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

Bing Wang [a,b], Guang-Hui Zhang [a,b,*], Yang-Yang Shi [c], X.C. Zhang [d]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Water and Soil Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China
[b] School of Geography, Beijing Normal University, Beijing 100875, China
[c] Shanxi Architectural College, Taiyuan, Shanxi 030006, China
[d] USDA ARS, Grazinglands Research Laboratory, El Reno, OK, USA

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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.

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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* Corresponding author at: State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Water and Soil Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China.
E-mail addresses: bwang@ms.iswc.ac.cn (B. Wang), ghzhang@bnu.edu.cn (G.-H. Zhang).

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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.