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Soil detachment by overland flow under different vegetation restoration models in the Loess Plateau of China

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ABSTRACT

Land use change has significant effects on soil properties and vegetation cover and thus probably affects soil detachment by overland flow. Few studies were conducted to evaluate the effect of restoration models on the soil detachment process in the Loess Plateau where a Grain for Green Project has been implemented in the past fourteen years. This study was performed to study the effects of vegetation restoration models on soil detachment by overland flow and soil resistance to rill erosion as reflected by rill erodibility and critical shear stress. The undisturbed soil samples were collected from five 37-year-restored lands of abandoned farmland, korshinsk peashrub land (*Caragana korshinskill* Kom.), black locust land (*Robinia pseudoacacia* Linn.), Chinese pine land (*Pinus tabuliformis* Carr.) and mixed forest land of amorpha and Chinese pine. The samples were subjected to flow scouring in a 4.0 m long by 0.35 m wide hydraulic flume under six different shear stresses ranging from 5.60 to 18.15 Pa. The results showed that the measured soil detachment capacities were affected significantly by the restoration models. The mean detachment capacity of cultivated farmland was 23.2 to 55.3 times greater than those of the restored or converted lands. Abandoned farmland showed maximum soil detachment capacity and was 1.02 to 2.29 times greater than the other four restored lands. Soil detachment capacity of the restored lands was significantly influenced by shear stress, cohesion, bulk density, total porosity and root mass density. Detachment capacities were negatively related to cohesion ($p < 0.01$) with linear function and root mass density ($p < 0.05$) with exponential function, but positively to total porosity ($p < 0.01$) with linear function. The rill erodibility would be negatively related to cohesion ($p < 0.01$) with power function. Besides, the low rill erodibility in the restored lands always had a low soil detachment capacity, while the critical shear stress in the restored lands varied non-monotonically with detachment capacity. The mixed forest land of amorpha and Chinese pine was considered as the best restoration model for its important role in reducing soil detachment capacity.

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1. Introduction

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 surface flow of water, which may lead to the formation of rills and gullies (Govers et al., 1990). The mechanisms of soil detachment by inter-rill erosion and rill erosion are different and therefore they are considered as separate sub-processes in process-based erosion models (Zhang et al., 2003). The detachment in inter-rill erosion is mainly caused and enhanced by raindrop impacts, while the raindrop-impacted overland flow is the main transporting agent (Beuselinck et al., 2002; Bradford et al., 1987; Ferris et al., 1987; Gilley et al., 1985; Young and Wiersma, 1973). Rill erosion, in contrast, is considered to be the most important process of sediment production on steep slopes and is mainly caused by overland flow, while the impact of raindrops on detachment is insignificant (Owoputi and Stolte, 1995).

Over the last several decades, the increased interest in overland flow erosion such as rill erosion is reflected in the numerous attempts to incorporate overland flow erosion in process-based water erosion models, e.g. CREAMS (Knisel, 1980), WEPP (Nearing et al., 1989), EUROSEM (Morgan et al., 1992), and EGEM (Woodward, 1999). The effect of overland flow on soil detachment capacity has been studied extensively under different environmental conditions in both laboratory and field experiments, using hydraulic parameters such as flow regime, discharge, slope gradient, flow depth, velocity, friction, and sediment concentration (Cochrane and Flanagan, 1997; Govers et al., 1990; Nearing et al., 1999; Poesen et al., 2003; Zhang et al., 2002).

Erosion process by overland flow is also controlled by the resistance of the top soils or erodibility of the soil (Knapen et al., 2007).

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Table 1
Basic information of land-use, topography, and vegetation for the sampling sites.

Site[a]	Age (yr)	Slope (%)	Elevation (m)	Undergrowth vegetation	
				Coverage (%)	Dominant communities[b]
SF	0	8.7	1194	38.9	*Giycine max* (*L*)*Merrill*
AF	37	10.5	1213	60.7	*Stipa bungeana* +*Artemisia sacrorum*
KP	37	14.8	1210	51.0	*Artemisia sacrorum* +*Stipa przewalskyi*
BL	37	15.6	1204	55.5	*Artemisia sacrorum* +*Stipa przewalskyi*
CP	37	19.1	1163	48.2	*Artemisia sacrorum* +*Carex lanceolata*
ACP	37	20.8	1136	47.3	*Artemisia sacrorum* +*Artemisia giraldii*

[a] SF refers to the slop farmland, AF the abandoned farmland, KP the korshinsk peashrub, BL the black locust (*Robinia pseudoacacia* Linn.), CP the Chinese pine (*Pinus tabuliformis* Carr.) and ACP the mixed forest of amorpha (*Amorpha fruticosa* Linn.) and Chinese pine.
[b] All soil types are loessial soil and all landforms are hillside.

The resistance of top soils is mainly related to soil properties and vegetation characteristics. Soil type, texture and soil physicochemical properties of porosity, bulk density, cohesion, clay content, aggregate stability, organic matter content, soil moisture, and infiltration rate are demonstrated to have close relationships with soil detachment capacity (Ghebreiyessus et al., 1994; Khanbilvardi and Rogowski, 1986; Morgan et al., 1998; Nearing et al., 1988; Zheng et al., 2000). Torri et al. (1998) found that soil detachment capacity could be simulated with aggregate median diameter, clay content, soil bulk density and soil strength as a fractional function. Knapen et al. (2008) showed that soil detachment capacity decreased with increasing of soil organic matter, soil moisture content and bulk density. Any change in soil properties produced by farming activities, land use adjustment, soil consolidation, and vegetation growth would certainly alter soil detachment by overland flow (Abrahams et al., 1994; Parsons et al., 1996; Wainwright et al., 2000; Zhang et al., 2008a, 2009). Vegetation plays a great role in soil detachment process by changing soil properties (i.e. soil nutrient elements, soil bulk density and soil porosity) during the growth period, thus influencing the infiltration rate and soil erosion indirectly (Dunne and Dietrich, 1980). Vegetation root networks have an important role in protecting soil against water erosion and enhance its stability by binding soil particles at or near the soil surface, and thus reduce soil detachment (De Baets et al., 2006). De Baets et al. (2007) reported that the ability of vegetation roots to reduce soil erosion was greater than that suggested in previous studies (Dissmeyer and Foster, 1980; Wischmeier, 1975). To simulate the effects of roots on soil detachment capacities by overland flow, different root parameters, i.e. dry weight, mass density, length density, diameter, surface area density, and area ratio, were measured and used in those studies (De Baets et al., 2006; De Baets et al., 2007; Li et al., 1991; Mamo and Bubenzer, 2001a, b; Zhou and Shang Guan, 2005). The erosion-reducing effects of roots are also affected by root architecture. In general, tap roots reduce erosion rates to a lesser extent compared to fibrous roots (De Baets et al., 2007; Dissmeyer and Foster, 1980; Wischmeier, 1975). Biological soil crusts, which are thin layers of organic and mineral particles at the soil surface (Issa et al., 1999), affect soil detachment by altering soil strength, water infiltration and runoff (Issa et al., 2011). Moreover, soil surface resistance to water is also different in landscape positions, which influence runoff, drainage, soil erosion and soil formation, consequently affecting the soil detachment process of overland flow (Wang et al., 2001).

Soil erosion in the Loess Plateau is severe with the mean annual soil loss rates ranging from 5000 to 10,000 tons km^{-2} caused by the combined effects of rainfall, topography, soil, vegetation and human activities (Fu and Gulinck, 1994; Zhang and Liu, 2005; Zhang et al., 2008b). In the past several decades, many biological and engineering measures were implemented in the Loess Plateau to control soil erosion and soil degradation as well as to restore the ecological integrity of disturbed ecosystems. The soil properties and vegetation characteristics changed greatly due to the implementation of the above ecological restoration measures, and hence probably affected the resistance of top soils to soil detachment by overland flow. The history of vegetation restoration in the Loess Plateau can be traced back to 1970s (Zhang et al., 2008b). In the early 1970s, soil erosion control was mainly relied on extensive tree planting. In 1980s and 1990s, the integrated soil erosion control was carried out at the watershed scale. From 1984 to 1996, cultivated slope farmland decreased by 43%, forest and grassland increased by 36% and 5%, respectively (Fu et al., 2000). However, soil erosion was still severe on cultivated slope farmlands until late 1990s. Farmland is considered as a principal sediment source in the Loess Plateau since it is the mostly eroded land use in the region caused by disturbance of farming activities (Zhang et al., 2003, 2009). The average detachment capacity of cropland is 2 to 13 times greater than that of shrub land, grassland, wasteland, and woodland (Zhang et al., 2008a). In 1999, the project of "Grain for Green" was initiated to reduce soil erosion on cultivated slope farmland (Fu et al., 2000). In this project, farmers were compensated with grain in exchange for converting steep croplands (>15°) to green land (Fu et al., 2000). As a result, part of farmland was converted to forest-land or shrub-land mainly by planting black locust (*Robinia pseudoacacia* Linn.), korshinsk peashrub (*Caragana korshinskill* Kom.) and Chinese pine (*Pinus tabuliformis* Carr.), and part of farmland was just abandoned and gradually converted to grass-land through natural succession. Land-use type changed with the implementation of "Grain for Green" project in the Loess plateau. Soil hydraulic properties or related parameters such as infiltration rate and saturated conductivity are important factors in predicting runoff rates and closely relate to soil type and land use (Stolte et al., 2003). Jiao et al. (2011) found that land use had an important impact on soil bulk density, total porosity and capillary porosity of the surface soil layer, which indicated that land use change and re-vegetation of eroded soils resulted in significant changes in soil properties. Land use and soil management practice also influence the erosion process, consequently, modify the processes of transport and re-distribution of nutrients (Hontoria et al., 1999). Besides, other soil properties such as cohesion, and vegetation characteristics such as coverage and litters also changed with the land use transformation and vegetation restoration, which probably influenced soil detachment process (Hu et al., 2008; Jiang et al., 2003; Li et al., 1995; Li and Shao, 2006; Liu et al., 2003; Xu et al., 2006).

Table 2
Selected soil physical and biological properties on each site (Mean ± Std. Error).

Land-use types	Bulk density (kg m^{-3})	Cohesion (Pa)	Capillary porosity (%)	Total porosity (%)	Organic matter (g kg^{-1})	Biological crust thickness (mm)	Root weight density (kg m^{-3})
SF	1275 ± 5	8310 ± 1432	44.30 ± 0.15	46.10 ± 0.83	4.17 ± 0.02	–	0.51 ± 0.07
AF	1187 ± 19	8781 ± 825	47.74 ± 0.25	53.21 ± 0.45	6.12 ± 0.15	1.49 ± 0.45	6.35 ± 0.44
KP	1227 ± 17	9016 ± 1313	47.63 ± 0.13	52.29 ± 0.58	4.56 ± 0.13	0.20 ± 0.04	8.00 ± 0.78
BL	1213 ± 9	8585 ± 1299	46.73 ± 0.31	52.37 ± 0.35	5.79 ± 0.23	1.82 ± 0.59	7.66 ± 0.70
CP	1230 ± 68	9741 ± 795	48.93 ± 0.79	51.43 ± 0.29	6.69 ± 0.23	2.57 ± 0.76	9.37 ± 0.70
ACP	1233 ± 7	11309 ± 1194	47.63 ± 0.57	50.94 ± 0.24	4.82 ± 0.03	1.09 ± 0.25	13.21 ± 1.67

SF refers to the slop farmland, AF the abandoned farmland, KP the korshinsk peashrub, BL the black locust, CP the Chinese pine, ACP the mixed forest of amorpha and Chinese pine.

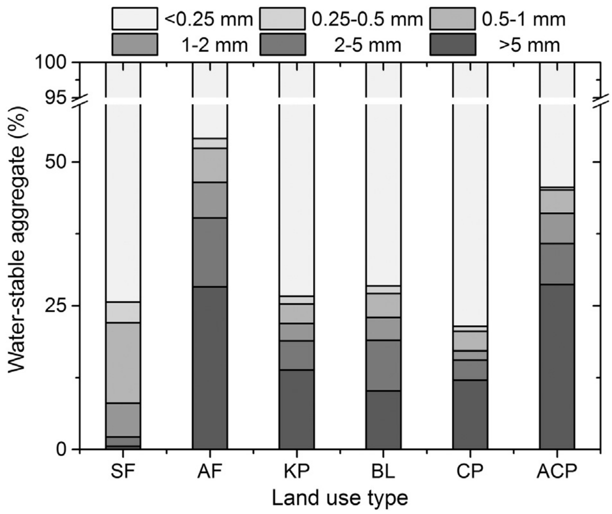

Fig. 1. Soil water-stable aggregate under different land uses. SF refers to the slop farmland, AF the abandoned farmland, KP the korshinsk peashrub, BL the black locust, CP the Chinese pine, ACP the mixed forest of amorpha and Chinese pine.

Rill erosion is a major erosion form in process-based water erosion models, and the study on soil erosion mechanism would be helpful to solve serious erosion issue in the Loess Plateau. As mentioned above, significant advances have been made in the understanding of characteristics of soil detachment by overland flow in rill erosion. It is well known that soil detachment process is closely related to hydraulic parameters of overland flow, which is also confirmed by laboratory flume studies using soils from the Loess plateau (Zhang et al., 2002, 2003, 2008a). However, the effects of soil resistance on soil detachment by overland flow of top soil under different restoration models are not clear, especially in the region of the Loess Plateau. The severity of soil erosion in the Loess Plateau has attracted considerable attention over the past several decades. Zhang et al. (2002, 2003) quantified the relationships between detachment capacity of the loessial soils and hydraulic parameters (i.e. slope gradient, flow discharge, shear stress and stream power) of disturbed and undisturbed lands by overland flow in laboratory experiment in the Loess Plateau. Although vegetation recovery is considered as an effective measure to erosion control and environmental construction in this region; however, the quantitative relationships between soil detachment capacity and vegetation restoration especially under different restoration models are still lacking and need to be quantified. The aims of this study were to quantify the effects of restoration models on soil detachment capacity by overland flow, and to compare differences in soil resistance to concentrated flow erosion resulting from land-use conversion as reflected by rill erodibility (K_r) and critical shear stress (τ_c) in the Loess Plateau of China.

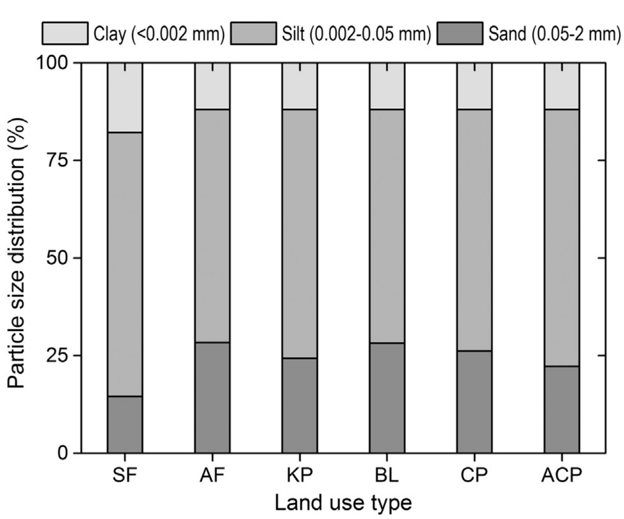

Fig. 2. The soil particle size distribution under different land uses. SF refers to the slop farmland, AF the abandoned farmland, KP the korshinsk peashrub, BL the black locust, CP the Chinese pine, ACP the mixed forest of amorpha and Chinese pine.

2. Materials and methods

2.1. Study area

The experiments were conducted in Zhifanggou small watershed of Ansai Research Station of Soil and Water Conservation (36°46′28″–36°46′42″N, 109°13′03″–109°16′46″E, 1010 to 1431 m altitude, 8.27 km^2). It is located in the typical loess hilly and gully region and situates near the center of the Loess Plateau in the Shaanxi Province. The loess-derived soils are fertile but extremely susceptible to erosion. Soil erosion in the study area is much higher than that in the southern part of the Loess Plateau. The climate belongs to transition zone of warm temperate semi-humid to semi-arid, which is dry and windy in spring, hot and rainy in summer, and dry and cold in winter. The mean annual temperature is 8.8 °C. The minimum and maximum temperatures are −23.6 °C in February and 36.8 °C in July. The frost-free period is 157 days. The mean annual precipitation is 505 mm, 70% of which falls between July and September in the form of short heavy storm. The soil is silt loam with the contents of sand, silt, and clay being 24%, 65%, and 11%. The natural vegetation belongs to forest steppe region of warm-temperate deciduous broad-leaved forest to steppe. The original vegetation was disappeared due to the intensive human activities, and the current vegetation types are mainly the native secondary vegetation of herbaceous plant community and miscellaneous shrub, and planted forests and shrubs.

2.2. Site selection

Samples were taken from fields of abandoned farmland, korshinsk peashrub land, black locust land, Chinese pine land, and mixed forest of amorpha and Chinese pine, which were retired from cultivated land for 37 years to allow natural re-vegetation. The restoration history of the sites was confirmed by consulting the village elders and scientists at the station. The slope aspect, slope gradient, elevation, soil type, and previous farming practices of the selected sites were similar to minimize the effects of these factors on experimental results. For comparison, one site was selected in slope farmland planted in soybean. Vegetation of abandoned farmland and under forest was all annual or perennial herbs. For all the selected sites, the soil was silt loam loess soil. Soil texture, properties and morphological traits of herbage in each group are listed in Table 1.

The soil properties of bulk density, capillary porosity, total porosity, soil cohesion, water stable aggregate, clay content and soil organic matter content were measured. Vegetation characteristics were also observed during sampling. To determine soil bulk density, capillary porosity and total porosity, three soil cores (5 cm in diameter, 5 cm in height) were taken from top soil (0 to 10 cm, Humus horizon, A1). Each core was weighed after wetted for six hours with water level of 5 mm to determine capillary porosity, and weighed after wetted for another 12 h with water level of 5 cm to test total porosity, then weighed after dried for 24 h at 105 °C to measure bulk density. Soil cohesion was measured with a pocket vane (14.10, Netherlands) of CL 100-standard vane (0 to 98000 Pa) for ten times on each site at the land surface after wetted to saturation by a sprayer. Sieves with apertures (0.25, 0.5, 1.0, 2.5, 5.0 mm) were used to test soil water stable aggregate. The saturated soil sample of 50 g was placed on the sieves and then immersed into water and shaken up and down for 30 times in 1 min. The aggregate left on each sieve was weighed and the percentage of each class was calculated. For each site, six extra soil samples, collected from the top 20 cm soil as an “S”-shaped pattern, were combined and

Table 3
Statistical parameters of measured soil detachment capacity (D_C).

site	Mean D_C ± Std. error (kg m^{-2} s^{-1})	Maximum D_C–minimum D_C (kg m^{-2} s^{-1})	Coefficient of variation
SF	0.915 ± 0.173	4.167–0.159	0.928
AF	0.039 ± 0.004	0.080–0.006	0.480
KP	0.022 ± 0.003	0.067–0.002	0.746
BL	0.038 ± 0.004	0.083–0.003	0.640
CP	0.021 ± 0.002	0.039–0.000	0.558
ACP	0.017 ± 0.002	0.050–0.001	0.745

SF refers to the slop farmland, AF the abandoned farmland, KP the korshinsk peashrub, BL the black locust, CP the Chinese pine, ACP the mixed forest of amorpha and Chinese pine.

air-dried. Root and other debris were removed by sieving through a 2 mm mesh. Samples were analyzed for clay content (hydrometer method) and soil organic matter (potassium dichromate colorimetric method). Thickness of biological crust on soil surface was measured using a caliper and ten replicates were made for each site.

2.3. Soil sampling for detachment measurement

For soil detachment measurement in the flume experiments, soil samples were collected with steel rings (9.8 cm in diameter and 5 cm in height). The detailed procedures for soil sampling could be found in the previous studies of Zhang et al. (2003, 2008a, 2009). Before sampling, weeds and litter were cleared completely. Soil and roots surrounding the ring were cut or excavated to ensure minimum disturbance of the sample while gently pressing the ring into the soil. When the top rim was flushed with the ground surface, the sample was taken out carefully and was trimmed slowly to remove the excess soil in the bottom. Both the top and bottom of the ring were cushioned with cotton cloth and capped to prevent disturbance as much as possible (Poesen et al., 2003). Totally, 198 soil samples were collected for six sites.

For each site, thirty-three samples were wetted for eight hours in a metal container. The water level was increased gradually and the final water level was 1 cm below the soil surface. Then drained for 12 h and weighed. Three of them were oven dried for 24 h to determine soil water content and the mean was considered as the initial sample water content to calculate the initial dry soil mass for other thirty soil samples.

2.4. Determination of hydraulic parameter

The soil detachment capacity was measured in a 4.0 m long and 0.35 m wide hydraulic flume, which was the same one used in the previous studies of Zhang et al. (2003, 2008a, 2009). A local Loess soil collected from cropland was glued on the flume bed surface so that the hydraulic roughness was similar to that of the soil sample surfaces and remained constant during the experiments. The flow discharge was adjustable and was measured in the flume outlet by collecting water flowing to a plastic-bucket in a given time frame, and then the volume of water was accurately measured with a graduate cylinder. Velocity of the water flow was measured using a fluorescent dye technique and was modified by a reduction factor according to flow regimes (Luk and Merz, 1992). The mean velocity was used to compute the flow depth h (m):

$$h = \frac{Q}{vB} \tag{1}$$

where Q is the flow discharge (m^3 s^{-1}), v is the flow velocity (m s^{-1}), and B is the flume width ($B = 0.35$ m). The mean flow depth ranged from 0.003 to 0.005 m. The flow shear stress τ (Pa) was calculated as:

$$\tau = \rho g h S \tag{2}$$

where ρ is the density of water (kg m^{-3}), g is the constant of gravity (m s^{-2}), and S is the slope gradient (m m^{-1}). Six combinations of unit width discharge (ranged from 0.003 to 0.007 m^2 s^{-1}) and flume bed gradient (from 17.4 to 42.3%) were designed, resulting shear stresses of 5.83, 8.69, 11.31, 13.67, 15.73, and 18.15 Pa.

2.5. Measurement of soil detachment capacity

For each restoration model, thirty soil samples were tested to determine soil detachment capacities. The wetted sample was placed in a hole (10 cm in diameter) in the flume bed, which located at a distance of 0.5 m from the flume outlet (Zhang et al., 2003). Then the soil detachment capacity was tested under designed flow shear stress. The test time (varied from 137.12 to 617.69 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 detachment capacity D_C (kg m^{-2} s^{-1}) was calculated as follows:

$$D_C = {}^{\Delta w}\!/_{tA} \tag{3}$$

where Δw is the dry weight of soil detached (kg, oven-drying for 24 h at 105 °C), t is the test period (s), and A is the section area of the soil sample (m^2). Five samples were tested under each flow shear stress and the mean was used for further analysis. Following each scouring, plant roots in each core were collected by washing, and then oven dried for 24 h at 65 °C.

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). Rill 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 the regression line between soil detachment capacity and shear stress as described in WEPP (Water Erosion prediction project) model (Nearing et al., 1989) as follows:

$$D_C = K_r(\tau - \tau_C). \tag{4}$$

Table 4
Correlation results of soil detachment capacity (D_C) with soil properties and vegetation characteristics.

	Bulk density	Cohesion	Capillary porosity	Total porosity	Water stable aggregate >0.25 mm	
D_C	−0.589**	−0.519**	−0.322	0.569**	0.204	
	Particle-size distribution (mm)			Organic matter	Root mass density	Crust thickness
	Sand 2–0.05 mm	Silt 0.05–0.002 mm	Clay <0.002 mm			
D_C	−0.001	−0.339	0.428*	0.269	−0.388*	0.137

* Significant at $p < 0.05$ (n = 30).
** Significant at $p < 0.01$.

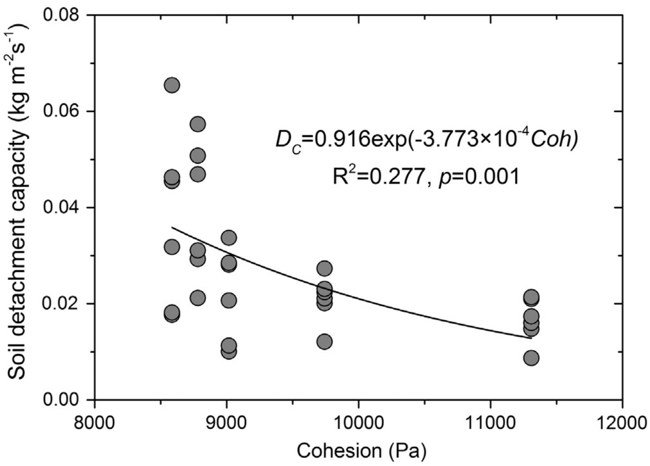

Fig. 3. Soil detachment capacity (D_C) as a function of cohesion (*Coh*).

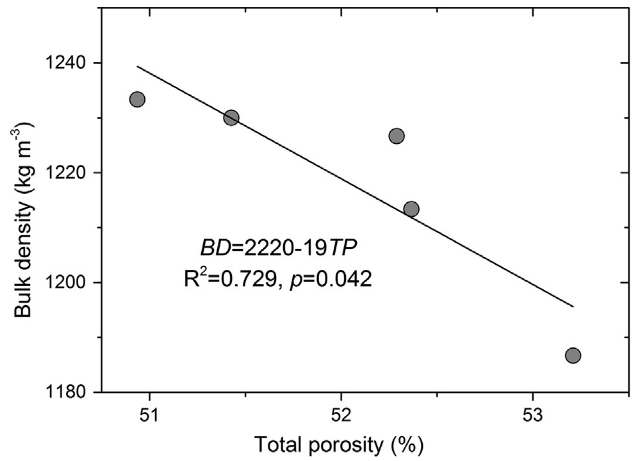

Fig. 5. Soil bulk density (*BD*) as a function of total porosity (*TP*).

2.6. Statistical analysis

One-way ANOVA was used to analyze soil detachment capacities between restoration models. The relationships between soil detachment capacities, and hydraulic parameters and soil properties were analyzed by a simple regression method. The stepwise regression method was used to analyze the relationship between soil detachment capacity and all factors (both hydraulic parameters and soil properties). The goodness of fit was evaluated by the coefficients of determination and Nash–Sutcliffe efficiency, *NSE* (Nash and Sutcliffe, 1970). All analyses were carried out with the SPSS 17.0 software.

3. Results

3.1. Variations of soil and vegetation properties after vegetation restoration

For all selected sites, the soil is silt loam loess with similar morphological characteristics. However, the soil properties, represented by bulk density, soil cohesion, capillary porosity, total porosity, water stable aggregate, clay content and soil organic matter content, and vegetation characteristics of biological crust and vegetation root system were quite different after 37 years of vegetation restoration (Table 2, Figs. 1 and 2).

Soil physical properties were greatly influenced by vegetation restoration. Soil bulk densities of restored lands were numerically 3 to 7% less than that in the slope farmland. Soil cohesions, capillary porosities and total porosities under different restoration models increased significantly after 37 year restoration compared with the slope farmland ($p < 0.05$, Table 2), with soil cohesions being 1.03 to 1.36, capillary porosities 1.05 to 1.10, and total porosities 1.10 to 1.15 times greater. The sand contents of the restored lands were 1.53 to 1.93 times greater than that in the slope farmland, while the silt and clay contents were 2.6 to 11.4% and 10.7 to 33.2% less than that in the slope farmland. Soil organic matter contents in the restored lands were significantly greater than that in the slope farmland except for the korshinsk peashrub due to the vegetation recovery. No statistical differences of soil cohesions and capillary porosities were found among the five restored land uses ($p > 0.05$). For total porosity, a significant difference was only detected between the abandoned farmland and the mixed forest land of amorpha and Chinese pine ($p < 0.05$). Water-stable aggregate reflecting soil's stability in water is considered as one of the indicators of soil erosion resistance. Percentage of water stable aggregate of size >0.25 mm of the restored lands tended to be greater than that of the slope farmland, except for Chinese pine, in which the water stable aggregate was 16.4% less than the slope farmland. The big difference appears to be that restoration dramatically increased the >2 mm aggregate content at the expense of the 0.5–1 mm aggregates. No significant difference of clay content was found among the restored lands. The root mass densities of restored lands were significantly greater than that in the slope farmland. The ratio of root mass density in the restored lands to that in the slope farmland averaged 12.46, 15.03, 15.70, 18.40 and 25.93 for the abandoned farmland, black locust, korshinsk peashrub, Chinese pine and mixed forest of amorpha and Chinese pine, respectively. The biological soil crusts developed in all restored lands due to the absence of tillage operations, with its thickness varying from 0.2 mm to 2.57 mm under different land uses.

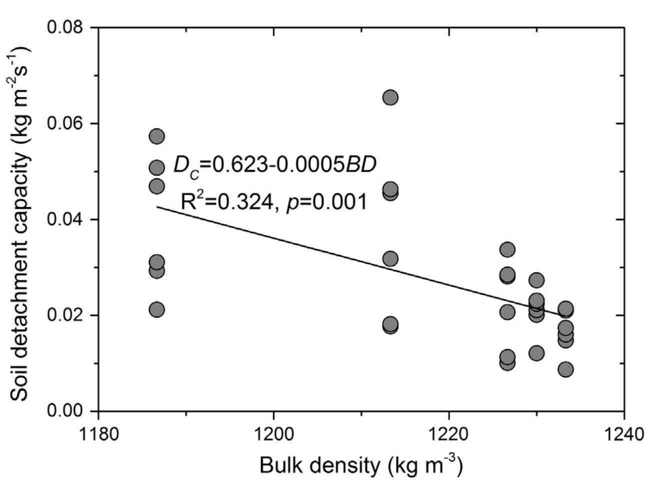

Fig. 4. Soil detachment capacity (D_C) as a function of bulk density (*BD*).

3.2. Soil detachment capacity under different restoration models

The measured soil detachment capacity differed significantly between the slope farmland and the restored lands (Table 3, $p < 0.05$). The surface soil of the slope farmland was disturbed by farming operations and therefore was easier to be detached. The mean soil detachment capacity of the farmland was 0.915 kg m^{-2} s^{-1}, whereas restored or abandoned land soil detachment capacity was over an order of magnitude smaller, ranging between 0.017 and 0.039 kg m^{-2} s^{-1} (Table 3). This result indicated that the slope farmland was the major source of eroded sediment on the Loess Plateau (Zhang et al., 2009). The significant reduction of soil detachment capacity in the restored lands, compared with the slope farmland, also confirmed that vegetation restoration in the Loess Plateau played an important role in controlling soil and water losses (Fu et al., 2011; Zheng, 2006). Among the five restored land uses, a significant difference in soil detachment capacity was only found between the abandoned farmland and the mixed forest land of amorpha and Chinese pine ($p < 0.05$). The mean soil detachment capacity in mixed forest of amorpha and Chinese pine land was numerically the lowest, and 21.2 to 58.0% less than that of the other four restored

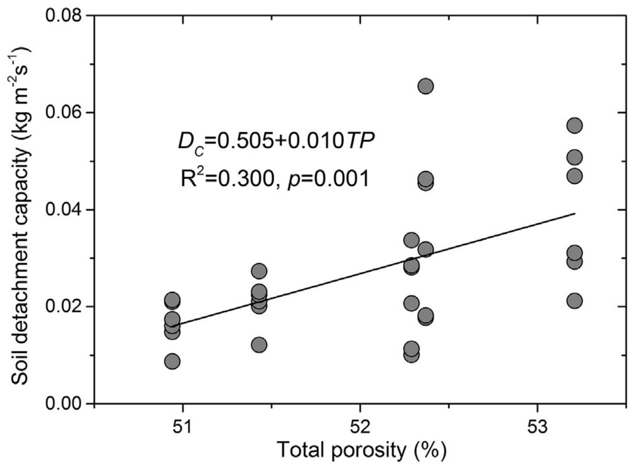

Fig. 6. Soil detachment capacity (D_C) as a function of total porosity (*TP*).

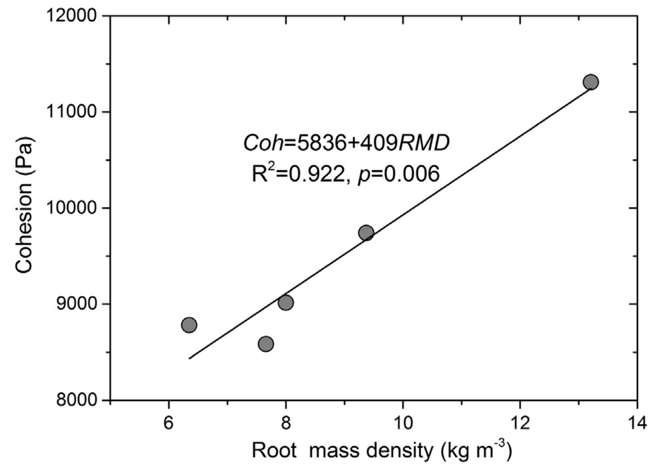

Fig. 8. Cohesion (*Coh*) as a function of root mass density (*RMD*).

lands. In this study, weeds were clipped and litter on the soil surface was brushed off before sampling, and thus any difference in soil detachment capacity among restored lands was not caused by differences in vegetation cover, although some studies suggested that vegetation cover was negatively correlated with soil erosion (Smets et al., 2008; Zhou et al., 2006). Gyssels et al. (2005) concluded that vegetation cover was the most important factor for controlling splash and inter-rill erosion based on an analysis of available data, whereas for rill erosion canopy cover might not be so important or even insignificant. The variation in soil detachment capacity among restored lands might be caused by other factors such as vegetation root growth, biological soil crusts, soil physical properties of soil cohesion, bulk density and total porosity (Table 4).

4. Discussions

4.1. Relationship between soil detachment capacity and soil and vegetation properties

Soil detachment capacity was negatively correlated with soil cohesion, bulk density, and root mass density ($p < 0.05$ or $p < 0.01$, Table 4), while it was positively correlated with total porosity, and clay content ($p < 0.05$ or $p < 0.01$, Table 4). However, the significant correlation between soil detachment capacity and clay content might be a false positive because the measured clay contents for all samples collected in the restored lands were nearly the same (from 11.95% to

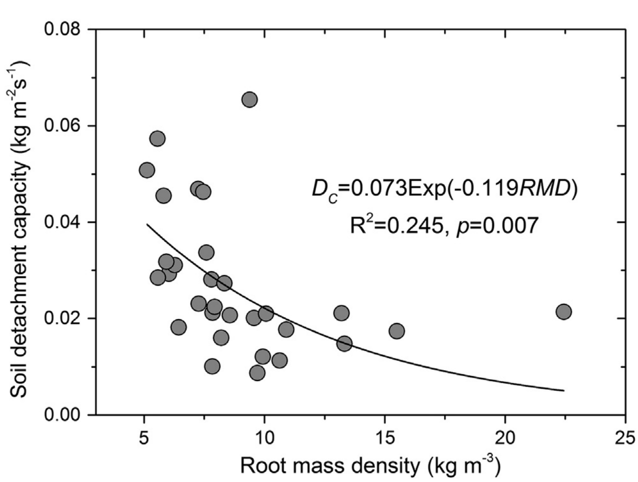

Fig. 7. Soil detachment capacity (D_C) as a function of root mass density (*RMD*).

11.97%). Soil cohesion was an important parameter in the Limburg Soil Erosion Model (LISEM) for calculating soil erosion caused by overland flow (De Roo et al., 1996a, b), and it was used to reflect the soil resistance to water erosion (Liu et al., 2003). In this study, soil cohesion tended to be reversely related to soil detachment capacity in a power function (Fig. 3). This was probably because greater soil cohesion would be more resistible to overland flow detachment (Liu et al., 2003). Soil bulk density also showed a negative correlation with soil detachment capacity ($p < 0.01$), and a power relationship was found between soil detachment capacity and bulk density (Fig. 4). Greater soil bulk density was caused by greater soil consolidation, and thus a soil sample with higher bulk density was harder to be detached (Cao et al., 2009). The total porosity, which was negatively related with soil bulk density ($p < 0.01$, Fig. 5), was positively correlated with soil detachment ($p < 0.01$), and a power relationship was detected between soil detachment capacity and total porosity (Fig. 6).

The root mass density was negatively correlated with soil detachment capacity ($p < 0.05$). Soil detachment capacities in the restored lands decreased exponentially with an increase in root mass densities (Fig. 7). From a hydrological point of view, root systems of plants reduce soil detachment capacity by binding soil particles at or near the soil surface, which increased soil cohesion (Fig. 8) and enhanced soil stability, hence protecting soil against water erosion (De Baets et al., 2006, 2007). Also, plant roots, especially fine roots, could improve soil permeability effectively to reduce runoff and soil erosion (Gyssels et al., 2005). Moreover, soil detachment capacity would be reduced by plant roots for it could provide additional surface roughness and add organic substances to the soil (Viles, 1990).

The biological soil crusts could play an important role to affect soil detachment process in arid and semiarid area (Rodriguez-Caballero et al., 2012; Xiao et al., 2011). Biological soil crusts were reported to have potential to increase surface roughness, and hence decreasing overland flow (Belnap, 2006; Belnap et al., 2005). However, in this study, it seemed that biological soil crusts had no significant effect on soil detachment capacity ($p > 0.05$). Probably because the growth of biological crust was curtailed by vegetation and the crust was not well developed. The biological crust thickness in this study was relatively thin compared with the previous study on the abandoned farmland in the Loess Plateau reported by Wang et al. (2013), and its cover was low (less than 20%). Xiao et al. (2011) demonstrated that the effect of biological soil crusts on surface runoff became significant only when the cover of biological soil crusts was greater than 29%. No statistical significant relationships were found between soil detachment capacity and capillary porosity, water stable aggregate (>0.25 mm) and organic matter in this study, probably caused by the relatively small variations of these factors between the different restoration models.

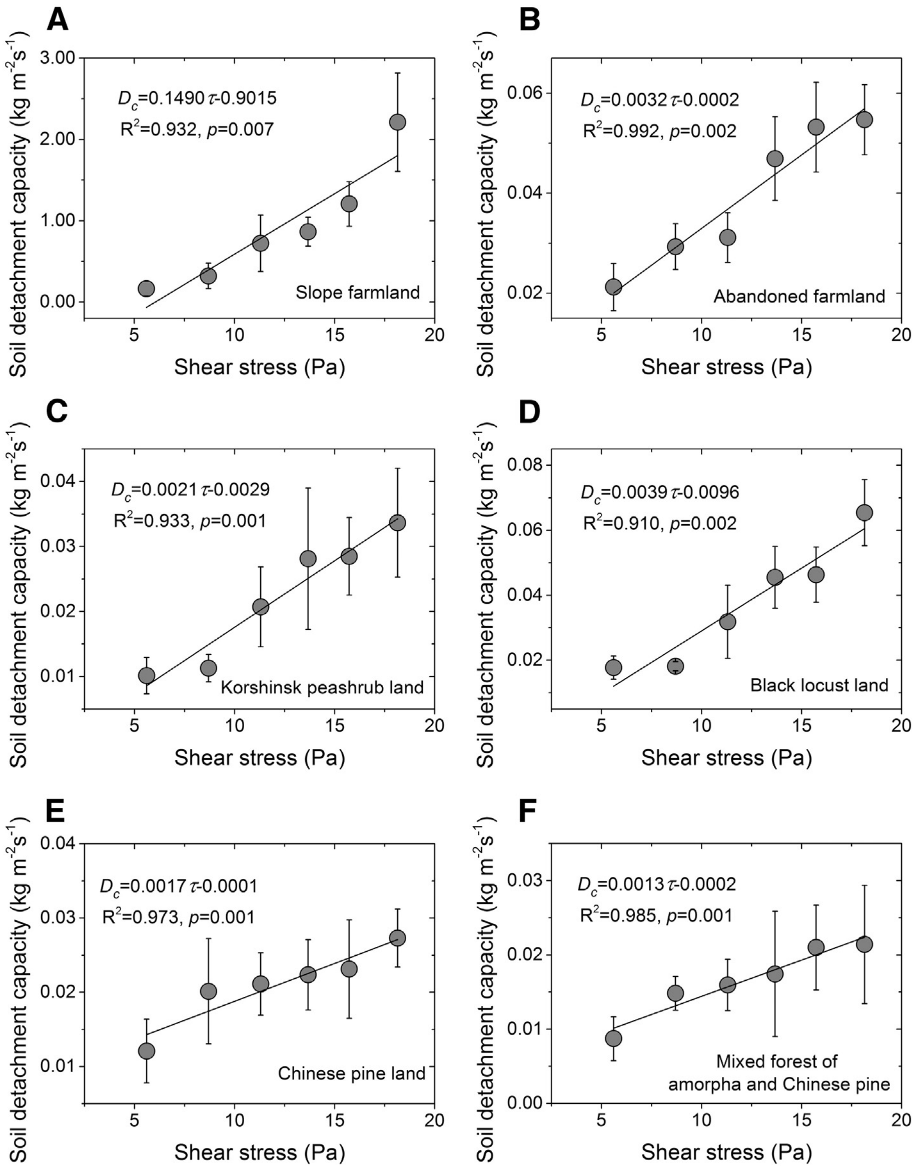

Fig. 9. A to F soil detachment capacity (D_C) as a function of shear stress (τ).

4.2. Effects of soil properties and vegetation characteristics on soil detachment process

Overland flow also has great effect on the process of soil detachment for it was the driving force of the soil detachment occurs. For all the experimental sites, soil detachment capacity increased linearly with shear stress ($p < 0.01$), and the coefficients of determination were greater than 0.910 (Fig. 9). To better understand the relationship between soil detachment and vegetation restoration, nonlinear regression was employed to analyze the effects of soil properties, vegetation characteristics and hydrodynamic conditions of overland flow on the process of soil detachment. The results showed that soil detachment capacity by overland flow under different restoration models could be estimated from shear stress, cohesion and root mass density ($R^2 = 0.653$, $p < 0.01$, NSE = 0.652):

$$D_C = 0.868\tau^{1.051}\mathrm{Coh}^{-0.623}\exp(-0.031\mathrm{RMD}) \quad (5)$$

where τ is the shear stress (Pa), *Coh* is the soil cohesion (Pa), and *RMD* is the root mass density (kg m^{-3}).

Soil properties and vegetation characteristics were the main factors affecting the process of soil detachment capacities under a given flow hydraulic condition used in this study. During the past 37 years, land-use types changed with the implementation of vegetation reconstruction, which was considered as a major measure to control soil and water losses in the Loess Plateau. Soil properties and vegetation characteristics varied with the driving force of land-use adjustment, and thus affected the soil detachment by overland flow. As discussed above, cohesion, bulk density, total porosity and root mass density had important influence on soil detachment process. Soil detachment capacity would be reduced with increases in soil cohesion, bulk density and root mass density. Moreover, soil cohesion and root mass density were most influential factors in the process of soil detachment (Eq. (5)).

4.3. Soil resistance to rill erosion

Rill erodibility (K_r) and critical shear stress (τ_c) are always considered as important parameters in rill erosion process reflecting soil resistance to rill erosion (Nearing et al., 1989). Rill erodibility and critical shear stress of each site were estimated with the linear model of Eq. (4) and the results are shown in Fig. 9 and Table 5. Erodibility of the farmland was 0.1164 s m^{-1}, whereas restored or abandoned land erodibility was over two orders of magnitude smaller, ranging between

Table 5
Values of rill erodibility (K_r) and critical shear stress (τ_c) based on the regression results between soil detachment capacity (D_C) and shear stress (τ).

Land-use types	K_r	τ_c
Slope farmland	0.1164	2.5876
Abandoned farmland	0.0032	0.0498
Korshinsk peashrub	0.0021	1.4146
Black locust land	0.0039	2.4806
Chinese pine land	0.0017	0.0602
Amorpha and Chinese pine land	0.0013	0.1128

0.0013 and 0.0039 s m^{-1}. Low detachment capacity in the restored lands was caused by the low erodibility due to interactive effects of vegetation and soil. The rill erodibility (K_r) in the restored lands decreased exponentially with an increase in soil cohesion (Fig. 10, $p < 0.01$). K_r also positively correlated with total porosity and negatively correlated with soil cohesion and root mass density. The best fitting between erodibility and those factors was ($R^2 = 0.780$, $p < 0.01$, NSE $= 0.794$):

$$K_r = 0.217\,\exp(-0.0004\text{Coh} + 0.034\text{TP} - 0.031\text{RMD}) \tag{6}$$

where *TP* is the total porosity (%).

Critical shear stress in cropland was the largest among all the land uses, though some previous studies indicated that cropland had the minimum critical shear stress compared to restored lands (Zhang et al., 2008a). In this study, the detachment capacity in cropland was rather high and about two orders of magnitude greater than those of restored lands. The larger regression slope in the linear model (K_r) in cropland tended to result in the larger intercept (τ_c) in this study. The abandoned farmland had a minimum critical shear stress among all restored lands, and the ratios of critical shear stress of abandoned farmland to those of other restored lands were 0.04 for the korshinsk peashrub land, 0.02 for black locust land, 0.83 for Chinese pine land and 0.44 for mixed forest land of amorpha and Chinese pine.

The estimated rill erodibilities (K_r) and critical shear stresses (τ_c) of this study were within the ranges reported by Nearing et al. (1999) and Zhang et al. (2002). But the rill erodibilities were two orders of magnitude greater than those reported in the WEPP rill erosion study (Laflen et al., 1991). In the WEPP model, the critical shear stress would make sense only if its value was greater than zero. In this study, the fitted negative critical shear strengths for the Chinese pine land and the mixed forest of amorpha and Chinese pine would not have any physical meaning. The regression lines should be forced through the origin within the range of the confidence interval ($p < 0.05$). However, the critical shear stress of the restored lands still varied non-monotonically with detachment capacity. This could probably be attributed to experimental error or the linear model assumed in the WEPP model, where the critical shear stress was defined as the intercept on the x axis of the regression line between the soil detachment capacity and shear stress. This means the value of critical shear stress was estimated by extending the regression line to the x axis without support of measured data.

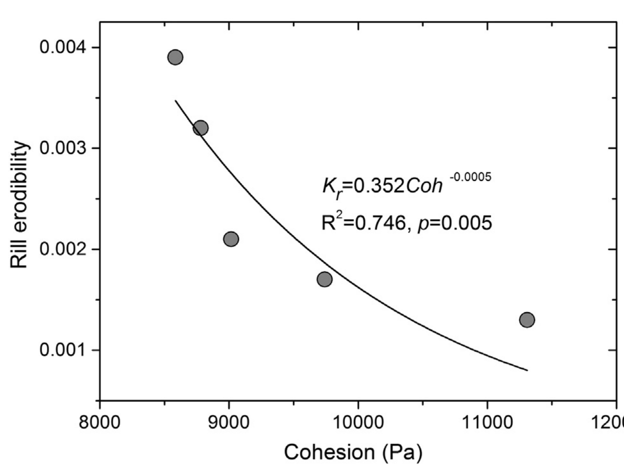

Fig. 10. The rill erodibility (K_r) as a function of soil cohesion (Coh).

5. Conclusions

The land use change by implementing the vegetation restoration project would reduce soil erosion by water, and the effectiveness in soil erosion reduction would depend on vegetation recovery models. This study was conducted to quantify the effectiveness of the restoration models on soil detachment capacity and soil resistance to flowing water erosion using undisturbed soil samples collected from one slope farmland and five restored lands of the abandoned farmland, korshinsk peashrub land, black locust land, Chinese pine land and mixed forest land of amorpha and Chinese pine in one typical small watershed located near the center of the Loess Plateau. The results showed that soil detachment capacity by overland flow decreased significantly after 37 years' vegetation restoration compared to the slope farmland. The mean detachment capacity of the currently cultivated slope farmland was 23.2 to 55.3 times greater than those of the restored lands, demonstrating the benefits of vegetation recovery in reducing soil erosion. Mixed forest land of amorpha and Chinese pine was the best restoration model for its effectiveness in reducing soil detachment capacity. The difference of soil properties and vegetation characteristics under different vegetation restoration models was the main reason that caused the variation in soil detachment capacity of the restored lands. Soil detachment was significantly influenced by shear stress, cohesion, bulk density, total porosity and root mass density, and it could be simulated well with power functions. Soil cohesion and root mass density were the most influential factors affecting the process of soil detachment under a given hydraulic condition of overland flow. The lower rill erodibility in the restored lands often resulted in lower soil detachment capacity, while the critical shear stress of the restored lands varied non-monotonically with detachment capacity. Further studies are needed to quantify the effects of vegetation on soil detachment process on a larger scale, which to create a generalizable soil erosion model in the Loess Plateau.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.catena.2013.12.010.

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