Effect of natural restoration time of abandoned farmland on soil detachment by overland flow in the Loess Plateau of China

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ABSTRACT: Vegetation restoration has significant effects on soil properties and vegetation cover and thus affects soil detachment by overland flow. Few studies have been conducted to evaluate this effect in the Loess Plateau where a Great Green Project was implemented in the past decade. This study was carried out to quantify the effects of age of abandoned farmland under natural vegetation restoration on soil detachment by overland flow and soil resistance to erosion as reflected by soil erodibility and critical shear stress. The undisturbed soil samples were collected from five abandoned farmlands with natural restoration age varying from 3 to 37 years. 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 in currently cultivated farmlands were 24.1 to 35.4 times greater than those of the abandoned farmlands. For the abandoned farmlands, soil detachment capacities fluctuated greatly due to the complex effects of root density and biological crust thickness, and could be simulated well by flow shear stress and biological crust thickness with a power function (NSE = 0.851). Soil erodibility of abandoned farmlands decreased gradually with restoration age and reached a steady stage when restoration age was greater than 28 years. The critical shear stress of the natural abandoned farmlands declined when restoration age was less than 18 years and then increased due to the episodic influences of vegetation recovery and biological crust development. More studies in the Loess Plateau are necessary to quantify the relationship between soil detachment capacity and biological crust thickness for better understanding the mechanism of soil detachment under natural vegetation restoration. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS: soil erosion; flow detachment; vegetation; restoration age; Loess Plateau

Received 29 May 2012; Revised 6 June 2013; Accepted 10 June 2013

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Introduction

The Loess Plateau is one of the mostly severely eroded regions in the world. Severe erosion by water is caused by frequent heavy storms, steep slopes, easily eroded silty loam soils, scarce vegetation, and intense human activities. The mean annual soil erosion rates ranged from 5000 to 10 000 tonnes km⁻² yr⁻¹ (Fu and Gulinck, 1994; Zhang and Liu, 2005; Zhang et al., 2008b). Such serious soil erosion has slowed down socio-economic and environmental development by its direct and indirect influence in this region. The Chinese government realized the seriousness of this issue and began to implement a series of biological and engineering measures and conservation tillage practices in the Loess Plateau in order to achieve sustainable development of the socio-economic environment by controlling soil erosion and restoring the disturbed ecosystem (Li et al., 2012; Zhang et al., 2008b).

Govers et al. (1990) defined soil erosion by overland flow as the detachment and displacement of soil particles by overland flow. Describing soil detachment from land surface mathematically is an essential process of soil erosion modeling (Laffon et al., 1991). Different relationships for soil detachment by overland flow are used in soil erosion models to estimate initiation and rates of erosion by scouring in rills. These models are usually quite sensitive to both rill erosion rates and rill flow hydraulics used to describe soil detachment in a rill (Govers et al., 2007). Many experiments have been conducted in past decades to study the mechanism of soil detachment by overland flow. Results indicate that soil detachment is strongly influenced by hydraulic parameters of overland flow, such as flow regime, discharge, slope gradient, flow depth, velocity, friction, and sediment concentration (Govers et al., 1990; Cochrane and Flanagan, 1997; Nearing et al., 1999; Zhang et al., 2002, 2003). In process-based erosion models, hydraulic parameters of shear stress (Nearing et al., 1991), stream power (Hairsine and Rose, 1992a, 1992b; Zhang et al., 2002, 2003), and unit stream power (Morgan et al., 1998) are normally used to simulate soil detachment processes.
Soil properties have strong effects on soil detachment by overland flow. Recent studies showed that soil detachment was closely related to soil type, texture, bulk density, cohesion, clay content, organic matter content, soil moisture, and infiltration rate (Khanbilvari and Rogowsky, 1986; Nearing et al., 1988; Ghebreiyussus et al., 1994; Morgan et al., 1998; Zheng et al., 2000). Torri et al. (1998) found that soil detachment capacity increased as dry soil bulk density and aggregate median diameter increased, whereas it decreased as clay content and soil strength increased. Knappen et al. (2008) reported that soil detachment capacity decreased with increase in soil water content and organic matter. Any change in soil properties produced by farming activities, land use adjustment, soil consolidation, and vegetation growth certainly would result in changes in soil detachment by overland flow (Zhang et al., 2008a, 2009).

Vegetation root networks probably play a great role in protecting soil against water erosion and enhance its stability by binding soil particles and aggregates (De Baets et al., 2006), and thus reduce soil detachment. Root protection is even more important in semi-arid environments, where vegetation coverage is sparse and seasonal. De Baets et al. (2007) reported that the effect of roots on erosion reduction during an overland flow event was more profound than that indicated in previous studies (Wischmeier, 1975; Dissmeyer and Foster, 1980). Different root variables (e.g. mass density, length density, surface area density, dry weight, area ratio, and diameter) were used to predict the erosion-reducing effects of roots on soil detachment capacities by overland flow (Li et al., 1991; Mamo and Bubenzer, 2001a, 2001b; Zhou and Shang-Guan, 2005; De Baets et al., 2006, 2007). The influences of root system on soil detachment capacity were also related to root architectures. Some studies showed that tap roots, compared with fibrous roots, were less effective in reducing erosion rates (Wischmeier, 1975; Dissmeyer and Foster, 1980; De Baets et al., 2007).

Farmland is a principal sediment source in the Loess Plateau since it is the predominant eroded land use type in this region, and the average detachment capacity is 2.05 to 13.32 times greater than those of grassland, wasteland, shrub land, and woodland (Zhang et al., 2008a) caused by disturbance of farming activities (Zhang et al., 2003, 2009). Land use in the Loess Plateau has changed since several projects of ecological restoration were carried out in the 1970s to control soil erosion (Chen et al., 2007). Extensive tree planting on slope farmland (1970s) and integrated soil erosion control at watershed scales (1980s and 1990s) were carried out in the Loess Plateau. Between 1984 and 1996, slope farmland decreased by 43%, while forest land and grassland increased by 36% and 5%, respectively (Fu et al., 2000). However, soil erosion was still very severe on cultivated slope farmlands until the late 1990s when the project ‘Grain for Green’ was implemented. In this project, farmers were compensated with grain in exchange for taking their steep croplands (> 25.9%) out of production and allowing natural vegetation recovery (passive restoration) (Fu et al., 2000).

Land use change in the Loess Plateau might have altered both soil properties and vegetation characteristics. Soil hydro-physical parameters such as infiltration, cohesion, water-holding capacity, soil porosity, bulk density, aggregate stability, and saturated hydraulic conductivity were closely related to land use conditions (Li et al., 1993; Liu et al., 2003; Li and Shao, 2006; Xu et al., 2006; Hu et al., 2008). Vegetation characteristics (e.g. coverage, community structure, and species composition and diversity) were also greatly affected by land use conversion (Jiang et al., 2003). Both changes in vegetation and soil property characteristics caused by land use adjustments are probably related to the chronosequence of natural vegetation restoration, and the particular mechanisms need to be investigated. With progression in natural restoration chronosequence, hydraulics characteristics, physical and chemical properties of soils, and vegetation characteristics changed greatly (Jiao et al., 2007; Zhu et al., 2009; Wang et al., 2011), certainly resulting in changes in soil detachment processes. However, the quantitative relationships between soil detachment capacity and plant restoration age are not known in the Loess plateau. The aims of this study were to quantify the effects of the age of natural restoration on soil detachment by overland flow following abandonment of steep farmland and to investigate the changes in soil resistance to erosion with restoration age as reflected by soil erodibility (Ks) and critical shear stress (τc) in the Loess Plateau of China.

### Materials and Methods

#### Study area

The study was performed in the Zhifanggou small watershed (longitude 109°19′23″E, latitude 36°51′30″N; 1068 to 1309 m elevation; 8.27 km², Figure 1) of Ansai Soil and Water Conservation Station, Chinese Academy of Sciences (CAS) and Ministry of Water Resources (MWR). The mean annual temperature at the station is 8.8°C and mean annual precipitation is 505 mm. The study area is located in the typical loess hilly and gully region of the Loess Plateau. The soil is silt loam loess; climate is temperate, semi-arid; and vegetation type belongs to forest-steppe zone. In this area, serious soil erosion is caused primarily by human activities, which has important significance for conserving soil and water resources in the region.

#### Sites selection

Abandoned farmlands in different ages of natural restoration were selected in the Zhifanggou small watershed. The natural restoration age of the abandoned farmland 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. All the sites have a similar loessial loam soil. The selected sites have been abandoned for 3, 10, 18, 28, and 37 years. For comparison, one site was selected as a baseline or control in slope farmland planted in soybean. Vegetation of the abandoned farmlands were all annual or perennial herbs. Land-use and vegetation information for selected sites are listed in Table I.

#### Soil and sampling

Soil bulk density, soil cohesion, thickness of biological crust, clay content, and soil organic matter content of each site were measured. Steel rings (5 cm in height and 5 cm in diameter) were used to determine bulk density of the top soil layer and three replicates were measured for each site. Soil strength of these factors on experimental results. All the sites have a similar loessial loam soil. The selected sites have been abandoned for 3, 10, 18, 28, and 37 years. For comparison, one site was selected as a baseline or control in slope farmland planted in soybean. Vegetation of the abandoned farmlands were all annual or perennial herbs. Land-use and vegetation information for selected sites are listed in Table I. Steel rings (5 cm in height and 5 cm in diameter) were used to determine bulk density of the top soil layer and three replicates were measured for each site. Soil strength of these factors on experimental results. All the sites have a similar loessial loam soil. The selected sites have been abandoned for 3, 10, 18, 28, and 37 years. For comparison, one site was selected as a baseline or control in slope farmland planted in soybean. Vegetation of the abandoned farmlands were all annual or perennial herbs. Land-use and vegetation information for selected sites are listed in Table I.
then well-mixed and air-dried. Roots and other debris were re-
moved for each combined sample with a 2 mm sieve. The
sieved soil samples were stored for laboratory analysis of soil
particle size distribution (hydrometer method) and soil organic
matter (potassium dichromate colorimetric method). The basic
soil properties data are shown in Table II.

Iron rings (5 cm in height and 9.8 cm in diameter) were used
to collect intact soil samples from the surface soil layer for
detachment capacity measurement by overland flow. The
sampling process was the same as in previous studies and can
be found in Zhang et al. (2003, 2008a, 2009). Thirty-three
samples were collected for each site and wetted for 8 h (the
water level was increased gradually and the final water level
was 1 cm below the soil surface) in a metal container, and then
drained for 12 h and weighed. Thirty of them were used to
determine soil detachment capacities, soil erodibility, and
critical shear stress under different shear stresses while the
remaining three were used to measure the field water holding
capacity and dry soil mass for each site. Lastly, the three cores
were oven dried for 24 h to determine soil moisture and the
mean value that was used to calculate the initial dry soil mass
for the other thirty soil samples.

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

<table>
<thead>
<tr>
<th>Site code</th>
<th>Age (yr)</th>
<th>Landform</th>
<th>Slope (%)</th>
<th>Elevation (m)</th>
<th>Vegetation coverage (%)</th>
<th>Dominant communities</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF</td>
<td>0</td>
<td>hillside</td>
<td>8.7</td>
<td>1194</td>
<td>38.9</td>
<td>soybean</td>
</tr>
<tr>
<td>AF3</td>
<td>3</td>
<td>hillside</td>
<td>14.0</td>
<td>1184</td>
<td>42.3</td>
<td>Achillea capillaris</td>
</tr>
<tr>
<td>AF10</td>
<td>10</td>
<td>hillside</td>
<td>12.2</td>
<td>1089</td>
<td>40.9</td>
<td>Achillea capillaris-Artemisia sacrorum</td>
</tr>
<tr>
<td>AF18</td>
<td>18</td>
<td>hillside</td>
<td>14.0</td>
<td>1342</td>
<td>56.1</td>
<td>Artemisia sacrorum- Stipa bungeana</td>
</tr>
<tr>
<td>AF28</td>
<td>28</td>
<td>hillside</td>
<td>17.5</td>
<td>1167</td>
<td>60.7</td>
<td>Artemisia sacrorum- Stipa bungeana</td>
</tr>
<tr>
<td>AF37</td>
<td>37</td>
<td>hillside</td>
<td>10.5</td>
<td>1213</td>
<td>60.7</td>
<td>Stipa bungeana-Artemisia sacrorum</td>
</tr>
</tbody>
</table>

* SF is slope farmland.
* AF is abandoned farmlands, and the number is the abandonment age in years.
* All soils type are loessial soil.

Infiltration rate measurements

Infiltration rate was measured using a CSIRO disc permeameter
(Center for Environmental Mechanics, Canberra, Australia).
The supply water pressure heads ($\psi$) was $-20$ mm. The detailed
measuring procedure is described by Joel and Messing (2001).
For each site, infiltration rate was duplicated three times and
the mean value was considered as the mean infiltration rate.
The initial infiltration rate and steady infiltration rate were
calculated as follows:

$$f_0 = \frac{h_0 D_1^2}{t_0 D_1^2(0.7 + 0.03 T)} \quad (1)$$
Table II. Selected soil physical and biological properties on each site

<table>
<thead>
<tr>
<th>Site</th>
<th>Soil bulk density (kg m⁻³)</th>
<th>Soil cohesion (Pa)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Sand (%)</th>
<th>Organic carbon (g kg⁻¹)</th>
<th>Biological crust thickness (mm)</th>
<th>Root mass density (kg m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF</td>
<td>1250</td>
<td>10257</td>
<td>15.96</td>
<td>63.83</td>
<td>20.21</td>
<td>4.63</td>
<td>-</td>
<td>0.29</td>
</tr>
<tr>
<td>AF3</td>
<td>1247</td>
<td>11050</td>
<td>15.96</td>
<td>57.85</td>
<td>26.19</td>
<td>3.24</td>
<td>2.99</td>
<td>1.12</td>
</tr>
<tr>
<td>AF10</td>
<td>1267</td>
<td>10290</td>
<td>15.93</td>
<td>61.73</td>
<td>22.34</td>
<td>5.09</td>
<td>1.95</td>
<td>4.35</td>
</tr>
<tr>
<td>AF18</td>
<td>1239</td>
<td>9839</td>
<td>11.93</td>
<td>59.65</td>
<td>28.42</td>
<td>4.14</td>
<td>1.56</td>
<td>2.82</td>
</tr>
<tr>
<td>AF28</td>
<td>1188</td>
<td>10310</td>
<td>9.97</td>
<td>63.83</td>
<td>26.19</td>
<td>4.56</td>
<td>1.97</td>
<td>4.18</td>
</tr>
<tr>
<td>AF37</td>
<td>1186</td>
<td>8781</td>
<td>11.95</td>
<td>59.73</td>
<td>28.33</td>
<td>6.12</td>
<td>1.35</td>
<td>6.35</td>
</tr>
</tbody>
</table>

* SF means slope farmland.
* AF is abandoned farmlands, and the number is the abandonment age in years.
* All sites have similar loam soil texture.

where \( t_0 \) is the initial infiltration rate at 10°C standard water temperature for the first 3 min (mm min⁻¹), \( h_0 \) is the water level drop height of the reservoir for the first 3 min (mm), \( t_3 \) is the infiltration time (\( t_3 = 180 \) s), \( D_1 \) is the diameter of base disk (\( D_1 = 200 \) mm), \( D_2 \) is the diameter of reservoir (\( D_2 = 47 \) mm), \( T \) is the mean water temperature for the first 3 min (°C).

where \( f_s \) is the steady infiltration rate at 10°C standard water temperature (mm min⁻¹), \( \Delta h \) (mm) is the water level drop height of reservoirs for a certain time (\( \Delta t \) s), \( T \) is the water temperature (°C). The initial infiltration rate and steady infiltration rate of each site are shown in Table III.

### Hydraulic parameter determination

The soil detachment capacity was measured in a 4.0 m long and 0.35 m wide flume, as used in previous studies by Zhang et al. (2003, 2008a, 2009). The test soil collected from the farmland was glued on to the flume bed surface, and the surface remained constant throughout the whole experiment process so that the hydraulic roughness was similar to that of the soil sample surfaces. The flow discharge was calibrated to the desired rate in the flume outlet with a plastic bucket and a scale prior to test. The volume of water in the bucket was accurately measured with a graduated cylinder. For a given combination of flow discharge and slope gradient, flow velocity was measured 12 times using a fluorescent dye method and modified by a reduction factor according to flow regime (Luk and Merz, 1992). The mean velocity was used to compute the flow depth \( h \) (m):

\[
h = \frac{Q}{VB} \quad (3)
\]

where \( Q \) is the flow discharge (m³ s⁻¹), \( v \) is the flow velocity (m s⁻¹), and \( B \) is the flume width (B=0.35 m). The mean flow depth varied from 0.003 to 0.005 m. The flow shear stress (\( \tau \), Pa) was calculated as:

\[
\tau = \rho ghS \quad (4)
\]

where \( \rho \) 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 m² s⁻¹) and flume bed gradient (from 17.4 to 42.3%) were tested, resulting in shear stresses of 5.83, 8.69, 11.31, 13.67, 15.73, and 18.15 Pa.

### Measurement of detachment capacity

The flume gradient and water discharge rate were adjusted to the desired values. The wetted sample was set into a hole in the flume bed (0.5 m from the flume outlet), and was scoured under the desired flow shear stress and ended until a certain scouring depth was reached to standardize the influence of the ring rim (Nearing et al., 1991; Zhang et al., 2002). The scouring time varied from 15.04 to 316.70 s. Soil detachment capacity was calculated as follows:

\[
D_C = \frac{W_D - W_e}{t \times A} \quad (5)
\]

where \( D_C \) is the soil detachment capacity (kg s⁻¹ m⁻²), \( W_D \) is the dry weight of soil sample (kg) before the detachment test, \( W_e \) is the dry weight of the soil sample (kg) after the test (oven-drying for 24 h at 105°C), \( t \) is the test period (s), and \( A \) is the section area of the soil sample (m²). Five samples were tested under each shear stress condition. The average value was deemed the mean detachment capacity for that shear stress. Altogether, 180 soil samples were tested. After that, soil root of each core was measured by watering and weighing (oven-drying for 24 h at 65°C), and the root mass density (kg m⁻³) was calculated by dividing the root weight (kg) by the ring volume (3.77x10⁴ m⁻³).

Soil erodibility of rill (\( K_r \)) and critical shear stress (\( \tau_c \)) were important parameters to reflect the soil resistance to erosive forces (Nearing et al., 1988; Zhang et al., 2002). Soil erodibility (\( K_r \)) and critical shear stress (\( \tau_c \)) were estimated as the slope and intercept...
farmlands, the farming disturbance ceased and soil began to form aggregate and consolidate gradually. The resistance of soil to erosion increased, causing soil detachment capacity to decrease. For abandoned farmlands with different restoration ages, the measured detachment capacity varied with chronological series. The average soil detachment capacity increased gradually from 0.032 to 0.047 kg m⁻² s⁻¹ when the restoration age was less than 18 years and then decreased continually to 0.039 kg m⁻² s⁻¹ by the restoration age of 37 years (Table IV).

The reduction of soil detachment capacity following slope farmland abandonment also resulted from vegetation recovery. Due to the vegetation restoration in abandoned farmlands, which was considered as a process of secondary succession (Pugnaire et al., 2006), runoff generation was reduced by the interception of plant and the increased soil infiltration rates (García-Ruiz and Lana-Renault, 2011). In China, as a result of the implementation of the ‘Grain for Green’ project, the runoff was reduced by 18% after vegetation recovery (Deng et al., 2012). In the Loess Plateau, the runoff generation in abandoned farmland is reduced by 30% to 62.4% compared with that in the slope farmland due to the improved soil infiltration capacity (Hou and Zou, 1987; Hou and Cao, 1990). In this study, the infiltration rate (both initial infiltration rate and steady infiltration rate) of abandoned farmland increased with the restoration chronosequence when the age of abandonment was greater than 10 years (Table III). The fluctuation in infiltration rate during the early stage of natural vegetation succession was probably caused by the process of consolidation (Liu et al., 2012). The initial infiltration rate and steady infiltration rate in 37-years-old abandoned farmland were 1.3 and 1.8 times greater than that in control farmland. Soil infiltration increases with root mass density (P<0.01; Table V), although it was negatively or not correlated with biological soil crust thickness (P<0.05 or P>0.05; Table V). The overland flow for a given rainfall event declines as soil infiltration rate increases with abandoning age, which certainly leads to further decrease in soil detachment capacity of abandoned farmland (Zhang et al., 2002, 2003).

Soil detachment by overland flow decreased with soil cohesion (De Roo et al., 1996; Torri et al., 1998; Zhang et al., 2008), which increased with root density (Comino and Marengo, 2010: Comino et al., 2010; Du et al., 2010). Nevertheless, no significant correlation was found between soil cohesion and soil detachment capacity in this study. The effects of abandon age on soil detachment were complex and influenced by many factors of soil properties or vegetation characteristics except soil cohesion (Table V). However, the measured depth of the pocket vane used in this study was only 5 mm, and the effects of roots on soil cohesion were probably not detected. The measured soil cohesion was closely related to soil surface characteristics such as the depth of crust (Figure 3).

Table IV. Statistical parameters of measured soil detachment capacity (DC)

<table>
<thead>
<tr>
<th>Site code</th>
<th>n</th>
<th>Mean (kg m⁻² s⁻¹)</th>
<th>Minimum (kg m⁻² s⁻¹)</th>
<th>Maximum (kg m⁻² s⁻¹)</th>
<th>Standard error (kg m⁻² s⁻¹)</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF</td>
<td>30</td>
<td>1.132³</td>
<td>0.187</td>
<td>2.627</td>
<td>0.132</td>
<td>0.638</td>
</tr>
<tr>
<td>AF3</td>
<td>30</td>
<td>0.032³</td>
<td>0.001</td>
<td>0.228</td>
<td>0.008</td>
<td>1.438</td>
</tr>
<tr>
<td>AF10</td>
<td>30</td>
<td>0.046³</td>
<td>0.002</td>
<td>0.170</td>
<td>0.006</td>
<td>0.752</td>
</tr>
<tr>
<td>AF18</td>
<td>30</td>
<td>0.047³</td>
<td>0.001</td>
<td>0.094</td>
<td>0.004</td>
<td>0.513</td>
</tr>
<tr>
<td>AF28</td>
<td>30</td>
<td>0.035³</td>
<td>0.004</td>
<td>0.107</td>
<td>0.004</td>
<td>0.679</td>
</tr>
<tr>
<td>AF37</td>
<td>30</td>
<td>0.039³</td>
<td>0.006</td>
<td>0.080</td>
<td>0.003</td>
<td>0.481</td>
</tr>
</tbody>
</table>

⁳SF means slope farmland.
⁴AF is abandoned farmlands, and the number is the abandonment age in years.
⁵The same letter means there is no difference between them (P>0.05).
⁶Coefficient of variation is the ratio of the standard deviation to mean value of detachment capacity.
Plant root networks and depth distribution were probably related to the fluctuation in soil detachment capacities. Well-developed root networks could bind soil particles and soil aggregates together and increase the soil’s resistance to erosion. The root mass density of the 37-years-old abandoned farmland was the maximum value among the slope and other abandoned farmlands. It was 21 times greater than the control farmland, and 1.5 to 5.7 times greater than other abandoned farmlands. Soil detachment capacity decreased as an exponential function of root mass density ($P < 0.000, R^2 = 0.901$, Figure 4):

$$DC = 5.809 \exp(-5.851RMD)$$

(6)

where $DC$ is the soil detachment capacity ($\text{kg m}^{-2} \text{s}^{-1}$), and $RMD$ is the root mass density ($\text{kg m}^{-3}$).

Biological crust composed mostly of moss was another important factor influencing the soil detachment process in the idled farmlands. The biological crust quickly developed in the initial stage of restoration due to the low vegetation and litter cover, and was effective in protecting the surface soil from flow detachment (Muscha and Hild, 2006; Rodríguez-Caballero et al., 2012). The biological crust of a 3-year abandoned farmland was the thickest among the studied sites and was 1.5 to 2.2 times greater than the other abandoned farmlands. The thickness of biological crust decreased gradually with increasing vegetation coverage as restoration age increased. As a result, the potential effects of biological crust on soil detachment were reduced (Rodríguez-Caballero et al., 2012). The relationship between soil detachment capacity and biological crust thickness could be expressed well with an exponential function as follows ($P < 0.000, R^2 = 0.785$, Figure 5):

$$DC = 1.117 \exp(-2.119C_{TH})$$

(7)

where $C_{TH}$ is the biological crust thickness (mm). No significant relationship was found between soil detachment capacity and soil bulk density or clay content in this study. This result was probably caused by small ranges of measured soil bulk density and clay content of sites for soil sample collected.

Soil detachment increased with shear stress as a power function for all experimental sites. The coefficients of determination were greater than 0.902 and the Nash–Sutcliffe efficiencies were greater than 0.915 (Table VI). This result agreed with the report of previous studies by Zhang et al. (2008a) and the technology of WEPP model (Nearing et al., 1988). For the dataset of all the restoration age groups, the regression result was

$$DC = 0.001 \tau^{3.330}$$

(8)

![Figure 3. Soil cohesion (Coh) as a function of biological soil crusts thickness (C_{TH}).](image3)

![Figure 4. Soil detachment capacity (D$_C$) as a function of root mass density (R$_{MD}$).](image4)

![Figure 5. Soil detachment capacity (D$_C$) as a function of biological crust thickness (C$_{TH}$).](image5)
The result indicated that soil detachment capacity could be influenced by biological crust, soil properties and vegetation characteristics as shown above. Hence, the relationship between soil detachment capacity and all these factors measured could be analyzed using a stepwise regression method. In the study, the lower vegetation cover resulted in lower ability to stabilize 28 years after abandonment (Figure 9). Soil erodibility of 3-year-old abandoned farmland declined by 95.6% compared with the slope farmland. With natural vegetation restoration and increases in species diversity, soil erodibility of the abandoned farmland decreased gradually with restoration age, and tended to stabilize 28 years after abandonment (Figure 9). Soil erodibility of 28-year-old abandoned farmland was 41.2% lower than that of 3-year-old abandoned farmland, and was similar to that of 37-year-old abandoned farmland. Erodibilities of the abandoned farmlands of this study ranged from 0.003 to 0.005 m s⁻¹, which were 37.7% to 62.9%, and 35.7% to 59.5% of those reported by Zhang et al. (2003) and Nearing et al. (1999), respectively, but were one order greater than those reported by Laflen et al. (1991). These differences were probably caused by differences in land use, vegetation, soil, and surface properties. The soil samples were taken from a farmland planted with soybean in the work of Zhang et al. (2003), and from a stony hillslope in Nearing et al. (1999), but from the undisturbed abandoned farmlands of a loess soil with restored vegetation and biological crusts in this study. Soil erodibilities reported by Laflen et al. (1991) were obtained from runoff plot data of simulated rainfall, and the methodology was quite different from the other three studies in which the data were obtained using inflow.

Critical shear stress of the abandoned farmlands changed from 0.051 to 5.980 Pa (Figure 10), which were 2.3 to 273.1%, 1.3 to 149.9%, and 1.0 to 119.6% of those reported by Zhang (Equations (6) and (7)), root mass density was not included in the function when all the hydraulic parameters, soil properties and vegetation characteristics were considered when using the method of regression analysis. The coefficient of determination was 0.851 and the Nash–Sutcliffe efficiency was 0.845 (Figure 7). Compared with Equation (8), the fitting was slightly improved.

Soil erodibility (K) and critical shear stress (\( \tau_c \)) were important parameters reflecting soil resistance to rill erosion. Soil detachment in rills occurs when flow shear stress exceeds the critical shear stress of the soil as well as when sediment concentration is lower than sediment transport capacity of the flow. Hence, rill erodibilities and critical shear stress were normally estimated for soils of the slope and abandoned farmlands using simple linear regression based on the WEPP formulation (Nearing et al., 1988) and the results were shown in Figure 8.

Soil erodibility of the slope farmland differed significantly with those of the abandoned farmlands and it was 22.8 to 40.1 times greater than those of the abandoned farmlands. After farmland was abandoned, soil erodibility decreased rapidly due to biological crust formation, natural vegetation restoration, and soil consolidation in the absence of tillage disturbance (Zhang et al., 2009). Soil erodibility of 3-year-old abandoned farmland declined by 95.6% compared with the slope farmland. With natural vegetation restoration and increases in species diversity, soil erodibility of the abandoned farmland decreased gradually with restoration age, and tended to stabilize 28 years after abandonment (Figure 9). Soil erodibility of 28-year-old abandoned farmland was 41.2% lower than that of 3-year-old abandoned farmland, and was similar to that of 37-year-old abandoned farmland. Erodibilities of the abandoned farmlands of this study ranged from 0.003 to 0.005 m s⁻¹, which were 37.7% to 62.9%, and 35.7% to 59.5% of those reported by Zhang et al. (2003) and Nearing et al. (1999), respectively, but were one order greater than those reported by Laflen et al. (1991). These differences were probably caused by differences in land use, vegetation, soil, and surface properties. The soil samples were taken from a farmland planted with soybean in the work of Zhang et al. (2003), and from a stony hillslope in Nearing et al. (1999), but from the undisturbed abandoned farmlands of a loess soil with restored vegetation and biological crusts in this study. Soil erodibilities reported by Laflen et al. (1991) were obtained from runoff plot data of simulated rainfall, and the methodology was quite different from the other three studies in which the data were obtained using inflow.

Critical shear stress of the abandoned farmlands changed from 0.051 to 5.980 Pa (Figure 10), which were 2.3 to 273.1%, 1.3 to 149.9%, and 1.0 to 119.6% of those reported by Zhang et al. (2008a), eight-year-old Astragalus adsuusin Pall had tap roots and the restoration age of the idle land was shorter than most sites in this study. The tap roots of Astragalus adsuusin Pall were less effective in reducing soil detachment than the fibrous roots in the current study (Wischmeier, 1975; Dissmeyer and Foster, 1980; De Baets et al., 2007). For the wasteland, the lower vegetation cover resulted in lower ability to reduce soil detachment capacity, compared with abandoned farmlands in this study.

Despite flow shear stress, soil detachment capacity was also influenced by biological crust, soil properties and vegetation characteristics as shown above. Hence, the relationship between soil detachment capacity and all these factors measured in this study was analyzed using a stepwise regression method. The result indicated that soil detachment capacity could be simulated with a power function as follows:

\[
D_C = 0.00241^{1.224} C_{H0}^{-0.195}
\]

(9)

Although both root mass density and biological crust thickness had close relationships with detachment capacity

### Table VI. Results of nonlinear regression between soil detachment capacity (\( D_C \)) and shear stress (\( \tau_c \)) for different sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Power equation</th>
<th>( R^2 )</th>
<th>( p )</th>
<th>NSE</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF</td>
<td>( D_C = 0.0281^{1.460} )</td>
<td>0.926</td>
<td>0.001</td>
<td>0.953</td>
<td>30</td>
</tr>
<tr>
<td>AF3</td>
<td>( D_C = 0.0001^{1.479} )</td>
<td>0.947</td>
<td>0.001</td>
<td>0.965</td>
<td>30</td>
</tr>
<tr>
<td>AF10</td>
<td>( D_C = 0.0011^{1.953} )</td>
<td>0.902</td>
<td>0.002</td>
<td>0.930</td>
<td>30</td>
</tr>
<tr>
<td>AF18</td>
<td>( D_C = 0.0050^{0.870} )</td>
<td>0.974</td>
<td>0.000</td>
<td>0.941</td>
<td>30</td>
</tr>
<tr>
<td>AF28</td>
<td>( D_C = 0.0041^{0.861} )</td>
<td>0.927</td>
<td>0.001</td>
<td>0.915</td>
<td>30</td>
</tr>
<tr>
<td>AF37</td>
<td>( D_C = 0.0051^{1.330} )</td>
<td>0.835</td>
<td>0.000</td>
<td>0.830</td>
<td>150</td>
</tr>
<tr>
<td>Abandoned farmlands</td>
<td>( D_C = 0.0014^{0.930} )</td>
<td>0.835</td>
<td>0.000</td>
<td>0.830</td>
<td>150</td>
</tr>
</tbody>
</table>

* SF refers to slope farmland.
* AF is abandoned farmlands, and the number is the abandonment age in years.

![Figure 6](Image 62x84 to 275x252)  
**Figure 6.** Comparison between observed and predicted detachment capacity.

![Figure 7](Image 338x84 to 522x254)  
**Figure 7.** Comparison between observed and predicted detachment capacity.
et al. (2002, 2003) and Nearing et al. (1999), respectively. It varied with restoration age in a non-monotonic fashion, reaching the minimum around the abandonment age of 18. The farmland abandoned for 3 years had the maximum critical shear stress. It was 2.3 times greater than slope farmland, and 2.6 to 116.6 times greater than the other abandoned farmlands. The non-monotonic change pattern in critical shear stress was probably caused by inherent heterogeneity among soil samples or by the slight difference in soil properties and vegetation characteristics of the sampling points. Further analysis indicated that critical shear stress increased with an increase in thickness of biological crust ($P=0.026$, $R^2=0.806$):

$$\tau_c = 0.109C_{BH}^{-3.651}$$

(10)

Figure 8. Soil detachment capacity ($D_C$) as a function of shear stress ($\tau$).

Figure 9. Variation in soil erodibility with restoration age.

Figure 10. Variation in critical shear stress with restoration age.
where $\tau_c$ is the critical shear stress (Pa). The close correlation between critical shear stress and biological crust thickness reflected the complex relationship between soil detachment capacity and restoration age. This result indicated that the biological crust thickness played an important role in reducing soil detachment. Further studies are needed to quantify the relationship between soil detachment capacity and biological crust thickness to understand the mechanism of soil erosion during the progression of natural vegetation restoration in the Loess Plateau.

Conclusions

Soil erosion in the Loess Plateau could be greatly reduced by implementing natural vegetation restoration. This study was undertaken to assess the effects of age of farmland abandonment under natural vegetation restoration on soil detachment capacity and soil resistance to erosion using undisturbed soil samples collected from one slope and five abandoned farmlands in one typical small watershed located in the central Loess Plateau. The results indicated that soil detachment capacity by overland flow decreased significantly after slope farmland was abandoned for natural vegetation restoration. The mean detachment capacity of the currently cultivated slope farmland was 24.1 to 35.4 times greater than that of the abandoned farmlands, which, to some extent, demonstrates the benefits of vegetation and biological crust in reducing soil loss. Soil detachment was significantly influenced by shear stress, root mass density and thickness of biological crust, and it could be simulated well by flow shear stress and biological crust thickness with a power function ($NSE = 0.851$). Soil erodibility decreased with restoration age and gradually leveled off after 28 years of natural restoration. The critical shear stress of the abandoned farmland varied non-monotonically with restoration age, probably due to evolution in biological crusts and vegetation composition. Further studies, in the Loess Plateau, are needed to quantify the relationship between soil detachment capacity and biological crust thickness to better understand the mechanism of soil detachment during the progression of natural vegetation restoration.

Acknowledgements—Financial assistance for this work was provided by the Hundred Talents Project of the Chinese Academy of Sciences, the National Natural Science Foundation of China (No.41271287), and the Open Fund from State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau (K318009902-1313). The authors thank the members of the Ansai Research Station of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Recourses for technical assistance.

References


