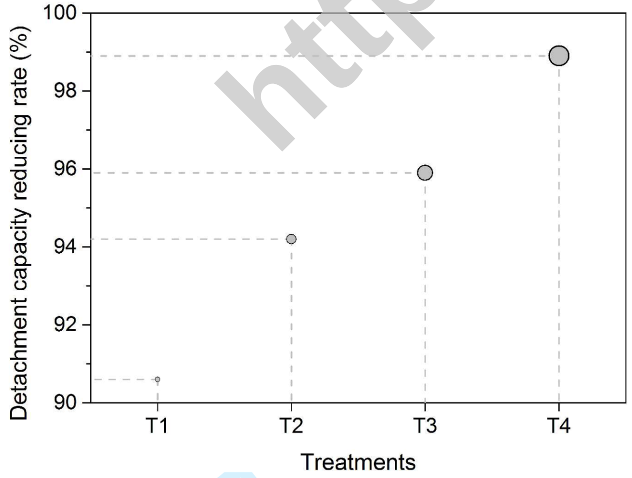

Fig. 3. Variation of mean values of detachment capacity under different treatment as compared to the bare Loess soil. The size of the scatter in the figure represented the number of influencing factors that operated in the process of soil detachment of each treatment; T_1 is the dead root effect, T_2 is the live root effect, T_3 is live root and biological soil crusts effect, and T_4 is the total grassland effect.

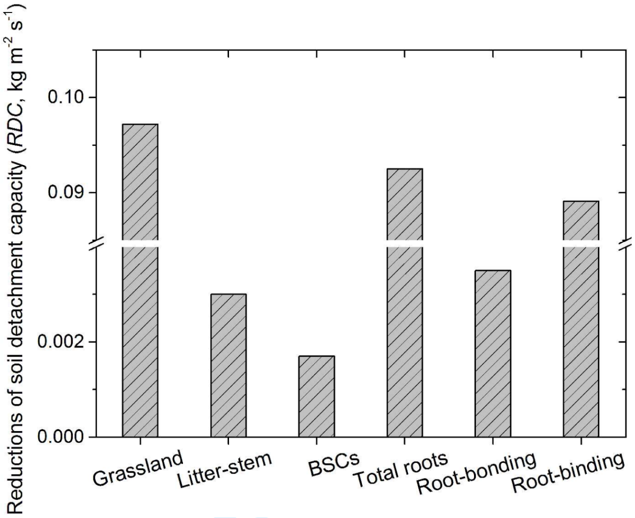

Fig. 4. Reduction in soil detachment capacity under different treatments relative to bare Loess soil. BSCs is biological soil crusts; Root-bonding is bonding effect of root exudates, and Root-binding is the physical binding effects of root.

intermolecular bonding force and Van Der Waals force (bonding effects). The effect of plant roots on improving soil properties would also influence the process of soil detachment though biochemical interaction between plant roots and soil because the soil properties was closely related with soil detachment capacity (Zhang et al., 2008). For example, the soil porosity increased during the process of vegetation root growth, which enhanced infiltrability of soil and reduced the runoff (De Baets et al., 2006, 2008). Finally, under the combined effects of plant litter-stem, BSCs, and plant roots, soil detachment capacity decreased significantly after 7 yr of vegetation restoration and was 98.9% less than that of the baseline loess soil.

Based on the above discussion, near soil surface characteristics of plant litter-stem, BSCs, and plant roots had great influence in reducing soil detachment capacity; however, the contributions of each factor in the process of soil detachment were still unclear and need to be estimated. Hence, contribution rates of each factor were calculated with Eq. [10] to [15] and showed in Fig. 5. The results showed that after 7 yr of natural vegetation restoration, soil detachment capacity of idled farmland totally reduced by 98.9% compared with the baseline loess soil, among which 30.3, 14.9, and 53.7% were reduced by plant litter, BSCs, and plant roots. The effects of plant litter-stem on the process of soil detachment deserved more attention for its greater contribution in reducing soil detachment capacity (accounted for 56.4%r of the plant roots). Previous studies focused the role of plant litter on regulating runoff and delaying the runoff initiation time in the process of runoff generation (Nicolau et al., 1996; Zavala et al., 2009), while the combined effect of plant litter and stems was ignored during the process of soil detachment by overland flow. Many researches showed that both factors had great effects on soil detachment process while no attempt was made to isolated their effect and to compare their contributions (De Baets et al., 2007; Xiao et al., 2011; Wang et al., 2013). Among the total contribution of plant roots, 14.7 and 39.0% were contributed by exudates-bonding and root physical binding, respectively (Fig. 5). The contribution of the exudates-bonding effect in reducing soil detachment capacity should not be overlooked for it accounted for more than a quarter of the total root effects. However, plant roots were generally considered as a whole when discussing their effects on the process of soil detachment, and this effect usually was referred to the root physical binding effect in the previous study (De Baets et al., 2007). The finding that exudates-bonding effects of plant roots had a substantial effect on the process of soil detachment process in this paper was undoubtedly a step further.

The RDC of each treatment varied with shear stress (Fig. 6). Reduction of soil detachment capacity of each near soil surface factor increased expectedly with the increases of shear stress except BSCs, whose RDC increased then decreased only when the shear stress was >10.97 Pa (Fig. 6c). A plausible explanation was that the BSCs might have been broken down at large shear stress, and the crust failure caused the increase in soil detachment capacity. Moreover, RDC of BSCs was calculated by subtracting detachment capacity of T_3 from T_2. Its value was negative in the case when the shear stress was >10.97 Pa, which indicated that BSCs not only failed to protect the soil from scouring, but also diminished the effect of roots on protecting soil.

The soil resistance to erosion (K_r and τ_c), estimated by shear stress of overland flow and soil detachment capacity (Formula 16, Nearing et al., 1989), was also affected by near soil surface characteristics of plant litter-stem, BSCs, and plant roots. The rill erodibility and critical shear stress of Loess soil (T_0) were 0.021 s m^{-1} and 4.377 Pa, respectively (Eq. [17], Fig. 7a). For all other treatments, the critical shear stress was assumed constant and equaled to that of the baseline Loess soil (T_0, 4.377 Pa). The effects of near soil surface characteristics on soil resistance to erosion were hence only reflected by the rill erodibility. In

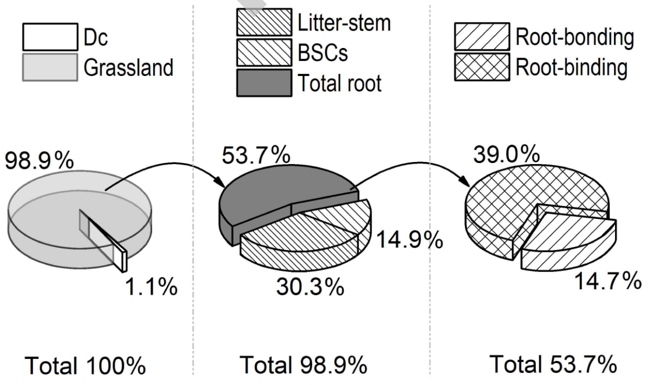

Fig. 5. Contribution rates of different near soil surface factors. The same letter means there is no difference between them (p > 0.05); D_C is soil detachment capacity, BSCs is biological soil crusts; Root-bonding is bonding effect of roots, and Root-binding is the physical binding effect of roots.

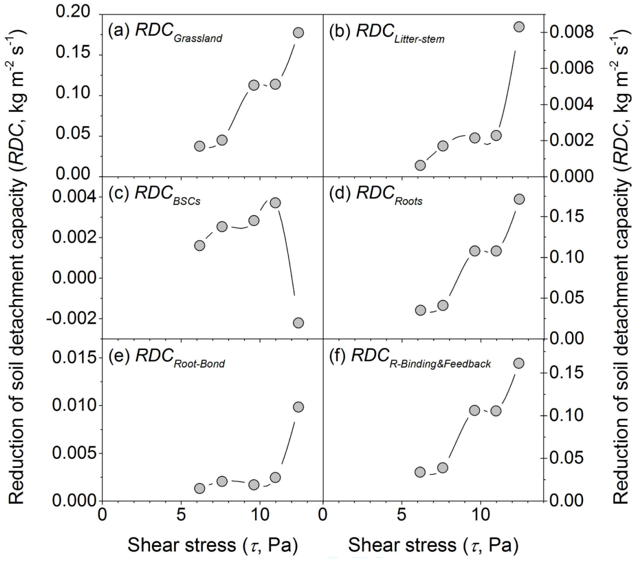

Fig. 6. Variations of reduction of detachment capacity with shear stress under different near soil surface factors. $RDC_{Grassland}$ is reduction of detachment capacity of grassland; $RDC_{Litter-stem}$, RDC_{BSCS}, $RDC_{Total-root}$ are reduction of detachment capacity of plant litter and stems, biological soil crusts and total plant roots, respectively; $RDC_{Root-bonding}$ is reduction of detachment capacity of root bonding effect; $RDC_{Root-Binding}$ is reduction of detachment capacity of root binding effect.

this study, the rill erodibility decreased with factors of dead root, live root, BSCs, and plant litter-stem with each factor successively superimposed (Fig. 7b). When the physical binding effect of plant roots was considered (dead plant roots, T_1), its rill erodibility reduced by 95.1% compared with the bare Loess soil (T_0). The exudates-bonding effect also substantially improved the soil resistance to erosion. With this effect in operation (Live plant roots, T_2), the rill erodibility further reduced by 36.1% relative to that under T_1 (dead plant roots). Biological soil crusts increased the ability of soil to resist erosion and hence the rill erodibility under BSCs and live plant roots (T_3) was reduced by 28.7% relative to that under the T_2 treatment (live plant roots). The plant litter-stem dissipated the kinetic energy and shearing force of flowing water and protected soil surface from scouring. As a result, the rill erodibility was further reduced by 74.4% relative to that in the T_3 treatment (BSCs and live plant roots). Finally, according to the Eq. [18], the soil detachment capacity of 7-years-old idled farmland ($D_{C\text{-}Grassland}$) would be described as following:

$$\begin{aligned} D_{C-Grassland} &= C_{T1}C_{T2}C_{T3}C_{T4}K_{r-T0}(\tau-\tau_{c-T0}) \\ &= 0.085\times0.639\times0.713\times0.256\times0.021(\tau-4.377) \\ &= 0.0002(\tau-4.377) \end{aligned} \quad [19]$$

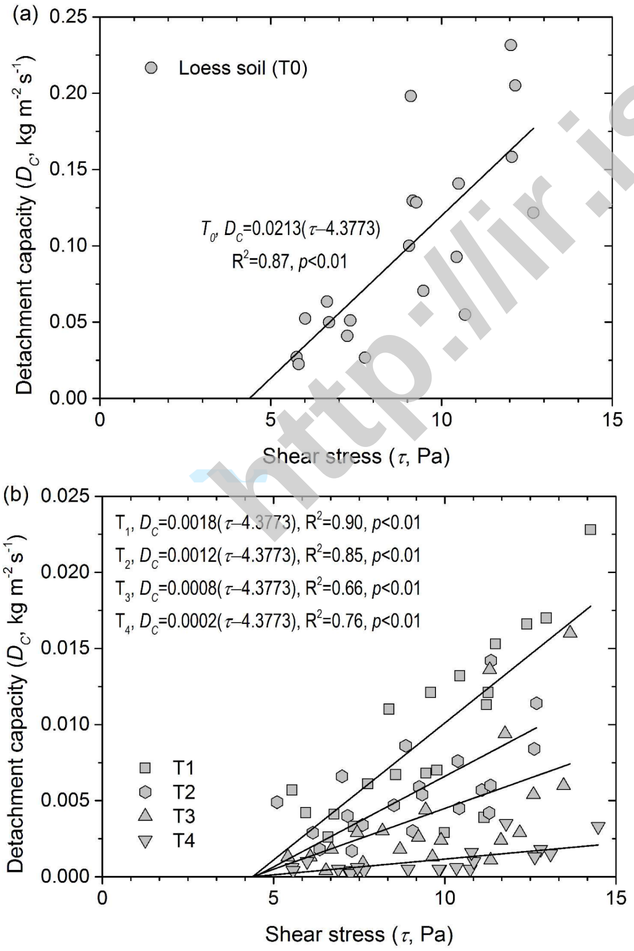

Fig. 7. Detachment capacity as a function of shear stress. T_1 is the dead root effect, T_2 is the live root effect, T_3 is live root and biological soil crusts effect, and T_4 is the total grassland effect.

where $C_{T1} = K_{r\text{-}T1}/K_{r\text{-}T0} = 0.085$, $C_{T2} = K_{r\text{-}T2}/K_{r\text{-}T1} = 0.639$, $C_{T3} = K_{r\text{-}T3}/K_{r\text{-}T2} = 0.713$, $C_{T4} = K_{r\text{-}T4}/K_{r\text{-}T3} = 0.256$, $K_{r\text{-}T0} = 0.021$ and $\tau_{c\text{-}T0} = 4.377$. Equation [19] was an erodibility adjustment equation for the WEPP model for use in the 7-yr natural succession grassland in the Loess Plateau of China. Parameters C_{T1}, C_{T2}, C_{T3}, and C_{T4}, could be considered as adjustment coefficients and could be used to adjust soil erodibility to account for the effects of the various near soil surface characteristics during vegetation restoration in the study region. The effects of dead roots, live roots, biological crust, and surface litter and stem were well accounted by the adjustment equation (Fig. 7b) and the result seemed satisfactory with the NSE coefficients ranging from 0.28 to 0.77 (Fig. 8).

CONCLUSIONS

Near soil surface characteristics had great effects on the process of soil detachment by overland flow during the vegetation restoration. This study showed that near soil surface factors of plant litter-stem, BSCs, and roots enhanced the resistance of soil to water erosion significantly. With these factors successively superimposed, soil detachment capacity and soil erodibility decreased subsequently. Taking all factors together, the naturally recovered grassland (7-yr-old idled farmland) reduced soil detachment capacity by 98.9% relative to the baseline Loess soil, among which 30.3% was attributed to plant litter-stem, 14.9% to BSCs, and 53.7% to total roots. The combined effect of plant litter and stems had the greatest contribution in reducing soil detachment and deserved more attention, for previous studies largely focused on their effects on regulating runoff and delaying the runoff initiation in the process of rainfall erosion. For the live plant roots, the contribution of exudates-bonding effect to reducing soil detachment capacity should not be overlooked, accounting for more than a quarter of the total root effect. BSCs

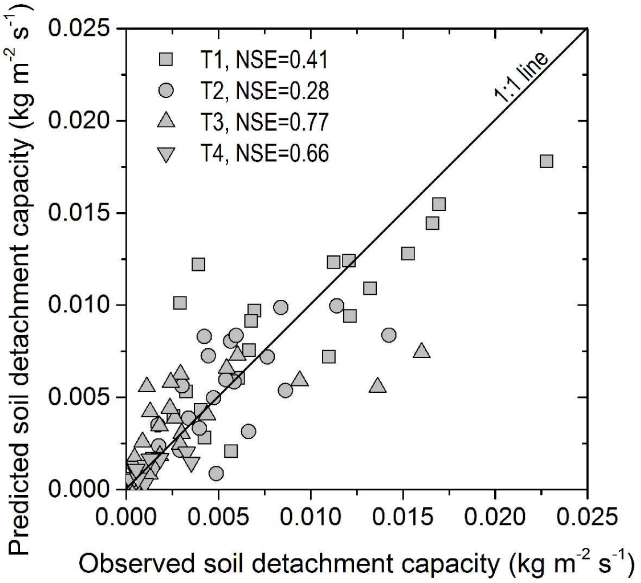

Fig. 8 Comparison between observed detachment capacity and those calculated with the fitted detachment equations in Fig. 7b. T_1 is the dead root effect, T_2 is the live root effect, T_3 is live root and biological soil crusts effect, and T_4 is the total grassland effect.

failed to protect the soil from scouring when the shear stress was greater than 10.97 Pa, resulting in considerable soil detachment after failure. This paper developed an adjustment equation for WEPP's rill erodibility parameter for use in the natural succession grassland in the Loess Plateau of China. The effects of dead roots, live roots, biological crust, and surface litter and stem were well accounted by the adjustment equation.

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