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Effect of Vegetation Changes on Soil Erosion on the Loess Plateau*1

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ABSTRACT

Vegetation is one of the key factors affecting soil erosion on the Loess Plateau. The effects of vegetation destruction and vegetation restoration on soil erosion were quantified using data from long-term field runoff plots established on the eastern slope of the Ziwuling secondary forest region, China and a field survey. The results showed that before the secondary vegetation restoration period (before about 1866–1872), soil erosion in the Ziwuling region of the Loess Plateau was similar to the current erosion conditions in neighboring regions, where the soil erosion rate now is 8 000 to 10 000 t km^{-2} year^{-1}. After the secondary vegetation restoration, soil erosion was very low; influences of rainfall and slope gradient on soil erosion were small; the vegetation effect on soil erosion was predominant; shallow gully and gully erosion ceased; and sediment deposition occurred in shallow gully and gully channels. In modern times when human activities destroyed secondary forests, soil erosion increased markedly, and erosion rates in the deforested lands reached 10 000 to 24 000 t km^{-2} year^{-1}, which was 797 to 1 682 times greater than those in the forested land prior to deforestation. Rainfall intensity and landform greatly affected the soil erosion process after deforestation. These results showed that accelerated erosion caused by vegetation destruction played a key role in soil degradation and eco-environmental deterioration in deforested regions.

Key Words: deforestation, Loess Plateau, natural vegetation restoration, soil erosion

Conversion of permanent vegetation to cropland or restoration of natural vegetation greatly affects soil erosion processes and eco-environmental changes. During the past several decades, there is worldwide concern that re-establishing perennial vegetation reduces soil erosion and protects environment. For example, in the United States, the Official Government established CRP (Conservation Reserve Program) lands for reducing soil erosion (Davie and Lant, 1994; Gilley *et al.*, 1997; Zheng *et al.*, 2004).

Studies of soil erosion on the Loess Plateau have focused on soil erosion processes and erosion control in severely eroded regions, where vegetation over the past centuries has been completely destroyed. The research (Huang, 1953; Zhu, 1956; Tang, 1990; Xu, 1999; Ni *et al.*, 2004) focused on soil erosion and its associated environmental problems. In the other areas of China, much attention has been paid to quantifying effects of soil erosion on soil degradation (Zhang *et al.*, 2004; Zheng, 2005; Jiang *et al.*, 2004; Sun and Yan, 2004; Cui *et al.*, 2005). However, there is little data available for quantitatively identifying the effects of vegetation destruction and natural vegetation restoration on soil erosion. The Ziwuling secondary forest area on the Loess Plateau, where secondary vegetation has been restored during the past 140 years, provides an experimental area to quantify the effects of vegetation change on soil erosion and the eco-environment.

MATERIALS AND METHODS

Site description

The Ziwuling Forest, covering an area of about 23 000 km^2, is the only naturally occurring secondary

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vegetation region on the Loess Plateau. It is situated in the hilly region (33° 50′–36° 50′ N and 107° 30′–109° 40′ E) between the Dongzhi and Luochuan tablelands. About 140 years ago, the eco-environment of the Ziwuling region was similar to regions in the neighboring vicinity, that is, vegetation was completely destroyed; soil erosion was severe; and the eco-environment was deteriorating. Later the secondary forest vegetation naturally developed to its present state.

This field experiment, conducted at the Fuxian Ziwuling Soil Erosion and Eco-environmental Observatory established in 1989 (Tang *et al.*, 1993; Zheng, 2005), is situated on the eastern slope of the Ziwuling secondary forest region. Low mountains and hills (100 to 150 m high) covered by loess with elevations ranging from 920 to 1 683 m characterize the landform. Gully density averages about 4.5 km km^{-2}. The average annual temperature is 6 °C to 10 °C; precipitation ranges from 560 to 700 mm with 60% occurring from June to September. The maximum monthly precipitation in August is 25% to 40% of the annual total, and the maximum daily rainfall is 87 mm.

In the forest area, the main tree species were oak (*Quercus liaotungensi* Koidzumi), poplar (*Populus davidiana* Dode), and birch (*Betula platyphylla* Sukaczev). The canopy density of the forest was greater than 70%, and in the forested area a two to five centimeter deep litter layer covered the soil surface. The soil was calcic loess with a particle size distribution of 6.7% sand, 72.1% silt, and 21.2% clay. Also, the soil profile had an obvious organic horizon, well-developed soil aggregates, and a dense rooting system with no obvious argillic horizons.

Runoff plot establishment

Topography in the hilly-gully region of the Loess Plateau was complex. In general, slope gradient increased as slope length increased, that is, the slope shape was convex. Slope gradients ranged from 3° to 12° at the shoulder on a hillslope where sheet erosion was dominant, 12° to 25° at the upper backslope on the hillslope where rill erosion was dominant, 18° to 35° at the lower backslope where shallow gully erosion was dominant, and 37° to 42° on the gully slope where gully erosion was dominant. Contour maps and aerial photos were analyzed to identify replicable slope sections to establish runoff plots. Information used included slope gradient, length, shape, and dimension of shallow gullies. Field surveys were then made to select representative hillslopes to establish runoff plots, and in the summer of 1989, eight runoff plots were constructed on a hillside.

Established runoff plots are shown in Table I with Plots 1–3 running from the summit (watershed boundary) to the gully edge; Plots 4–6 running from the end of the hillslope to the toe of the gully slope; and Plots 7 and 8 running from the summit to the toe of the gully slope. Each plot was bordered with concrete blocks, and a trough for runoff collection was installed at the outlet of each plot.

TABLE I

Description of the field runoff plots

Plot No.	Land cover	Topographic location	Length	Width	Area	Slope gradient
			m	m	m^2	°
1	Deforested (bare and fallow)[a]	Hillslope	86.3	13.6	995.2	5–32
2	Deforested (bare and fallow)[a]		99.2	13.8	1 144.3	5–32
3	Forested		80.2	14.2	965.8	5–32
4	Deforested (bare and fallow)[a]	Gully slope	41.0	10.0	406.5	38–41
5	Deforested (bare and fallow)[a]		41.0	5.8	243.8	37–42
6	Forested		38.2	8.4	253.5	37–42
7	Deforested (bare and fallow)	Entire slope	136.3	13.5	1 409.7	5–42
8	Forested		141.4	14.8	1 664.8	5–42

[a] Plots are replicated at the topographic location.

Data collection and measurements

For each runoff event, storage containers were used to measure runoff volume from each runoff plot.

Multi-slot divisors were installed in case the first collection container could not hold all runoff in an extreme rainfall event. To collect runoff for each of the three forested plots, one collection container with a diameter of 80 cm and height of 110 cm was used; for each of the two deforested land plots on the hillslopes from the summit to the gully edge, two nine-slot divisors having a diameter of 80 cm and a height of 60 cm and one collection container with a 95 cm diameter and 110 cm height were used; for each of the two deforested land plots on the gully slopes and the one deforested land plot on the entire slope, two eleven-slot divisors having an 80 cm diameter and 60 cm height and one collection container with a 95 cm diameter and 110 cm height were used. During an erosive rainfall event, for each of the three forested plots the trough discharged runoff into a collection container; for each of the five deforested land plots the trough discharged runoff into the first multi-slot divisor, and the central slot drained into the next connected container.

After each runoff event, the water level in each container was measured to calculate the runoff volume; and after mixing, sediment samples from each storage container were collected in 1-liter bottle. Next, the sediment samples sat overnight, and the excess water was poured from the bottles. Then, the sediment samples were placed in an oven at 105 °C until the sediment was dry. The dry sediment weight was then taken to calculate the sediment concentration and erosion rates.

Field investigation, aerial photo interpretation, and analysis

To obtain erosion data in the Ziwuling region before secondary vegetation restoration as well as the current erosion rates in the neighboring regions, a field survey was made in areas that included Ansai and Zhidan counties and Yan'an City. Three sites in each area were selected to measure the shallow gully catchment area, dimensions of shallow gullies (including length, width, and depth), slope gradients, landslides, land slumps, and plow scenarios. Vegetation surveys at different topographical locations in the Ziwuling region were also made, and the sediment deposition in the shallow gullies and gully channels in the Ziwuling Forest area was measured. Meanwhile, aerial photos in the typical research areas were analyzed to obtain the shallow gully catchment area, the distribution density of shallow gullies, and land use. Also, soil erosion intensity was calculated according to the dimensions and distribution density of shallow gullies.

In order to quantify influences of rainfall factor on soil erosion, the LSD Test was performed to determine whether there were significant differences in soil erosion from the forestlands or from deforested lands on gully slopes under variations of precipitation, I_{30} (30-min maximum rainfall intensity), PI_{30} (the product of rainfall amount and I_{30}).

RESULTS AND DISCUSSION

Soil erosion characteristics before secondary vegetation restoration

Shallow gullies were formed by concentrated-flow erosion and plough activity (Zhu, 1956; Foster *et al.*, 1983). On the Loess Plateau, generally, shallow gully erosion occurred on the cultivated steep slopes of greater than 15°. In the Ziwuling Forest area, shallow gullies were formed before the secondary vegetation restoration, *i.e.*, about 140 years ago. According to the field survey and aerial photo interpretation, soil erosion was very severe before the secondary vegetation restoration. Shallow gully erosion scenarios on the hillslopes were similar to present soil erosion conditions in nearby regions of the Yan'an -Ansai-Zhidan Zone where today soil erosion intensity is 8 000 to 10 000 t km^{-2} $year^{-1}$. Shallow gullies on the hillslopes were well developed with a distribution density of 20 to 40 km^{-2}, which was similar to nearby regions, such as Ansai, Zhidan, Yan'an, and Bayushan (Table II). Meanwhile, the Ziwuling region is in the active regions of tectonic movement, gravitational erosion such as landslides and land slumps on gully slopes frequently occurred. For example, landslide density was 5.3 landslides km^{-2}. Thus, in the Ziwuling region before the secondary vegetation was restored, soil erosion was very severe, and the soil erosion status was similar to the present-day neighboring regions of the Yan'an-Ansai-Zhidan Zone.

TABLE II

Shallow gully distribution densities in the Ziwuling region and its neighboring regions

Region	No. of shallow gullies (km^{-2})					
	< 20	≥ 20 and < 30	≥ 30 and < 40	≥ 40 and < 50	≥ 50	≥ 20 and < 40
	%					
Ansai[a]	19.0	41.0	30.0	6.6	3.4	71.0
Ansai	16.0	38.6	31.8	7.2	6.4	70.4
Zhidan	17.0	39.0	28.9	8.8	6.3	67.9
Yan'an	14.0	36.6	32.1	10.7	6.6	68.7
Baiyushan[a]	9.0	31.8	40.9	13.6	4.7	72.7
Ziwuling	16.2	23.9	45.1	11.2	3.6	69.0

[a]Data from Zhang and Tang (1992)

Soil erosion features after secondary vegetation restoration

From 1866–1872, the population in the Ziwuling region moved to other places because of the war between the Hui and Han nationalities. Since then, the secondary forest vegetation has been naturally developing to its present state and the eco-environment has improved. Thus, the Ziwuling region provides an experimental area where the effect of vegetation change on the soil erosion process and the ecological environment can be evaluated. At present, on the Ziwuling forested lands, soil erosion rates are very low, and sheet erosion is predominant.

According to the field survey, the secondary vegetation initially grew in depression, such as shallow gullies and gully bottoms, where the soil moisture condition was better compared to other areas between shallow gullies and gully bottoms. On the hillslopes, vegetation grew earlier in the shallow gully channels than in areas between shallow gullies (Fig. 1). Similarly, vegetation grew earlier in gully channels than in areas between gullies. After secondary vegetation was established, soil erosion in these gully channels was reduced. Meanwhile, growing vegetation captured eroded sediment from areas between the shallow gullies (hillslopes) or between gullies (gully slopes), which caused deposition of eroded sediment in shallow gully channels on hillslopes and gully channels on gully slopes.

Fig. 1 Vegetation growth in the shallow gully and gully channels at the beginning stages of restoration.

The sediment deposition profile in the shallow gully channels (Fig. 2a) showed that the depth of sediment deposition on the hillslopes was 20 to 60 cm during the secondary vegetation restoration. Similarly, the depth of sediment deposition in gully channels was above 100 cm (Fig. 2b). In addition, sediment deposition in shallow gully or gully channels reduced relief of the cross section. Because the sediment transport rates from hillslopes to shallow gully channels or from gully slope to gully channels were reduced, it resulted in a decrease in sheet erosion and rill erosion. In the gully channels the sediment deposition profile showed that the depth of each sediment deposition circle decreased from the gully channel bottom to the gully top. Moreover, vegetation growth stabilized the gully slope, especially the gully-head, which decreased gravitational erosion.

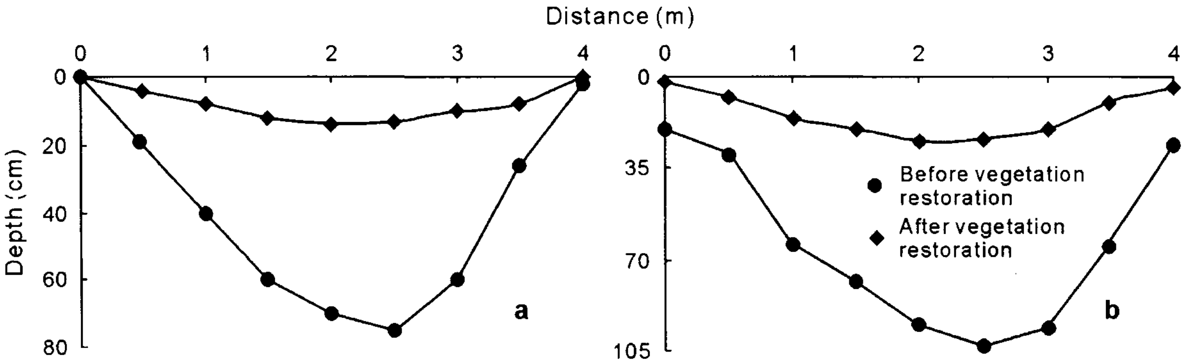

Fig. 2 Cross section of a transient shallow gully channel (a) and gully channel (b) before and after secondary vegetation restoration (the space between the two cross sections represents sediment deposition).

The field survey demonstrated that vegetation grown on old landslides was similar to that on the surrounding areas (Fig. 3), and new landslides and land slumps, as compared to the neighboring regions of Ansai and Zhidan counties and Yan'an City, occurred rarely. These results showed that during the secondary vegetation restoration of the Ziwuling region, soil erosion changed from artificially accelerated soil erosion to a natural erosion process under balanced natural ecological conditions. Therefore, in places on the Loess Plateau, where human activities have completely destroyed the original vegetation, implementing natural vegetative restoration could be the best strategy for reducing soil loss and improving the eco-environmental condition.

Fig. 3 Current vegetation growth on old landslides.

The data from the field runoff plots (Table III) showed that soil erosion rates from the current forested lands were very low, ranging from 10.0 to 14.4 t km^{-2} year^{-1} regardless of differences in topographical locations. This indicated that slope degree and slope length were not key factors affecting soil erosion in the current forested land.

Table IV showed that in four different erosive rainfall events, soil erosion on the gully slope from the current forested land was not significantly different ranging from 1.2 to 4.2 t km^{-2}. With four different precipitations, maximum 30-min rainfall intensity (I_{30}), and product of precipitation and I_{30} (PI_{30}) scenarios, soil erosion rates were not significantly different at the $P \leq 0.05$ level. This indicated that rainfall was not a key factor affecting soil erosion in the current forestland. These results also demonstrated that now in the Ziwuling forested land vegetation occupied a predominant position on soil erosion.

TABLE III

Annual soil losses from forested and deforested lands at different topographical locations

Plot location	Land	Plot No.	Soil loss		Rill erosion		Shallow gully erosion	
			Rate	Comparison	Rate	Of soil loss	Rate	Of soil loss
			$t\ km^{-2}\ year^{-1}$	Times	$t\ km^{-2}\ year^{-1}$	%	$t\ km^{-2}\ year^{-1}$	%
Hillslope	Forested	3	13.0	1	0	0	0	0
	Deforested	1	10 448	803.7	2 200	21.1	7 200	68.9
	Deforested	2	10 371	797.8	2 400	23.1	7 400	71.4
Gully slope	Forested	6	14.4	1	0	0	0	0
	Deforested	4	24 222	1 682.1	6 700	27.7	15 200	62.8
	Deforested	5	20 192	1 402.2	6 400	31.7	12 600	62.4
Entire slope	Forested	8	10.0	1	0	0	0	0
	Deforested	7	15 969	1 596.9	4 800	30.1	9 652	60.4

TABLE IV

Soil losses from forested and deforested lands on gully slopes for different erosive rainfall events

Land	Precipitation	I_{30}[a]	PI_{30}[b]	Soil loss
	mm	$mm\ min^{-1}$	$mm^2 min^{-1}$	$t\ km^{-2}$
Forested	22.3 c[c]	0.48 c	10.7 c	3.6 a
(Plot 6)	40.8 a	0.52 b	21.2 b	4.2 a
	15.1 d	0.38 d	5.7 d	2.5 a
	38.3 b	0.73 a	28.0 a	1.2 a
Deforested	38.3 c	0.73 a	28.0 a	4 080 a
(Plot 4)	40.8 b	0.52 b	21.2 a	3 602 b
	13.2 d	0.21 c	2.8 d	147 c
	64.2 a	0.23 c	14.8 c	105 c

[a] Maximum 30-min rainfall intensity under each erosive rainfall event.
[b] Product of precipitation and I_{30}.
[c] Values followed by the same letter within a column and for the same forested or deforested land are not significantly different at $P \leq 0.05$ level, as determined by Fisher's least significant difference test.

Accelerated soil erosion after conversion of the secondary forested land to cropland

After the secondary forested land of the Ziwuling region was destroyed in 1989, when the field plots was established, soil erosion greatly increased. Soil loss from the deforested land (Table III) for each plot location was 797 to 1 682 times greater than that from forested land, indicating that in places of the Loess Plateau where human activities had destroyed the original vegetation, accelerated erosion occupied the major position. Table III also revealed that on deforested lands, soil loss from the hillslopes was less than that on gully slopes. On account of an increase in slope degrees from 5°–32° on the hillslopes to 37°–42° on the gully slopes, soil loss on the gully slopes was 1.93 to 2.34 times greater than that on the hillslopes. This indicated that the slope gradient was a key factor affecting soil erosion on the deforested lands. However, compared to the slope gradient, on the deforested lands slope length had less influence on soil erosion.

From the deforested lands with four different erosive rainfall events, soil erosion ranged from 105 to 4,080 t km^{-2} on the gully slopes (Table IV). The erosion rates were significantly different at $P \leq 0.05$ level under the variations of rainfall, I_{30} and PI_{30}. For example, when I_{30} significantly increased so did soil loss. However, this was not always the case for PI_{30} and precipitation as the highest precipitation had the lowest soil loss. This indicated that rainfall intensity was the key factor affecting soil erosion on deforested lands.

As the secondary vegetation was destroyed (1989), on the hillslopes, rill erosion and shallow gully erosion dominated (Table III, Fig. 4). On the gully slopes, rill erosion and gully erosion dominated (Table III, Fig. 5), with rill erosion accounting for 27.7% to 31.7% and gully erosion 62.4% to 62.8% of their total soil losses.

Fig. 4 Soil erosion status (rill and transient gully erosion) on deforested lands located at the hillslope after the first storm event in 2003 (a) and after the wet season of 2003 (b).

Fig. 5 Soil erosion (rill and gully) on deforested land located at the gully slope after the wet season of 2003.

CONCLUSIONS

Before the secondary vegetation restoration, *i.e.*, about 140 years ago, soil erosion in the Ziwuling region was similar to neighboring regions of the Yan'an-Ansai-Zhidan Zone with soil loss rates reaching 8 000 to 10 000 t km^{-2} year^{-1}. On the hillslopes shallow gully erosion dominated, having a distribution density of 20 to 40 shallow gullies km^{-2}. On the gully slopes, gully erosion as well as gravitational erosion dominated, and there landslide density was 5.3 landslides km^{-2}.

During the past about 140 years of secondary forest restoration, vegetation initially grew in the depressions, such as shallow gully channels and gully channels, where soil moisture conditions were better than areas between shallow gullies and gullies. As natural vegetation was gradually restored, shallow gully erosion on hillslopes and gully erosion at gully slopes ceased, with sediment deposition occurring in the shallow gullies on the hillslopes and in the gully channels on the gully slopes. During secondary vegetation restoration, the depth of sediment deposition in the shallow gully channels on hillslopes was 20 to 60 cm and on gully slopes at the gully channels above 100 cm.

Under the new vegetation cover soil erosion changed from accelerated to natural erosion. Soil erosion rates on the current forested lands were very low regardless of topographical locations, indicating that the vegetation rather than the slope gradient and slope length was the key factor affecting soil erosion. Moreover, gravitational erosion such as landslides and land slumps rarely occurred on the gully slope, as compared to the disturbed neighboring areas. After the secondary forest of the Ziwuling region was destroyed in 1989 when the field plots was established, accelerated soil erosion greatly increased. Rill erosion and shallow gully erosion were predominant on the hillslopes, and gully erosion was predominant on the gully slopes. The effects of rainfall parameters such as rainfall, I_{30}, and PI_{30} were significantly different at the $P \leq 0.05$ level. Meanwhile, slope gradient was the key factor affecting soil erosion following the destruction of vegetation.

In places on the Loess Plateau, where human activity completely destroyed the original vegetation, conversion to natural vegetation could be the best strategy for eco-environmental rehabilitation. Artificially accelerated soil erosion caused by deforestation could be the primary cause of soil degradation and eco-environmental quality deterioration on the Loess Plateau.

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