Effects of Near Soil Surface Characteristics on the Soil Detachment Process in a Chronological Series of Vegetation Restoration

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The effects of near soil surface characteristics on the soil detachment process might be different at different stages of vegetation restoration. This study was performed to investigate the effects of near soil surface factors on the soil detachment process by overland flow. Soil samples were collected from two natural grasslands of different ages and subjected to flow scouring. The results indicated that the effects of near soil surface characteristics on soil detachment were substantial during vegetation restoration. The total reduction in soil detachment capacity of the 1-yr-old grassland was 98.1%, and of this total, 7.9, 30.0, and 60.2% was attributed to the litter, biological soil crusts (BSCs), and plant roots, respectively. In the 24-yr-old grassland, the soil detachment capacity decreased by 99.0%, of which 13.2, 23.5, and 62.3% were due to litter, BSCs, and plant roots, respectively. Combined with previously published data for a 7-yr-old grassland, the influence of plant litter on soil detachment was demonstrated to increase with restoration time, but soil detachment was also affected by the litter type and composition. The role of BSCs was greater than that of plant litter during the early stages of vegetation recovery. However, its contribution weakened with time. The influence of plant roots accounted for half to two-thirds of the total near soil surface factors, of which >72.6% was attributed to the physical binding effects of roots. The correction coefficients of near soil surface characteristics for rill erodibility were determined for the Water Erosion Prediction Project model.

Abbreviations: BSC, biological soil crust; NSE, Nash–Sutcliffe efficiency; WEPP, Water Erosion Prediction Project.

Soil erosion is severe on the Loess Plateau of China due to overgrazing, cultivation, scarce vegetation with low coverage, concentrated and intense precipitation, and the erodible loess soil (Douglas, 1989; Fu, 1989; He et al., 2004). In most areas of the Loess Plateau, the erosion rate reaches 5000 to 10,000 Mg km^{-2} yr^{-1} (Zhang and Liu, 2005). To effectively alleviate this situation, great efforts have been made in soil and water conservation and ecosystem restoration by the Chinese government (Zheng, 2006; Zhou et al., 2006). Starting in the 1950s, several vegetation restoration projects have been implemented to control soil erosion. For example, afforestation through aerial seeding was implemented in the 1970s, and integrated soil erosion control at the small watershed scale was applied in the 1980s and early 1990s (Chen et al., 2007). But soil erosion is still out of control and a major environmental problem on the Loess Plateau. Sloping farmland is still the principal sediment source in this region because the soil detachment capacity of this type of land is 2 to 13 times greater than that of other land uses (Zhang et al., 2008, 2009). Another project, "Grain for Green," was implemented in 1999 across the Loess Plateau for environmental rehabilitation. To complete this project, steep cropland (>25.9%) was abandoned to allow recovery

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of the natural vegetation, and local farmers were compensated by the government with grain for the food loss caused by the decrease in cropland (Chen et al., 2007). As a result, vast areas of sloping farmland have been converted to forestland or grassland, and the ecological environment has been improved on the Loess Plateau (Fu et al., 2000; Chen et al., 2007; Liu et al., 2012).

Land use conversion certainly causes changes in the near soil surface characteristics, e.g., plant litter, biological soil crusts (BSCs), plant roots, and soil properties. The interspecific differences among land uses greatly affect the production, type, and composition of litter (i.e., the proportions of leaf litter and woody litter) and thus have a great influence on the processes of litter accumulation and decomposition (Ruiz-Jaén and Aide, 2005; Descheemaeker et al., 2006). For example, graminoid litter has a faster decomposition rate than litter from deciduous shrubs (Hobbie, 1996). Biological soil crusts, considered to be important components of vegetative ecosystems, are found in a variety of habitats throughout the world (Belnap and Lange, 2003). The development of BSCs (such as species composition, coverage, internal and external structure, chlorophyll content, and water repellency) depends on the soil moisture and temperature conditions of the land use (Belnap and Lange, 2003; Xiao et al., 2011). Plant roots are also affected by land use conversion. Under different land uses, the root characteristics of plants differ in root architecture (topology and link length), root size (root length, diameter, and surface area), biomass, and distribution within the soil profile (Arredondo and Johnson, 1999; Li and Shao, 2006; Jiao et al., 2011). As a consequence of land use conversion, the structure (aggregated stability, total porosity, and pore continuity), fertility level (soil organic matter and total N), physical characteristics (bulk density, cohesion, and roughness) and chemical characteristics (pH, cation exchange capacity, and conductivity) of the soil change greatly (Berger and Hager, 2000; Belnap, 2006; Descheemaeker et al., 2006; Jiao et al., 2011).

The time necessary to restore vegetation also has a profound effect on the near soil surface characteristics. The coverage, thickness, and biomass of plant litter vary with the vegetation recovery time. Litter production generally increases with restoration time and is exponentially related to litter coverage (Descheemaeker et al., 2006). The biomass of the litter also has a significant seasonal variation. As reported by Wang et al. (2008), litter biomass in the cool and dry season (November–March) accounted for nearly two-thirds of the total annual litter production in southern China. Moreover, plant litter greatly affects humus formation, the buildup of soil fertility, and species richness, and these effects are enhanced with time following vegetation restoration (Descheemaeker et al., 2006; Jiao et al., 2011). Biological soil crusts generally progress from cyanobacteria, green algae, or lichens to bryophytes or the coexistence of multiple species. Correspondingly, the composition, height, coverage, biomass, and roughness of BSCs vary during this succession process (Belnap and Lange, 2003). During the natural succession of abandoned farmland, Wang et al. (2013) found that the BSCs were mainly composed of cyanobacteria, green algae, and lichens when the restoration age was <18 yr. The coverage was large due to the relatively open canopies at the beginning of the vegetation succession. The BSCs were then altered by bryophytes, but only in limited areas, and were eventually displaced by a closed vascular plant canopy (Bowker, 2007). The differentiation of plant species during vegetation succession results in different root structures (e.g., a tap root or fibrous roots). The root biomass also changes with restoration time. However, there is disagreement regarding the cause for this change. Some studies have indicated that the root biomass in grasslands increases with vegetation succession time (Wang et al., 2013). Nevertheless, other studies revealed that the root biomass was not significantly related to restoration age but depended closely on the composition of the functional group and species richness, which could explain 72% of the variation in the root biomass (Ravenek et al., 2014).

Soil detachment by overland flow, which is generally considered the most important sediment source on a hillslope (Govers et al., 1990; Poesen et al., 2003; Knapen et al., 2007), is closely related to the near soil surface characteristics (Wang et al., 2013, 2014). The presence of plant litter can reduce the flow velocity and dissipate runoff energy, thereby reducing the erosive energy of a concentrated flow (Nicolau et al., 1996; Zavala et al., 2009). Decomposed or semi-decomposed plant litter can reinforce the stability of soil that is subject to erosion (Descheemaeker et al., 2006). Soil detachment by overland flow is closely related to BSCs and declines exponentially with the thickness of the BSCs (Wang et al., 2013). The roughness of the surface soil also increases with the growth of BSCs (Verrecchia et al., 1995; Al-Qinna and Abu-Awwad, 1998). The root systems of plants can bind the soil mass and enhance soil stability during their growth process, and root exudates around the rhizosphere firmly adhere to soil particles. The effects of both physical binding and the bonding of exudates of the plant root system increase the resistance of the soil to scouring by flowing water (Wang et al., 2014). Many studies have proven that soil detachment capacity decreases exponentially with the density of the root mass (De Baets et al., 2006, 2007; Zhang et al., 2013). The coupling interaction between the root system of plants and the soil mass also affects soil properties and thus influences the process of soil detachment. The increase in soil porosity and decrease in bulk density of the soil can promote the soil infiltration rate, thereby affecting the hydraulic conditions of overland flow. The increases in soil cohesion, organic matter, and water-stable aggregates as the vegetation restoration age increases can increase the resistance of soil to erosion by flowing water (Knapen et al., 2007; Zhang et al., 2008, 2009; Jiao et al., 2011).

The effects of varying the near soil surface characteristics on the process of soil detachment may be different as the restoration age increases. Many studies have investigated and quantified the effects of litter, BSCs, and plant roots on soil detachment independently (Zhang et al., 2008, 2009; Wang et al., 2013, 2014; Li et al., 2015a, 2015b). The relative contributions of these near soil surface factors to the process of soil detachment have not been fully quantified. Although Wang et al. (2014) studied the relative contributions of near soil surface factors in reducing the soil detachment capacity by overland flow in a 7-yr-old natural grassland, the effects of the near soil surface characteristics in a chronological series of restored vegetation are still unknown. Hence, the aims of this study were as follows: (i) detect the effects of near soil surface characteristics on the process of soil detachment by overland flow and their contributions in reducing soil detachment in a chronological series of vegetation succession; and (ii) provide the correction coefficients of near soil surface characteristics under different ages of restored vegetation for rill erodibility in the Water Erosion Prediction Project (WEPP) model.

MATERIALS AND METHODS

Sampling Sites

The study was conducted at the Ansai Soil and Water Conservation Station of the Chinese Academy of Science and Ministry of Water Resources, which is within a typical loess hill and gully region of the Loess Plateau. Two grasslands, located at the Dun Mountain near the Ansai station, with different ages (1 and 24 yr old) were selected for soil sampling (Table 1). The two selected grasslands faced north, and the slope, soil, roughness, vegetation coverage, and near-surface characteristics were relatively homogeneous. The annual *Artemisia annua* L. was the dominant species in the 1-yr-old grassland. However, in the 24-yr-old grassland, the perennial *Astragalus melilotoides* Pall. was the dominant species, along with some other species including *Artemisia sacrorum* Ledeb. and *Stipa bungeana* Trin. In each grassland, the near soil surface was covered with plant litter and BSCs of cyanophytes and moss (Fig. 1). The physical properties of the soil of the two grasslands are listed in Table 2.

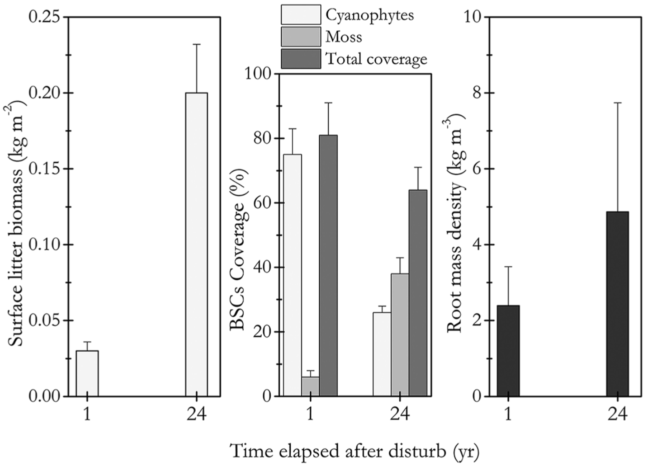

Fig. 1. Near soil surface characteristics of plant litter, biological soil crusts (BSCs), and plant roots at the sampling sites.

Treatments

Four treatments were designed in this study to evaluate the potential effects of the near soil surface characteristics (litter, BSCs, root chemical bonding, and root physical binding) of restored vegetation of different ages on soil detachment by overland flow. The bare loess soil (T_0) reported by Wang et al. (2014) was considered as the baseline because the same soil was tested in this study. For T_1, only the dead roots within the soil were included and compared with the baseline, representing the physical binding effect of plant roots on the process of soil detachment by overland flow. For T_2, only the live roots were included, reflecting the chemical bonding effect and the physical binding effect of the plant root system. For T_3, both the live plant roots and the BSCs were considered, representing the total effect of the plant roots and BSCs. For T_4, all the near soil surface factors of litter, BSCs, and root system were included, reflecting the total effects of the near soil surface characteristics of a natural succession grassland on the process of soil detachment (Table 3). These treatments were the same as those in the previous study of Wang et al. (2014).

Soil Sampling and Experimental Procedures

Intact soil samples were collected using a rectangular bottomless iron box (1 m in length, 0.1 m in inner width, 0.05 m in height at width, 0.1 m in height at length) from the surface soil layer to measure the detachment capacity by overland flow (Fig. 2). Before sampling, the soil and roots surrounding the iron box were cut off or excavated to ensure the minimum amount of disturbance to the soil sample. The box was gently pressed into the soil. When the top rim was flush with the ground surface, the sample was carefully removed and trimmed slowly to remove the excess soil from the bottom. The bottom of the iron box was cushioned with cotton cloth and capped to prevent disturbance as much as possible.

For the experimental process, clean water was supplied in a barrel with a constant water level (0.8 m in diameter, 1.2 m in height, and with an overflow port at 1-m height) and five outlets in the bottom. Flowing water entered the buffering pit (0.2 m in length, 0.1 m in width, and 0.3 m in height) to dissipate the flow energy and emerged smoothly and uniformly through a flume (3 m in length, 0.1 m in width, and 0.15 m in height) before soil detachment occurred in the testing area. This experimental setup was similar to that in the previous study by Wang et al. (2014), except for the testing area. In this study, the sample container (1.2 m in length, 0.1 m in width, 0.05 m in height at the upper part of the flume connection, and 0 m in height at the other end of the runoff and sediment outlets) was connected to the flume.

Table 1. Basic information on the topography and vegetation of the sampling sites. All sites have a similar hillside landform and all soil types are loess.

Site age	Location	Elevation	Slope	Vegetation characteristics: Primary vegetation	Vegetation characteristics: Coverage
yr		m	%		%
1	36°51′22.14″ N, 109°19′18.34″ E	1228	26.2	*Artemisia annua* L.	55
24	36°51′17.96″ N, 109°19′31.83″ E	1147	26.2	*Astragalus melilotoides* Pall.	75

Table 2. Physical properties of the soils at the sampling sites.

Site	Cohesion	Bulk density	Particle size distribution			Water-stable aggregates
			Clay	Silt	Sand	>0.25 mm
	Pa	kg m^{-3}	%			
1-yr-old	5227	1200	10.7	56.7	32.6	32.2
24-yr-old	6337	1111	12.2	60.7	27.1	44.1

Table 3. Factors of each treatment that participated in the process of soil detachment.

Code†	Near soil surface factor	Effects
T_1	dead roots	root physical binding
T_2	live roots	total root effects of root chemical bonding and physical binding
T_3	biological soil crust (BSC) and live roots	BSC effect and total roots effect
T_4	litter, BSC, and live roots	total grassland effects
T_0	loess soil	baseline

† The soil was undisturbed for all treatments.

The soil sample was inserted into the sample container, with the soil surface flush with the bottom of the flume for scouring (Fig. 2). Before scouring, the surface of the soil sample was saturated with water 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 the sampling process. The test continued until a certain depth was reached (Nearing et al., 1991; Zhang et al., 2003), and the scouring time was recorded. Finally, the runoff and sediment were collected to calculate the soil detachment capacity according to

$$D_c = \frac{w}{At} \qquad [1]$$

where D_c is the soil detachment capacity (kg m^{-2} s^{-1}), w is the dry weight of sediment collected during scouring (kg), A is the scouring area (m^2), and t is the scouring duration (s).

Hydraulic Parameters Design and Measurement

Each treatment underwent five discharges of 0.2, 0.3, 0.4, 0.5, and 0.6 L s^{-1}, which were replicated three times for each flow rate. In total, for the two grasslands, 120 tests (2 sites × 4 treatments × 5 discharge rates × 3 replications) were conducted. For each test, the flow discharge (Q, m^3 s^{-1} × 10^{-3}), mean velocity (v, m s^{-1}), and scouring time (t, s) were measured (Table 4). The flow velocity was measured using a fluorescent dye technique and was modified by a reduction factor according to the flow regime (Luk and Merz, 1992). The water depth (h, mm) and shear stress (τ, Pa) were calculated based on the measured flow discharge and velocity, with ratios of flume width to flow depth ranging from 17.4 to 48.1, and neglecting the side-wall effects (Webel and Schatzmann, 1984; Knapen et al., 2007):

$$h = \frac{Q}{vB} \qquad [2]$$

$$\tau = \rho g h S \qquad [3]$$

where B is the flume width (B = 0.1 m); ρ is the clean water density (kg m^{-3}), g is the acceleration due to gravity (m s^{-2}), and S is the sine of the slope (S = 0.26 m m^{-1}).

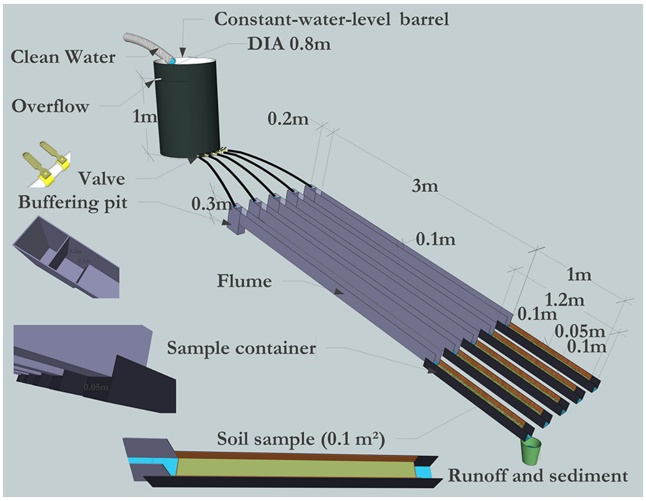

Fig. 2. Experimental setup.

Contributions of the Near Soil Surface Characteristics

For each site, the reduction in the soil detachment capacity (RDC) caused by near soil surface factors was calculated (Table 5). The contribution rates (CR) of each factor in reducing the soil detachment capacity were calculated according to

$$\mathrm{CR}_i = \frac{E_i}{\sum E_i} \mathrm{CR}_{\mathrm{grassland}} \qquad [4]$$

where CR_i is the contribution of the ith factor (litter, BSCs, root exudate bonding, and root binding) to reducing the soil detachment capacity (%), $\mathrm{CR}_{\mathrm{grassland}}$ is the contribution of the grassland in reducing the soil detachment (%, $\mathrm{CR}_{\mathrm{grassland}} = 100\ \mathrm{RDC}_{\mathrm{grassland}}/D_{\mathrm{c\text{-}T0}}$), $\mathrm{CR}_{\mathrm{total\_roots}} = \mathrm{CR}_{\mathrm{root\_bonding}} + \mathrm{CR}_{\mathrm{root\_binding}}$, and E_i is the effect of the ith factor on reducing the soil detachment (%, Table 6).

Soil Resistance to Erosion by Flowing Water

The soil resistance to erosion by flowing water (i.e., rill erodibility, K_r, and critical shear stress, τ_c) was estimated for each treatment as the slope and intercept on the x axis of a linear regression line between the soil detachment capacity (D_c) and the shear stress (τ) according to (Nearing et al., 1989)

$$D_c = K_r(\tau - \tau_c) \qquad [5]$$

The critical shear stress (τ_c) of all the treatments was assumed to be equal to that of a bare loess soil as reported by Wang et al. (2014). The effects of the near soil surface characteristics on the resistance of the soil to erosion were thus reflected by only the estimated rill erodibility (K_r). The correction coefficients (C_i) of each ith factor (litter, BSCs, root bonding, and root bind-

Table 4. Hydrological parameters measured during the soil detachment process.

Statistic	Discharge	Velocity	Test time	Water depth	Shear stress	Ratio of flume width to water depth
	$m^3\ s^{-1} \times 10^{-3}$	$m\ s^{-1}$	s	mm	Pa	
		1-yr-old grassland				
Max.	0.62	1.2	499.9	5.5	14.0	38.0
Min.	0.19	0.7	297.7	2.6	6.7	18.1
Mean	0.40	1.0	309.1	4.0	10.1	26.5
		24-yr-old grassland				
Max.	0.62	1.2	339.3	5.7	14.6	48.1
Min.	0.16	0.7	299.7	2.1	5.3	17.4
Mean	0.40	1.0	308.0	4.0	10.1	26.8

ing) to K_r were also calculated (Table 7), and the soil detachment capacity of the 1- or 24-yr-old grassland could be expressed as

$$D_{c,\text{grassland}} = \prod C_i K_{r\text{-T0}} \left(\tau - \tau_{c\text{-T0}}\right) \qquad [6]$$

where $K_{r\text{-T0}}$ (= 0.0213) and $\tau_{c\text{-T0}}$ (= 4.3773 Pa) are the soil resistance to erosion of a bare loess soil as reported by Wang et al. (2014).

Statistical Analysis

A regression line between the shear stress and soil detachment capacity of each treatment was analyzed and simulated using linear regression, and the coefficient of determination (R^2) and the Nash–Sutcliffe efficiency (NSE) were used to evaluate the goodness of fit (SPSS 17.0 software, SPSS Inc.).

RESULTS

Soil Detachment Capacity of Treatments in Grasslands of Two Ages

Soil detachment capacities varied significantly with the rate of overland flow in both the 1- and 24-yr-old grasslands. After 24 yr of natural vegetation restoration, the mean soil detachment capacity decreased by 45.3% compared with that of the 1-yr-old grassland (Fig. 3), and the mean value was 99.0% less than that of bare loess soil (0.0983 kg $m^{-2}\ s^{-1}$, Wang et al., 2014). The soil detachment capacity of each treatment varied significantly with flow discharge in both grasslands, ranging from 0.0004 to 0.0097 kg $m^{-2}\ s^{-1}$ for the 1-yr-old grassland and from 0.0003 to 0.0071 kg $m^{-2}\ s^{-1}$ for the 24-yr-old grassland (Fig. 3).

Table 5. Reduction in the soil detachment capacity (RDC) caused by near soil surface factors (*i*) for each treatment: T_1 is the dead root effect, T_2 is the live root effect, T_3 is the live root and biological soil crust effects, and T_4 is the total grassland effect. The soil detachment capacity of bare loess soil (T_0) is from Wang et al. (2014).

Factor (*i*)	Equation for RDC_i†
Root binding	$RDC_{\text{root\_binding}} = D_{c\text{-T0}} - D_{c\text{-T1}}$
Root bonding	$RDC_{\text{root\_binding}} = D_{c\text{-T1}} - D_{c\text{-T2}}$
Total roots	$RDC_{\text{total\_roots}} = D_{c\text{-T0}} - D_{c\text{-T2}}$
BSCs‡	$RDC_{\text{BSCs}} = D_{c\text{-T2}} - D_{c\text{-T3}}$
Litter	$RDC_{\text{litter}} = D_{c\text{-T3}} - D_{c\text{-T4}}$
Total grassland	$RDC_{\text{grassland}} = D_{c\text{-T0}} - D_{c\text{-T4}}$

† D_c, detachment capacity.

‡ Biological soil crusts.

Table 6. Effects (*E*, %) of near soil surface factors (*i*) on reducing the soil detachment capacity for each treatment: T_1 is the dead root effect, T_2 is the live root effect, T_3 is the live root and biological soil crust effects, and T_4 is the total grassland effect. The soil detachment capacity of bare loess soil (T_0) is from Wang et al. (2014).

Factor (*i*)	Equation for E_i†
Litter	$E_{\text{litter}} = 100\ RDC_{\text{litter}}/D_{c\text{-T3}}$
BSCs‡	$E_{\text{BSCs}} = 100\ RDC_{\text{BSCs}}/D_{c\text{-T2}}$
Root bonding	$E_{\text{root\_bonding}} = 100\ RDC_{\text{root\_bonding}}/D_{c\text{-T1}}$
Root binding	$E_{\text{root\_binding}} = 100\ RDC_{\text{root\_binding}}/D_{c\text{-T0}}$

† RDC, reduction in soil detachment capacity; D_c, detachment capacity.

‡ Biological soil crusts.

The near soil surface characteristics of plant roots, BSCs, and plant litter (including their decomposed or semi-decomposed residues) weakened the ability of flowing water to scour the soil. For the 1-yr-old grassland, the mean soil detachment capacities of dead roots (T_1) and live roots (T_2) were 95.2 and 95.5% less, respectively, than that of the bare loess soil. With the factors of BSCs and plant litter successively superimposed, corresponding to the T_3 and T_4 treatments, the mean soil detachment capacities of T_3 and T_4 were 97.8 and 98.1% less than that of the baseline. The effects of the near soil surface characteristics on the soil detachment of the 24-yr-old grassland were much more obvious than those of the 1-yr-old grassland. For the 24-yr-old grassland, with factors of dead roots, live roots, BSCs, and plant litter successively superimposed (corresponding to treatments T_1–T_4), the mean soil detachment capacities of each treatment were 23.6, 40.6, 35.7, and 45.3% less, respectively, than those of the 1-yr-old grassland (Fig. 3).

Reduction in Soil Detachment Caused by Near Soil Surface Characteristics

The near soil surface characteristics of litter, BSCs, and plant roots enhanced the ability of the soil to resist scouring by flowing water and decreased the soil detachment capacity

Table 7. Correction coefficients ($C_{i,\ \%}$) of each *i*th factor of rill erodibility (K_r) for each treatment: T_1 is the dead root effect, T_2 is the live root effect, T_3 is the live root and biological soil crust effects, and T_4 is the total grassland effect. The soil detachment capacity of bare loess soil (T_0) is from Wang et al. (2014).

Factor (*i*)	Equation for C_i
Root binding	$C_{\text{root\_binding}} = K_{r\text{-T1}}/K_{r\text{-T0}}$
Root bonding	$C_{\text{root\_bonding}} = K_{r\text{-T2}}/K_{r\text{-T1}}$
Total root	$C_{\text{total\_roots}} = C_{\text{root\_binding}} C_{\text{root\_binding}}$
BSCs†	$C_{\text{BSCs}} = K_{r\text{-T3}}/K_{r\text{-T2}}$
Litter	$C_{\text{litter}} = K_{r\text{-T4}}/K_{r\text{-T3}}$
Total grassland	$C_{\text{grassland}} = C_{\text{root\_binding}} C_{\text{root\_bonding}} C_{\text{BSCs}} C_{\text{litter}}$

† Biological soil crusts.

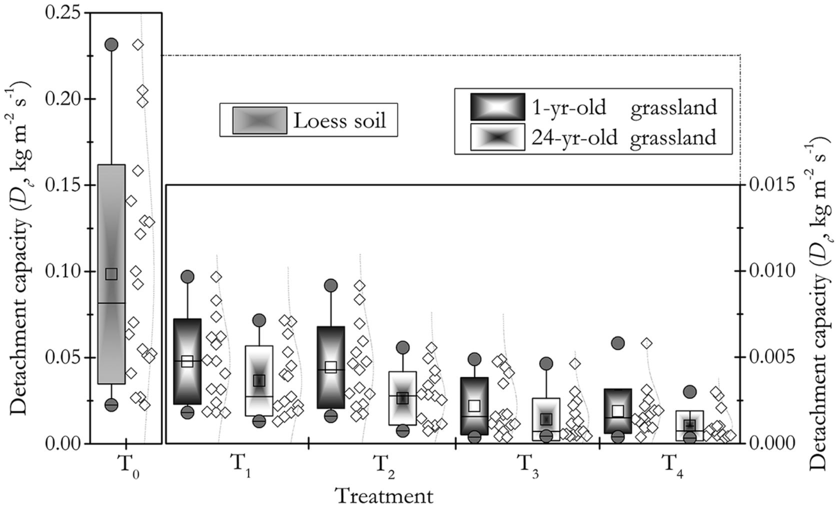

Fig. 3. Variation of the soil detachment capacity for each treatment: T_1 is the dead root effect, T_2 is the live root effect, T_3 is the live root and biological soil crust effects, and T_4 is the total grassland effect. The soil detachment capacity of bare loess soil (T_0) is from Wang et al. (2014).

significantly. Compared with the bare loess soil, the D_c of the 1-yr-old grassland decreased by 0.0964 kg m^{-2} s^{-1} and was even 0.9% less than that of the 24-yr-old grassland (Table 8). Litter and BSCs increase the surface roughness and reduce the flow velocity. Moreover, a covering of BSCs on the soil surface can protect the soil surface from detachment by flowing water. Through intermolecular bonding forces and the Van der Waals force, root exudates adhere closely to soil particles in the rhizosphere (chemical bonding effect). Moreover, plant root systems can bind and enlace the soil mass and make the soil structure more stable (physical binding effect). In this study, reductions in the soil detachment capacity caused by the near soil surface factors in the 1-yr-old grassland were lower and were 1.2 to 66.4% less than those of the 24-yr-old grassland, except for the reduction by the BSCs, which was 1.8 times greater than that of the 24-yr-old grassland (Table 8). The exception was probably caused by the decrease in the coverage of BSCs as the restoration age increased (Wang et al., 2013). These results indicated that the chronologically added series in vegetation restoration would make the near soil surface factors more efficient at enhancing the ability of the soil to resist scouring by flowing water.

Table 8. Reduction in the soil detachment capacity with different near soil surface characteristics relative to bare loess soil.

Factor	Reduction of soil detachment capacity	
	1-yr-old grassland	24-yr-old grassland
	kg m^{-2} s^{-1}	
Litter	0.0003 ± 0.0002†	0.0004 ± 0.0003
Biological soil crusts	0.0022 ± 0.0008	0.0012 ± 0.0005
Physical binding of root systems	0.0935 ± 0.0496	0.0947 ± 0.0506
Chemical bonding of root exudates	0.0003 ± 0.0001	0.0010 ± 0.0004
Total roots	0.0939 ± 0.0499	0.0957 ± 0.0509
Total vegetation restoration	0.0964 ± 0.0510	0.0973 ± 0.0516

† Means ± standard deviations.

Contribution Rates of Near Soil Surface Characteristics

The contributions of each near soil surface factor varied in different ways in the chronological series of vegetation restoration periods. For the 1-yr-old grassland, the soil detachment capacity was reduced by 98.1% compared with the bare loess soil (Wang et al., 2014), and the reductions were 7.9, 30.0, and 60.2% due to litter, BSCs, and plant roots, respectively. The contributions of plant roots (4.2% by exudate bonding and 56.0% by root physical binding) were 7.6 and 2.0 times those of the litter and BSCs, respectively (Fig. 3). For the 24-yr-old grassland, the soil detachment capacity was reduced by 99.0% compared with the bare loess soil (Wang et al., 2014), and the decreases were 13.2, 23.5, and 62.3% due to the litter, BSCs, and plant roots, respectively. The contributions of plant roots (14.0 and 48.3% contributed by chemical bonding and physical binding, respectively) were 4.7 and 2.7 times those of the litter and BSCs, respectively.

The contribution of the litter increased with the successional age of the vegetation because more litter accumulated on the soil surface. For example, the contribution of plant litter in the 24-yr-old grassland was 1.7 times greater than that in the 1-yr-old grassland. The coverage of BSCs decreased as the vegetation coverage and biomass increased, which led to a low influence of BSCs on the soil detachment capacity in the 24-yr-old grassland. The contribution of BSCs in the 24-yr-old grassland was 21.6% less than that in the 1-yr-old grassland. Although the total contribution of roots was nearly the same between the 1- and 24-yr-old grasslands, the effect of chemical bonding of root exudates on the soil detachment capacity increased with the chronological series of vegetation restoration time periods. The chemical bonding effect of the 24-yr-old grassland was 3.3 times greater than that of the 1-yr-old grassland (Fig. 3).

DISCUSSION

Contributions of Near Soil Surface Factors in a Chronological Series of Restored Vegetation

The restoration of vegetation has substantial effects on the process of soil detachment. Combined with the 7-yr-old grassland data reported by Wang et al. (2014), it is hard to imagine how serious the soil erosion would be on the Loess Plateau without the restoration of vegetation. The mean soil detachment capacity of a bare loess soil is quite high, reaching 52.5, 94.3, and 96.0 times greater than those of the 1-, 7-, and 24-yr-old grasslands, respectively. Due to the differences in litter accumulation and decomposition, plant root growth, and species succession (including BSCs) during the process of vegetation restoration, the effects of the near soil surface characteristics on the reduction in soil detachment might be quite different with time.

Plant litter that accumulated during the time period of vegetation restoration and the litter biomass in the 24-yr-old grassland was relatively high at 6.7 and 1.5 times greater than those of the 1- and 7-yr-old grasslands, respectively (Fig. 1; Wang et al., 2014). Contributions of the litter to the process of soil detachment generally followed the changes in the litter biomass with time, except for in the 7-yr-old grassland. In the 7-yr-old grassland, the contribution of litter was maximized at 3.8 and 2.3 times that of the 1- and 24-yr-old grasslands, respectively. This result indicated that the biomass of plant litter would not fully reflect the effects of litter on the process of soil detachment, and other traits of litter (e.g., type, coverage, and accumulation and decomposition rates) should also be considered (Al-Qinna and Abu-Awwad, 1998; Hobbie, 1996). Geddes and Dunkerley (1999) showed that the accumulation of litter to form composite litter dams or barriers has significant effects on the paths and behavior of surface runoff, which in turn modify the patterns of flow depth and speed across the slope. As reported by Wang et al. (2014), the litter of *Artemisia capillaris* Thunb. in the 7-yr-old grassland was mainly composed of thick branches with a slower decomposition rate than leaves. The undecomposed branches combined with small litter particles and plant stems to form a series of small dams, which greatly enhanced the effects of litter on reducing the flow velocity and dissipating the energy of flowing water.

The variation in the coverage of BSCs was inversely related to the plant litter biomass; the coverage of BSCs decreased as the plant canopy closed during vegetation restoration (Bowker, 2007). The coverage of BSCs in the 24-yr-old grassland was much lower, at 17.9 and 21.0% less than that of the 1- and 7-yr-old grasslands (Fig. 1; Wang et al., 2014). The contributions of BSCs were similar to their coverage and were reduced with time, except for in the 7-yr-old grassland. In the 7-yr-old grassland, the contribution of BSCs was at a minimum, which was 50.4 and 36.8% less than that of the 1- and 24-yr-old grasslands, respectively. This was mainly due to the BSCs being opened or scoured away by water in whole pieces in the 7-yr-old grassland when the flow shear stress was >11 Pa, and the remaining bare soil surface was more easily scoured by overland flow, which aggravated soil erosion (Wang et al., 2014). Ran et al. (2009) found that BSCs would be opened by water under a constant hydraulic flow (slope gradient = 26% and unit flow discharge = 5.7×10^{-3} m^{-2} s^{-1}) when the scouring time was >1000 s. This phenomenon also depended on the surface roughness of the BSCs. As reported by Belnap (2006), the surface roughness of the BSCs could be classified as smooth crust, bare ground, rugose crusts, rolling crusts, and pinnacled crusts. According to the dominant component in the BSC community, the roughness of the soil surface may vary considerably, changing the hydrologic and erosive responses of the soil (Rodríguez-Caballero et al., 2012). Biological soil crusts were not opened or scoured away by flowing water in the 1- or 24-yr-old grasslands. In the 1-yr-old grassland, the relatively thin and smooth cyanophytes were closely attached to the soil underneath and generally washed away together with soil particles (Chamizo et al., 2015). In the 24-yr-old grassland, BSCs were mainly composed of moss, which adsorbed to the soil surface well and were hardly moved by flowing water. Moreover, the contribution of each near soil surface factor was a relative value, which depended on the contribution of other near soil surface factors. Hence, to a certain extent, the relatively low contribution of BSCs was related to the high contribution of litter in the 7-yr-old grassland. This result also indicated that the effects of BSCs on reducing the soil detachment capacity was indeed weakened as the biomass of the plant litter increased.

The biomass of plant roots increased with an increase in the vegetation restoration time, and the root mass density in the 24-yr-old grassland was relatively high at 2.0 and 1.4 times greater than that of the 1- and 7-yr-old grasslands, respectively (Fig. 1; Wang et al., 2014). The effects of the plant root system on reducing the soil detachment capacity were always significant under the three different restoration ages and increased as the vegetation restoration period grew longer. The contributions of plant roots were substantial and accounted for half to two-thirds of the effects of the total near soil surface factors during the vegetation restoration, of which at least 72.6% was contributed by the physical binding effect of the roots. Plant roots play an important role in protecting the topsoil from erosion (De Baets et al., 2008). Especially in rill erosion, plant roots are at least as important as vegetation cover (Gyssels et al., 2005). Mamo and Bubenzer (2001a, 2001b) indicated that the soil detachment rate for rooted soils was reduced by as much as one half (field study) and 64% (laboratory study) of that of a fallow treatment, reflecting the effects of plant roots on enhancing the resistance of soil to incision from overland flow. It is worth noting that the contribution from bonding by root exudates was even greater than that of litter in the late stages of vegetation restoration. Generally, accumulated litter enhanced the ability of the soil to resist scouring by flowing water, and the litter contribution to reducing soil erosion increased as the vegetation restoration time increased. The types and composition of plant litter also significantly influenced the litter contribution to reducing soil detachment. Biological soil crusts were relatively more important than litter in reducing the detachment of soil during the early stages of vegetation recovery. As the chronological series of vegetation succession increased, the development of BSCs was limited by the increase in vegetation coverage. Meanwhile, the effects of plant litter and BSCs on reducing soil detachment was also influenced by the plant litter traits, such as type and composition, and the characteristics of the BSCs, such as species composition, coverage, and growth status. Plant roots were very important in reducing soil detachment during vegetation restoration. Their contribution to reducing soil detachment was always greater than other near soil surface factors in the chronological series of vegetation succession. The combination of the data from the 7-yr-old grass-

Table 9. Contributions of near soil surface characteristics to reducing the soil detachment capacity in grasslands of different ages.

Factor	Contribution to reduction 1-yr-old	 7-yr-old†	 24-yr-old
		%	
Litter	7.9	30.3	13.2
BSCs‡	29.9	14.9	23.5
Root bonding	4.2	14.7	14.0
Root binding	56.0	39.0	48.3
Total roots	60.2	53.7	62.3
Vegetation	98.1	98.9	99.0

† Contributions of 7-yr-old grassland are from Wang et al. (2014).

‡ Biological soil crusts.

Table 10. Correction coefficients of near soil surface characteristics to adjust the rill erodibility factor of the Water Erosion Prediction Project by the vegetation restoration time for grasslands of different ages.

Factor	Correction coefficient 1-yr-old	 7-yr-old†	 24-yr-old
Litter	0.8718	0.2517	0.6800
BSCs‡	0.5200	0.7130	0.5319
Root bonding	0.8721	0.6389	0.7460
Root binding	0.0404	0.0845	0.0296
Total roots	0.0352	0.0540	0.0221
Vegetation	0.0160	0.0097	0.0080

† Soil correction coefficients of 7-yr-old grassland are from Wang et al. (2014).

‡ Biological soil crusts.

land reported by Wang et al. (2014) and the 1- and 24-yr-old grassland data presented in Table 9 provides the contribution of near soil surface characteristics during vegetation succession.

Resistance of Soil to Erosion after Vegetation Restoration

The near soil surface characteristics of litter, BSCs, and plant roots also greatly affect the resistance of the soil to erosion by flowing water. The erodibility of rills exhibited a descending order with the near soil surface factors of dead roots, live roots, BSCs, and plant litter successively superimposed (Fig. 4). For the 1-yr-old grassland, rill erodibility under the T_1 treatment (dead plant roots) was reduced by 96.0% compared with the bare loess soil (T_0, Wang et al., 2014). When the exudate bonding effect of roots was considered (T_2, live plant roots), the rill erodibility was reduced by 12.8% compared with the T_1 treatment. The BSCs also substantially improved the resistance of the soil to flowing water. With the consideration of BSCs (T_3, BSCs and live plant roots), rill erodibility was reduced by 48.0%. Plant litter could protect the soil surface from scouring, and rill erodibility in the T_4 treatment (plant litter, BSCs, and live plant roots) was further reduced by 12.8% compared with the T_3 treatment. For the 24-yr-old grassland, this result was also confirmed. Rill erodibility under the physical binding effect of roots was reduced by 97.0% compared with the bare loess soil (T_0, Wang et al., 2014). Taking into consideration the near soil surface factors of exudate bonding effects, BSCs, and plant litter, these factors successively reduced rill erodibility by 25.4, 46.8, and 32.0%, respectively.

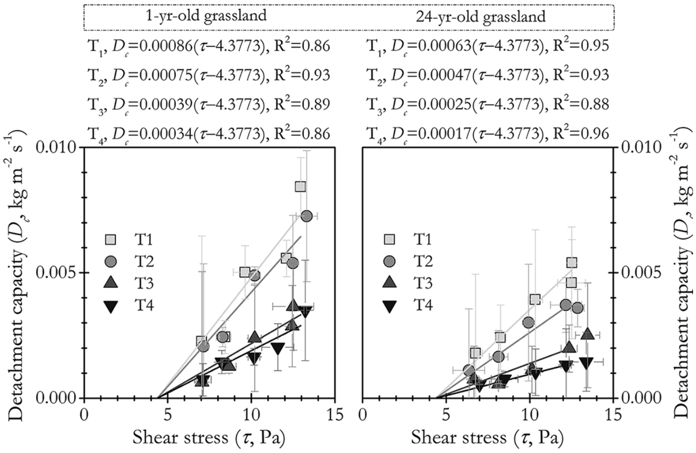

Fig. 4. Detachment capacity as a function of shear stress for each treatment: T_1 is the dead root effect, T_2 is the live root effect, T_3 is the live root and biological soil crust effects, and T_4 is the total grassland effect.

For each treatment, rill erodibility in the 1-yr-old grassland was generally high and was 1.4 to 2.0 times that of the 24-yr-old grassland. These results indicate that the effects of near soil surface characteristics on the resistance of soil to erosion were relatively small at the beginning of vegetation restoration. However, these effects were strengthened as the age of the vegetation increased. Moreover, for rill erodibility of the 1-yr-old grassland, its ratio of T_2 to T_3 (1.9) was much greater than that of T_1 to T_2 (1.1) and T_3 to T_4 (1.1), reflecting the large effect of BSCs in reducing soil detachment at the beginning of vegetation restoration (Fig. 4). Based on the rill erodibility adjustment equation (Eq. [6]; Table 7), the correction coefficient of each near soil surface factor could be calculated (Table 10), and the soil detachment capacity of the 1- and 24-yr-old grasslands can be described as

$$D_{\text{c,grassland(1-yr-old)}} = C_{\text{root\_binding}} C_{\text{Root\_bonding}} C_{\text{BSCs}} \times C_{\text{litter}} K_{\text{r-T}_0} \left(\tau - \tau_{\text{c-T}_0}\right) = 0.00034(\tau - 4.3773) \quad [7]$$

$$D_{\text{c,grassland(24-yr-old)}} = C_{\text{root\_binding}} C_{\text{root\_bonding}} C_{\text{BSCs}} \times C_{\text{litter}} K_{\text{r-T}_0} \left(\tau - \tau_{\text{c-T}_0}\right) = 0.00017(\tau - 4.3773) \quad [8]$$

A large correction coefficient of a near soil surface factor represents low soil resistance to erosion by flowing water. Soil resistance contributed by BSCs was generally greater than that of litter in the early stages of vegetation restoration. However, this situation reversed with the chronological addition of successive vegetation. This result confirmed that plant roots had

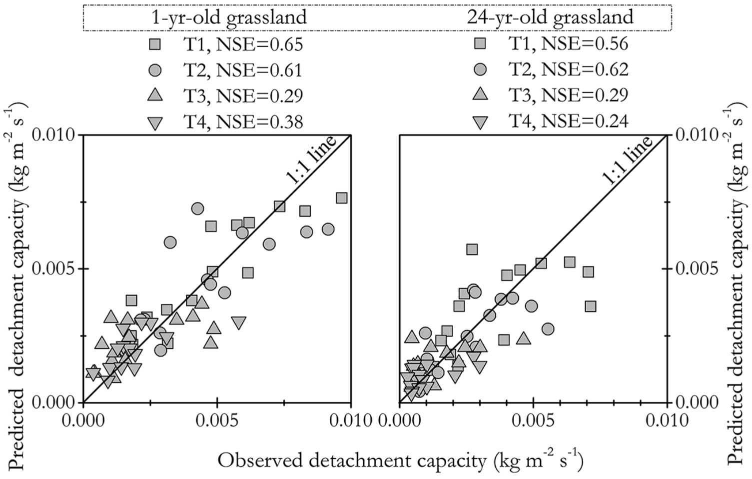

Fig. 5. Comparison between the observed detachment capacities and those calculated with the fitted detachment equations in Fig. 4 for each treatment: T1 is the dead root effect, T2 is the live root effect, T3 is the live root and biological soil crust effects, and T4 is the total grassland effect; NSE is the Nash–Sutcliffe efficiency.

the largest effect on increasing the soil resistance to erosion by flowing water and thus significantly decreased the soil detachment capacity compared with the other near soil surface factors (Table 10).

The effects of the near soil surface characteristics were well accounted for by the adjustment equation, and the results seemed satisfactory, with NSE coefficients ranging from 0.24 to 0.65 (Fig. 5). Combined with the 7-yr-old grassland data reported by Wang et al. (2014), a series of correction coefficients of near soil surface characteristics during the different vegetation stages can be provided for the WEPP model.

CONCLUSIONS

1. The restoration of vegetation significantly affected the process of soil detachment by overland flow on the Loess Plateau. The soil detachment capacity decreased as the time since restoration increased. Even in the 1-yr-old grassland, the soil detachment capacity was greatly reduced by 98.1% compared with the bare loess soil.

2. The contribution of litter to the reduction in soil detachment increased as the restoration time increased. However, the contribution of BSCs was more prominent in the early stage of vegetation recovery before weakening as time increased. The compositions of both litter and BSCs should be considered in simulations of soil erosion in grasslands because these components had large effects on the soil detachment process.

3. There was no doubt regarding the great importance of plant root systems in controlling soil detachment, which accounted for half to two-thirds of the total contributions of near soil surface characteristics in a natural succession grassland. More attention should be paid to the root exudate bonding effect in future studies because the contribution of this bonding effect was even greater than that of litter in the late stages of vegetation restoration.

4. The correction coefficients of plant litter, BSCs, and live and dead roots for rill erodibility in the WEPP model are presented for different vegetation stages on the Loess Plateau of China. These correction coefficients accounted well for the effects of near soil surface characteristics on the soil detachment by overland flow.

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