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Soil erosion resistance of “Grain for Green” vegetation types under extreme rainfall conditions on the Loess Plateau, China

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ABSTRACT

Objectives: Soil erosion, which is pronounced on the Loess Plateau of China, is generally caused by heavy rain or thunderstorms. To control soil and water losses and improve the eco-environmental condition of the Loess Plateau, the Chinese Central Government issued the “Grain for Green (GFG)” policy in 1999 to restore vegetation on previously farmed steep lands. This study will explore the value of the “GFG” policy by examining the response of three different “GFG” vegetation types (grassland, woodland and orchard) in controlling erosion from an extreme rainfall event in the Northern Shaanxi Province on the Loess Plateau of China.
Methods: The vegetation types, coverage, biological soil crust (BSC) coverage, plant species diversity, slope gradient, gully erosion of different “GFG” vegetation types under extreme rainstorm conditions (called “727” rainstorm) were assessed using field surveys.
Results: It was found that the grassland and woodland are more effective at reducing gully erosion than orchards, and compared with the sloping farmland, the conversion of sloping farmland to grassland or woodland can reduce gully erosion by more than 90%, whereas conversion of sloping farmland to orchards actually increases gully erosion by more than 60%. Furthermore, having a high surface vegetation cover and well-developed BSC were the most important factors in reducing soil erosion.
Conclusions: The “GFG” measures are beneficial in reducing soil erosion on the Loess Plateau, and rehabilitation efforts should focus on grassland and/or woodlands rather than attempting to achieve dual goals with economic gain (i.e., from orchard crops), as it appears that orchards are not conducive for controlling soil erosion.

1. Introduction

Soil erosion causes many serious problems in different ecosystems, such as rangeland degradation, desertification, deposition of the channel, and so on. Thus, how to control soil erosion to improve or protect ecosystems is of great concern (Bai et al., 2013; Li et al., 2013, 2014; Liu et al., 2012; Pimentel and Kounang, 1998). The Loess Plateau of China has historically suffered from considerable soil erosion affecting most of its land area, resulting in severe economic and environmental losses (Wei et al., 2006; Zhang et al., 2004). Indeed, more than two-thirds of the area of the Loess Plateau are affected by some degree of soil erosion (~4.3×10^5 km^2), and more than one-third of the area (approximately 2.5×10^5 km^2) are subject to extremely severe soil erosion rate, typically exceeding 500 kg per km^2 per year (Chen et al., 2007). These severe soil erosion rates have resulted in a significant decline in land productivity, environmental degradation and severe infilling and riverbed aggradation in the lower reaches of the Yellow River due to sedimentation (Shi and Shao, 2000).

On the Loess Plateau, most of the erosion are caused by a few times of infrequent intense rainfall events (Fu, 1989). These typically occur between June and September with 60–75% of the average annual rainfall of 400–550 mm. Between July and August, short duration, high-intensity rainfall is common over small areas. One of these individual short burst rainfall events can account for as much as 40–90% of the total annual soil erosion for any given location (Tang et al., 1992). The most serious erosion occurs on sloping farmlands, especially steep farmlands on the Loess Plateau (Shi and Shao, 2000). For example, a field survey conducted in the Xingzihe watershed of the Yan River on the Loess Plateau showed that the soil loss from sloping farmland accounted for 60% of the total sediment load of the river (Tang et al., 1998). To control soil erosion and improve the environment of the Loess Plateau region, the Chinese Central Government issued the “Grain for Green (GFG)” policy in 1999, with the aim of restoring vegetation on the Loess Plateau. A major emphasis of the “GFG” policy was to convert the croplands (particularly those on steep lands) to forests and grasslands (Jiao et al., 2008; Wang et al., 2011). In addition, other forms of land management and vegetation change under the “GFG” policy have

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included a shift from cropped and harvested agriculture to perennial crop plants such as orchard trees (Chen et al., 2007).

Many previous studies have shown that the amount of soil erosion has been significantly reduced and the ecosystem condition has been improved on the Loess Plateau after the implementation of the "GFG" policy. For example, according to an analysis in the Yanhe watershed located at the middle of the Loess Plateau, soil erosion rate was shown to decline by 34% on average after the implementation of the "GFG" policy (Wang et al., 2009a). The vegetation coverage on the Loess Plateau has increased from 31.6% in 1999 to 56.9% in 2013, and the annual sediment discharge of the Yellow River reduced to 0.2 billion tons which was similar to historic levels (Chen et al., 2015). Furthermore, the studies in the Wuqi county of the Loess Plateau found that the average soil moisture and moisture holding capacity after 5-year implementation of "GFG" policy were 48% and 55% greater, respectively, than those not abandoned (Liu et al., 2002; Liang et al., 2006), and the physical and chemical characteristics of the soils (i.e. soil bulk density, organic matter, total nitrogen, total potassium, and total phosphorus, etc.) greatly improved after the implementation of "GFG" policy (Yang et al., 2006). However, despite these impressive results, examples of severe erosion from the Loess Plateau are still common. For example, on 27 July 2012, Jiaxian County, situated in the northern Shaanxi Province on the Loess Plateau, experienced a severe rainstorm called the "727" rainstorm. The 24-h rainfall was above 100 mm for five towns and exceeded 200 mm in one town (Wangjiabian). This was the largest daily rainfall event since 1969 in this region, and it resulted in the destruction of more than 200 homes with 500 others severely damaged (Wang et al., 2012). Although large-scale "GFG" restoration had been implemented in this region, the rainfall event still caused serious destruction and major soil erosion. Nearly all of the existing research on the benefits of the "GFG" policy has focused on the long-term average reductions in soil erosion rate and the improvement of vegetation and soil properties (Cao et al., 2007; Liu et al., 2002; Liang et al., 2006; Yang et al., 2006; Zhang et al., 2015). Few studies have compared different "GFG" vegetation restoration types or the potential of vegetation restoration to reduce soil erosion in severe rainfall events. Consequently, it is imperative to assess the effectiveness of different "GFG" vegetation types in reducing soil erosion in the extreme rainfall events, such as the "727" rainstorm. The purpose of this study is to assess the effectiveness of different vegetation restoration types on reducing gully erosion and to identify the factors most responsible for reduced gully erosion by using the "727" rainstorm as a test case. The study will conclude with recommendations as to which vegetation restoration types are most suitable for reducing soil erosion in this region.

2. Materials and methods

2.1. Study area

The study area is the 32.13 km^2 Gaowugou watershed (110°09′29″–110°16′44″E, 38°09′50″–38°13′07″N), located at the center of the area impacted by the "727" rainstorm, in Wangjiabian, Jiaxian County, Northern Shaanxi Province (Fig. 1). The elevation ranges from 983 to 1248 m with the average of 1119.5 m. The climate can be described as a transitional zone between a semi-humid warm climate and a semiarid dry climate with an average annual precipitation of 386 mm. Most of the annual total rainfalls fall between July and September. Approximately 50% of total area of the Gaowugou watershed has a slope gradient of more than 8°. Soils (yellow–brown soil) are from loess sediments. Soil is typically composed of approximately 64% sand (50–2000 μm), 24% silt (2–50 μm), and 12% clay (<2 μm) (Wang et al., 2009b). Due to the loose soil particles and the poor corrosion resistance, the soil is prone to erosion (Shi and Shao, 2000). The Green for Grain program has been in effect at the study site since 1999 with the major measures of reforestation and the abandonment of farmland on slopes above 25°. The current land uses include slope farmland (25.6% of the area), woodland (12.6% of the area), orchards (9.8% of the area), and grassland (44.1% of the area). Major crops grown in the watershed include

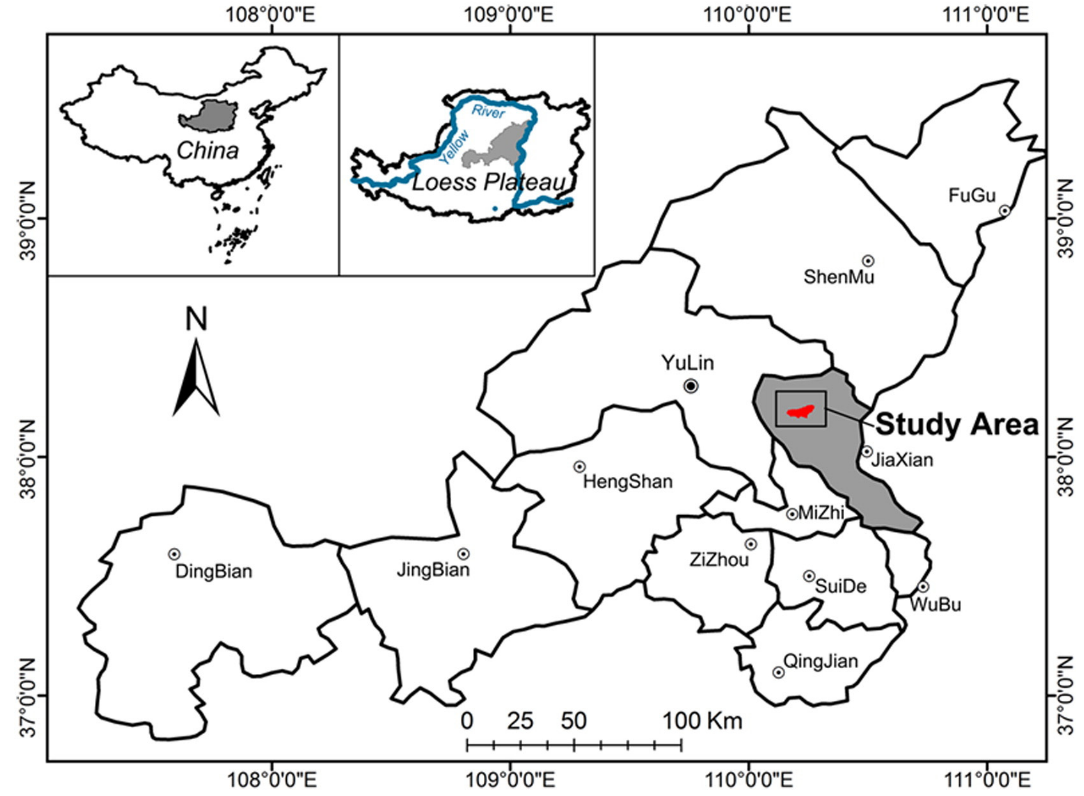

Fig. 1. Location of the study area on the Loess Plateau, China.

potatoes (*Solanum tuberosum*), beans (*Phaseolus vulgaris*), and maize (*Zea mays*) interspersed with orchards dominated by planted *Zizyphus jujube*. The woodlands are dominated by planted *Populus simonii*, *Robinia pseudoacacia*, and *Prunus armeniaca*, and the grassland vegetation is mainly composed of *Artemisia scoparia*, *Lespedeza davurica*, *Artemisia giraldii*, *Stipa bungeana*, *Melilotus suaveolens*, *Poa sphondylodes*, *Cleistogenes chinensis*, and *Heteropappus altaicus* (Wang et al., 2012).

2.2. Characteristics of the “727” rainstorm

Three rainfall events were recorded by the Wangjiabian and Shenjiawan rainfall stations in Jiaxian County on 27–30 July 2012. The maximum precipitation recorded by these two rainfall stations was registered on 27 July, with 226.4 and 216.4 mm total storm volume, 14.0- and 6.0-h duration, and 0.27 and 0.60 mm per min of average rainfall intensity, respectively. The maximum 30-min rainfall intensity (I_{30}) was 1.03 and 1.86 mm per min, and the product of precipitation and I_{30} (PI_{30}) reached 232.82 and 402.14 mm^2 per min, respectively (Table 1). It was reported by the Wangjiabian and Shenjiawan rainfall stations that the “727” rainstorm was the largest rainfall event in Jiaxian County since meteorological records began in 1969.

2.3. Sampling

To identify the potential of different “GFG” restoration types to resist soil erosion, three common “GFG” types were assessed: naturally rehabilitated grassland (grassland, GL), reforestation with trees for ecological service (woodlands, WL), and reforestation with cash trees (orchard, OR). As a benchmark to compare with, a typical sloping farmland (SF) was also included. For each of these three vegetation types and sloping farmland, 9 plots with different slope gradients, vegetation coverages and times since re-vegetation were assessed, as presented in Table 2, with 3 replicate quadrats established in each plot. The quadrat dimensions were 2 m × 2 m for GL and SF and 5 m × 5 m for WL and OR. A total of 36 plots and 108 quadrats were investigated.

2.4. Data collection

Field data were collected between the 8th and 12th of August 2012, one week after the “727” rainstorm. The dominant species, vegetation species composition, abundance, vegetation coverage, and the biological soil crust (BSC) coverage of each quadrat were recorded. The vegetation coverage of each quadrat was estimated visually by two observers working together. The geographical position and slope gradient of each plot were measured by a global positioning system and a slope gradient meter. The soil bulk density of each plot was determined by the cutting-ring method, and 3 replicate soil samples were collected for each plot. The fundamental properties and vegetation information of all of the plots are presented in Table 2.

On the Loess Plateau, rill erosion and ephemeral gully erosion was accounted for more than 70% and 30–80% of the amount of slope erosion, respectively (Zheng and Tang, 1997; Zhao et al., 2013). This gully erosion is easily visualized and measured in the field investigations. Therefore, to determine the gully erosion that occurred during the “727” rainfall events, three 5-m transects were established in each plot. Along each transect, the number of gully was recorded and sub-section measurements were divided due to the irregular gully shape. Then, the length, the width and the depth of each subsection were measured and summed to calculate the total volume of gully erosion (Fig. 2).

2.5. Data analysis

The Shannon–Wiener index (H) was used as the measure of plant diversity (Jiao et al., 2012). The number, width, length and depth of gully erosion in each transect were used to calculate the gully erosion intensity of the three “GFG” vegetation types and the control. The differences among GL, WL, OR and SF were compared by analysis of variance (ANOVA) and the Tukey–Kramer method test using SPSS V17.0. Pearson correlation analysis was used to analyze the relationship between gully erosion intensity and different factors (e.g., slope gradient, vegetation coverage, BSC, and species diversity). The equations used to calculate the Shannon–Wiener index (Shannon and Weaver, 1949) and gully erosion intensity (Wang et al., 2014) are as follows:

$$\text{Shannon–Weiner index (H)}: \quad \mathrm{H} = -\sum_{i=1}^{S} \left(P_i \ln(P_i)\right). \tag{1}$$

$$\text{Amount of gully erosion in each transect}: ARET = \sum_{j=1}^{m} \sum_{l=1}^{n} \left(W_{jl} \times L_{jl} \times D_{jl}\right). \tag{2}$$

$$\text{Gully erosion intensity of each plot}: REIP = \left(\sum_{k=1}^{3} \left(ARET_k / S'_k\right)\right)/3 \tag{3}$$

where S is the number of species, p_i is the proportion of all of the individuals in a sample that belongs to the ith species, ln is the log base-e, m is the number of gullies in each transect, n is the number of subsections of each gully, and W_{jl}, L_{jl} and D_{jl} are the width, length and depth of the lth subsection of the jth gully (m), respectively. S'_k is the area of the kth transect.

3. Results

3.1. Surface characteristics of different “GFG” vegetation types

There was a wide range of surface characteristics with clear differences between each “GFG” type and time since re-vegetation. Grasslands on slopes with only two years since the start or re-vegetation were covered by *A. scoparia* with minimal biological surface crust cover (8–13%) and low plant species diversity (H: 0.30–0.81), whereas grasslands that had been undergoing re-vegetation for 4–6 years were mainly covered by *S. bungeana*, *A. giraldii*, *L. davurica* and others with high biological surface crust cover (25–75%) and a comparatively high plant species diversity (H: 0.55–1.83). Meanwhile, a comparison of the woodlands and orchards shows that even though both types had similar times since re-vegetation had commenced, there were significant differences in terms of surface properties. The canopy coverage in orchards averaged only 16.1% with minimal grass species coverage under the trees, whereas the vegetation coverage in the woodlands averaged

Table 1
Characteristics of the “727” rainstorm.

Rainfall station	Date	Duration (h)	Precipitation (mm)	Average rainfall intensity (mm min^{-1})	I_{30} (mm min^{-1})[a]	PI_{30} (mm^2 min^{-1})[b]
Wangjiabian	27 July	14.0	226.4	0.27	1.03	232.82
	28 July	1.0	0.1	0.00	0.00	0.00
	30 July	3.0	3.2	0.02	0.03	0.09
Shenjiawan	27 July	6.0	216.4	0.60	1.86	402.14
	28 July	1.5	6.3	0.08	0.11	0.66
	30 July	8.7	18.1	0.04	0.30	5.46

[a] Maximum 30-min rainfall intensity.
[b] Product of precipitation and I_{30}.

Table 2
Fundamental information of the sample plots.

ID	Measures	Dominant species	Slope gradient (°)	Vegetation cover (%)	BSC coverage (%)	Shannon–Wiener index	Time since restoration (yr.)	Main species
1	GL	*M. suaveolens, A. scoparia*	25	26	60	1.83	4–6	*M. suaveolens, A. scoparia, Vicia sepium, P. sphondylodes, L. davurica, A. giraldii, H. altaicus, S. bungeana, Incarvillea sinensis, Chrysanthemum indicum*
2	GL	*A. scoparia*	24	86	10	0.64	2	*A. scoparia*
3	GL	*A. scoparia*	33	76	25	0.88	2	*A. scoparia, M. suaveolens, Ixeris sonchifolia, Chenopodium album*
4	GL	*A. scoparia*	11	17	60	1.31	4–6	*A. scoparia, Glycyrrhiza uralensis, A. giraldii, C. chinensis*
5	GL	*A. scoparia*	15	23	75	0.56	4–6	*A. scoparia, S. bungeana, L. davurica, C. chinensis, Gueldenstaedtia stenophylla*
6	GL	*A. scoparia*	15	27	40	1.14	4–6	*A. giraldii, G. uralensis, A. scoparia, C. chinensis, S. bungeana, L. davurica*
7	GL	*A. scoparia*	23	90	8	0.67	2	*A. scoparia*
8	GL	*A. scoparia*	25	75	13	0.81	2	*A. scoparia, Roegneria ciliaris, H. altaicus, Salsola ruthenica*
9	GL	*A. scoparia*	23	90	13	0.30	2	*A. scoparia, Calystegia sepium*
10	WL	*P. simonii, R. pseudoacacia*	35	36	60	1.97	4–6	*R. pseudoacacia, Prunus armeniaca, P. Simonii, Caragana korshinskii, Ailanthus altissima, Leymus scalinus, Setaria viridis, H. altaicus, Dracocephalum moldavica, L. davurica, Polygala tenuifolia, Rehmannia glutinosa*
11	WL	*P. Simonii, R. pseudoacacia*	25	48	42	1.55	4–6	*P. simonii, R. pseudoacacia, Ulmus pumila, A. scoparia, S. viridis, H. altaicus, L. scalinus, D. moldavica*
12	WL	*R. pseudoacacia*	35	69	25	1.63	4–6	*I. sinensis, L. scalinus, A. scoparia, I. sonchifolia, H. altaicus, S. viridis, R. pseudoacacia, U. pumila*
13	WL	*Zizyphus jujube*	32	76	15	0.18	4–6	*Z. jujube, A. scoparia*
14	WL	*Z. jujube*	39	55	17	0.12	4–6	*Z. jujubea, A. scoparia*
15	WL	*Z. jujube*	35	82	46	0.15	4–6	*Z. jujube, A. scoparia*
16	WL	*P. armeniaca*	20	53	50	1.13	4–6	*P. armeniac, A. scoparia, L. davurica, M.suaveolens, P. tenuifolia, S. bungeana*
17	WL	*Z. jujub, P. armeniaca*	24	37	13	1.33	4–6	*Z. jujuba, P. armeniaca, A. scoparia, R. glutinosa, L. davurica, S. bungeana*
18	WL	*P. armeniaca*	15	23	70	1.28	4–6	*P. armeniaca, H. altaicus, A. scoparia, P. tenuifolia, M. suaveolens, S. bungeana*
19	OR	*Z. jujube*	15	27	11	0.56	4–6	*C. indicum, A. scoparia, Z. jujube*
20	OR	*Z. jujube*	16	28	9	1.01	4–6	*Sonchus oleraceus, C. indicum, I. sinensis, Z. jujube*
21	OR	*Z. jujube*	18	24	11	0.97	4–6	*C. indicum, S. oleraceus, Z. jujube*
22	OR	*Z. jujube*	23	18	10	0.77	4–6	*S. oleraceus, A. scoparia, Z. jujube*
23	OR	*Z. jujube*	30	9	4	1.08	4–6	*S. oleraceus, C. indicum, Z. jujube*
24	OR	*Z. jujube*	32	7	7	0.93	4–6	*S. oleraceus, C. indicum, A. scoparia, Z. jujube*
25	OR	*Z. jujube*	30	10	2	0	4–6	*Z. jujube*
26	OR	*Z. jujube*	27	13	4	0	4–6	*Z. jujube*
27	OR	*Z. jujube*	33	9	7	0	4–6	*Z. jujube*
28	SF	*P. vulgaris*	31	13	0	0		
29	SF	*P. vulgaris*	39	11	0	0		
30	SF	*P. vulgaris*	34	21	0	0		
31	SF	*P. vulgaris*	27	20	0	0		
32	SF	*S. tuberosum*	40	23	0	0		
33	SF	*S. tuberosum*	23	20	0	0		
34	SF	*P. vulgaris*	26	45	0	0		
35	SF	*P. vulgaris*	32	37	0	0		
36	SF	*P. vulgaris*	31	43	0	0		

Note: GL, grassland; WL, woodland; OR, orchard; SF, sloping farmland.

50.9%, with abundant grasses present under the trees. In addition, the plant species diversity in the woodlands was twice that of orchards (H: 1.04 and 0.59, respectively), and the biological soil crust cover of woodlands ranged between 13% and 70%, with an average of 37.6% compared to a range of only 2% to 11% (average of 7.2%) in the orchards. On the sloping farmland, coverage was limited to the crops themselves (namely, soybeans and potato), with grass and biological soil crusts absent (Tables 2 and 3).

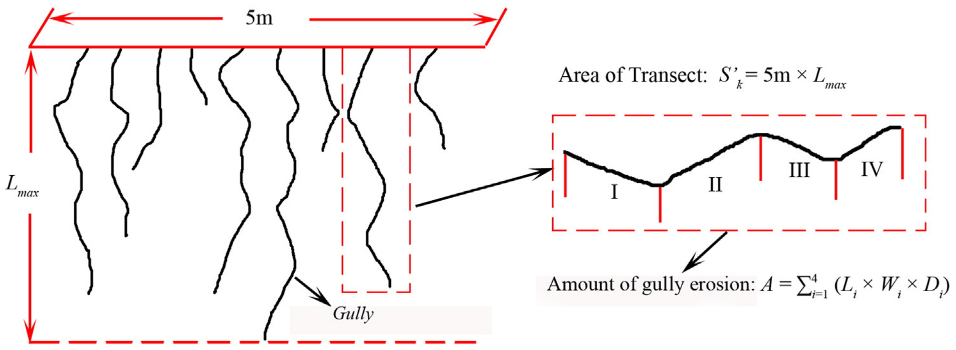

Fig. 2. Sketch map of transect and subsection measurement of gully.

Table 3
Surface characteristics of different “Grain for Green” vegetation types (mean ± SE).

GFG types	Vegetation coverage (%)	Shannon–Wiener index	BSC coverage (%)
GL	56.8 ± 32.3a	0.9041 ± 0.4607a	33.8 ± 25.7a
WL	50.9 ± 19.9a	1.0376 ± 0.7078a	37.6 ± 20.9a
OR	16.1 ± 8.3b	0.5917 ± 0.4684a	7.2 ± 3.3b
SF	24.3 ± 11.5b		

Note: GFG, Grain for Green; GL, grassland; WL, woodland; OR, orchard; SF, sloping farmland. The same letters in the same column indicate no significant differences between the measures, and different letters indicate significant differences between the measures based on the Tukey test ($P < 0.05$).

3.2. Gully erosion of different “GFG” types

The recorded gully erosion from the “727” rainfall event is quite different among “GFG” vegetation types. The most resistant to erosion is grassland, with the length, width and depth of gully significantly less than those of sloping farmlands and orchards ($P < 0.05$). Although the sloping farmlands had the largest number of gullies, the orchards actually experienced more severe gully erosion than the sloping farmlands, with an average length, width and depth of gully all higher in orchards than in the other vegetation types, including sloping farmland. It might be caused by lower vegetation coverage, BSC and species diversity in the orchards due to human disturbance (i.e. weeding). Woodlands performed well at reducing gully erosion, with the length, width and depth of gully all similar to but slightly higher than those found in grasslands (Table 4).

The grasslands and woodlands exhibited lower gully erosion intensity (average of approximately 1700 and 2460 t per km^2, respectively) compared to sloping farmlands and orchards (average of approximately 58,000 and 94,000 t per km^2, respectively). These results show that the conversion of sloping farmland to grassland or woodlands can reduce gully erosion by more than 90%, even for the most severe rainfall events, whereas the conversion of sloping farmland to orchards actually increases gully erosion by more than 60%. Statistically, grasslands and woodlands could not be differentiated ($P = 0.981$), nor could sloping farmland and orchards ($P = 0.656$). However, the erosion intensity of sloping farmlands and orchards is significantly different from that in grasslands and woodlands ($P < 0.05$) (Fig. 3).

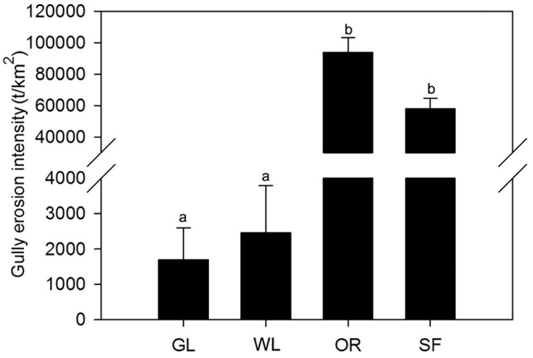

Fig. 3. Gully erosion intensity of different “Grain for Green” measures (mean ± SE). *Note*: GL, grassland; WL, woodland; OR, orchard; SF, sloping farmland. The same letters in the same column indicate no significant differences between the measures, and different letters indicate significant differences between the measures based on the Tukey test ($P < 0.05$).

3.3. Influencing factors on rainstorm erosion of different “GFG” vegetation types

Table 5 presents the correlation coefficients between gully erosion intensity and the vegetation and land cover factors assessed in this study. These results show that the slope gradient is positively correlated with the gully erosion intensity for all vegetation types, whereas the biological soil cover and plant species diversity were both negatively correlated with the gully erosion intensity for all vegetation types. Especially, the species under trees in the orchards was scarce with a small amount of *Sonchus oleraceus* and *A. capillaris*. However, the understory vegetation in the woodlands was composed by an abundant *A. capillaris*, *L. davurica*, *M. suaveolens*, *Polygala tenuifolia*, *S. Bungeana* etc. Thus, the plant species diversity was significantly negative correlated with the gully erosion intensity in the orchards ($P < 0.01$), but not significant in the woodlands ($P > 0.05$). The correlation between the vegetation coverage and gully erosion intensity was more complex. The vegetation coverage was negatively correlated with gully erosion intensity in the woodlands and orchards but not significant ($P > 0.05$), whereas crop coverage on the sloping farmlands was significant negatively correlated with gully erosion intensity ($P < 0.05$). Surprisingly, vegetation coverage was significant positively correlated with gully erosion intensity in the grasslands ($R = 0.898$, $P < 0.01$). However, the restoration periods were negatively related to gully erosion intensity in the grasslands with an average gully erosion intensity of approximately 2700 t per km^2 for 2-year periods and 900 t per km^2 for 4–6-year periods ($P < 0.01$) (Fig. 4).

Table 4
Gully caused by rainstorm erosion of different “Grain for Green” vegetation types.

GFG types	Mean no.	Length (cm)			Width (cm)			Depth (cm)		
		Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.
GL	6a	82.2b	210	22	8.4c	16	4	1.9b	6	0.5
WL	10b	93.2b	570	27	10.1bc	62	2	1.5b	6	0.5
OR	11b	531.4a	1700	7	17.5a	66	4	11.9a	260	1
SF	15c	441.9a	2900	147	13.2a	180	7	9.1a	320	3

Note: GFG, Grain for Green; GL, grassland; WL, woodland; OR, orchard; SF, sloping farmland. The same letters in the same column indicate no significant differences between the measures, and different letters indicate significant differences between the measures based on the Tukey test ($P < 0.05$).

4. Discussion

4.1. The erosion resistance efficiency of different “GFG” vegetation types

In this study, sloping farmland, especially steep sloping farmland, had relatively larger gully erosion intensity compared with the “GFG” vegetation types. This result is in accordance with those of previous studies. For example, Tang et al. (1998) reported that the soil losses from sloping farmland constitute 60% of total river sediment transportation from the catchment area of the Xingzihe River on the Loess Plateau. However, the rainstorm gully erosion of the two reforested types displayed a different response. The gully erosion amount was almost similar between the woodlands and grasslands, with an average gully erosion intensity of less than 2500 t per km^2, which is significantly lower than that of sloping farmlands. In contrast, the rainstorm gully erosion intensity for orchards averaged more than 93,000 t per km^2, which is even larger than that of sloping farmlands. These results

Table 5
Pearson correlation coefficient between gully erosion intensity and different factors.

GFG types	Slope gradient		Vegetation coverage		BSC coverage		Shannon–Wiener index	
	R	P	R	P	R	P	R	P
GL	0.563	0.115	0.898**	0.001	−0.874**	0.002	−0.563	0.114
WL	0.239	0.506	−0.245	0.496	−0.557	0.095	−0.155	0.670
OR	0.511	0.160	−0.471	0.200	−0.502	0.169	−0.815**	0.007
SF	0.595*	0.041	−0.622*	0.031				

Note: GFG, Grain for Green; GL, grassland; WL, woodland; OR, orchard; SF, sloping farmland.

* Significant at $P < 0.05$ level.

** Significant at $P < 0.01$ level.

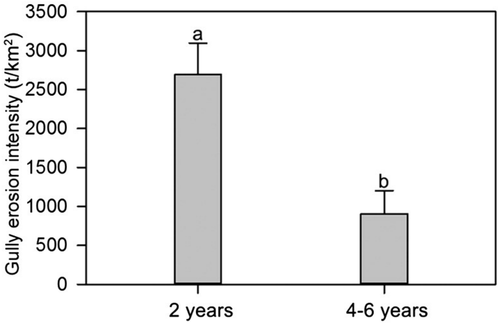

Fig. 4. Gully erosion intensity of different restoration periods in the grasslands (mean ± SE). *Note*: The same letters in the same column indicate no significant differences between the periods, and different letters indicate significant differences between the periods based on the Tukey test ($P < 0.05$).

illustrate that revegetation measures may either increase or decrease soil erosion depending on the type of revegetation undertaken. These findings support those of other researchers that claimed that afforestation is a potential strategy for helping to conserve soil on degraded land by reducing soil erosion (Cao et al., 2007). This is because such woodlands form a dense and multistory canopy with thick litter and extensive root systems that reduce soil erosion by intercepting and diminishing rain energy, capturing and sponging up raindrops, storing rainwater, and protecting the soil from the direct impact of raindrops and throughfall (Blanco-Canqui and Lal, 2010; Pimentel and Kounang, 1998). For example, Zhang et al. (2015) reported that the 5-year-old mixed grass-shrub-arbor forest with vegetation coverage of 95%, which had a rich distribution of roots and better vegetation structure, could reduce 76.9% soil erosion compared with no vegetation slope in the Loess Plateau by the field experiment. However, the ability of woodlands to reduce soil erosion can be impacted by human activities. Indeed, human activities that reduce surface (or understory) cover can dramatically increase soil erosion in forests. For example, Elliot et al. (1999) reported that the soil erosion intensity in disturbed forests could be as much as 10 times larger than that in undisturbed forests. Here, orchards represent a similar case, with the gully erosion of orchards being 30 times larger than that of woodlands (Fig. 3). Although the sloping farmland is replaced by perennial trees in the orchards, active management is undertaken to keep the area around the orchard trees clear of vegetation to promote tree growth. This direct human intervention has the consequence of significantly increasing soil erosion on these surfaces. Hence, effective soil erosion reduction via afforestation on the Loess Plateau should focus on woodlands without clearing of understory vegetation. Alternatively, promoting grassland vegetation on the Loess Plateau also shows promise at reducing soil erosion. In this study, it is clear that grassland vegetation is at least as effective, and typically more effective, at reducing soil erosion as woodland revegetation. The results of this study confirm those of several previous studies that have shown that grass can protect land surfaces against erosion by its dense cover (i.e., reducing the energy of raindrop impact), can consolidate soil by its abundant roots, can improve the soil physico-chemical properties, and can increase soil infiltration rates (Wang and Liu, 1999; Xu, 2005). Therefore, grassland vegetation is proposed as the most effective method of controlling soil erosion on former sloping farmlands on the Loess Plateau.

4.2. The factors influencing erosion resistance efficiency of "GFG" vegetation types

In this study, slope gradient played an important role in determining gully erosion intensity with the highest corresponding to the steepest slopes for every "GFG" vegetation type (Table 5). This finding confirms the result reported by Chen et al. (2010) on the Loess Plateau and showed that the slope gradient was an important factor affecting soil erosion rate, with steeper slopes leading to greater erosion. In this study, lower slopes were found on the grassland plots relative to the other types. Indeed, it is possible that the only reason that the grassland vegetation type slightly outperforms the woodlands in reducing gully erosion is because the grassland plots were generally on lower slopes than the woodland plots. However, in the cases in which the plots had similar slopes, the grassland still generally performed slightly better at reducing soil erosion than the woodlands. In contrast, the slopes of the woodlands and orchards were similar, indicating that the observations of their relative performance in reducing (or increasing in the case of orchards) gully erosion are not complicated by this factor but rather are more likely related to differing surface coverage between these two vegetation types.

Vegetation plays an important role in controlling soil erosion, as it intercepts rainfall, increases water infiltration, stabilizes soil, provides mechanical protection by reducing raindrop energy and 'splash' effects, and traps sediment (Shi and Shao, 2000; Bochet et al., 2006; Gyssels and Poesen, 2003; Rey et al., 2004; Wei et al., 2009). Previous studies have shown that vegetation cover generally reduces runoff and soil erosion on account of these positive benefits of vegetation on soils (Chaplot and Le Bissonnais, 2003; Dunjó et al., 2004; Kothyari et al., 2004; Mohammad and Adam, 2010; Reid et al., 1999; Zhang et al., 2004). However, in this study, gully erosion intensity was increased with increasing vegetation coverage in the grasslands. This result is in contrast to most existing studies on the negative relation between soil erosion and vegetation cover as described above. This result may be attributable to the characteristics of vegetation and soil of vegetation communities in different successional stages. In the study region, an *A. scoparia*-dominated community is found at the primary succession stage in the grassland, which is characterized by a relatively high vegetation coverage but low species diversity. In later stages of vegetation succession, *L. davurica*, *Artemisia giraldii* and/or *S. bungeana*-dominated communities replace *A. scoparia*-dominated communities. These later communities have comparatively low vegetation coverage but high species diversity compared with the *A. scoparia*-dominated communities. Several previous studies have shown that the species diversity is negatively related to the degree of soil erosion in other locations. For example, Wang (2004) reported that species diversity may be more important than vegetation coverage in controlling soil erosion. The previous study in Yangjuangou watershed on the Loess Plateau have also shown that the soil erosion in the initial successional stage was not decreased obviously, because a compaction process occurred in the soil surface layer which caused soil infiltration rate reduced significantly, although the vegetation coverage was increased during this stage (Liu et al., 2012). Furthermore, at the primary succession stage (*A. scoparia*-dominated community after 2 years restoration), the soil properties were poor and vegetation structure was simple. However, with increasing time since the onset of restoration, the soil properties (e.g., soil organic carbon, total nitrogen, and total phosphorus) gradually improved, community species composition tended to increase in complexity, and the recovered vegetation effectively protected the surface soil (Zhao et al., 2005). Thus, the gully erosion intensity in the later succession stages (*L. davurica*, *A. giraldii* and/or *S. bungeana*-dominated communities after 4–6 years restoration) was reduced because of the better developed nature of the soil and vegetation structure (Fig. 4).

Another factor that may be affecting soil erosion among "GFG" vegetation types is the biological soil crust (BSC) (Table 5). The BSC protects soils against erosion by increasing the roughness of soil surface and decreasing sediment yield from splash erosion and/or shear forces (Bowker et al., 2008; Liu et al., 2015). It has been observed that the better developed BSC, the higher is the soil surface roughness (Rodríguez-Caballero et al., 2012), and this BSC-induced roughness acts as a surface protective element in reducing water erosion due to the higher water flow resistance and the consequent reduction in water transport capacity (Gaur and Mathur, 2003; Helming et al., 1998; Liu and Singh, 2004; Sankey et al., 2011). In the present study, the rainstorm gully erosion intensity on grasslands and woodlands, which had abundant well-developed biological soil crusts, decreased with increasing BSC surface coverage ($R^2 = 0.8041$ and 0.4257, respectively). A more detailed comparison on the influence of biological soil crusts on soil erosion potential can be made by investigating the gully erosion from two similar plots (i.e., Plot 11 from the woodlands and Plot 34 from the sloping farmland). These two plots were similar in terms of total vegetation coverage (approximately 45% each), slope (approximately 25° each) and soil bulk density (1.23 g per cm^3 on the Plot 11 and 1.20 g per cm^3 on the Plot 34, respectively), but very different in terms of the biological soil crust cover (approximately 42% on the woodland plot and largely absent from the farmland plot). When comparing the gully erosion from these two plots, the sloping farmland plot had a five times greater gully erosion intensity than the forested plot. This result seems largely attributable to the difference in biological soil crust coverage between the two plots.

5. Conclusions

Reducing rainstorm erosion is a strategic mission for future soil and water conservation of the Loess Plateau region. Based on this study, it is concluded that the conversion of sloping farmland to grasslands and woodlands is more effective to control rainstorm gully erosion. However, orchards are not a suitable measure for reducing soil erosion in the Loess Plateau region. Rather, conversion of sloping farmlands to orchards actually seems to increase soil erosion. The mechanisms responsible for reducing soil erosion in the grasslands and woodlands seem to be increased in surface vegetation coverage and enhanced biological soil crust development. Hence, it is imperative that any revegetation measures undertaken on the Loess Plateau must minimize human activities to ensure that vegetated surface cover is maintained and that soil crusts are not disturbed. Similarly, grassland communities must be freely allowed to progress from early to late successional stages, as the concomitant increase in species diversity associated with such changes also seems to reduce soil erosion. The results of this study also show that the "GFG" measures are important, as the erosion rate from existing sloping farmlands is unsustainable. However, the "GFG" vegetation type is a critical factor, as not every type is equally beneficial.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:http://dx.doi.org/10.1016/j.catena.2016.02.025. These data include the Google map of the most important areas described in this article.

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