Prevalent sediment source shift after revegetation in the Loess Plateau of China: Implications from sediment fingerprinting in a small catchment

Wendi Wang | Nufang Fang | Zhihua Shi | Xixi Lu

1 State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi Province 712100, PR China
2 Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi Province 712100, PR China
3 College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, PR China
4 Department of Geography, National University of Singapore, 117576, Singapore

Correspondence
Nufang Fang, Institute of Soil and Water Conservation, Northwest A&F University, 26 Xinong Road, Yangling, Shaanxi Province 712100, China. Email: fnf@ms.iswc.ac.cn

Funding information
National Natural Science Foundation of China, Grant/Award Number: 41671282 and 41525003; National Key Research and Development Program of China, Grant/Award Number: 2016YFC0402401

Abstract
As an important soil and water conversation endeavor, the ‘Grain for Green’ project launched by the Chinese Central Government almost doubled the vegetation cover on the Loess Plateau between 1999 and 2013. The corresponding vegetation restoration considerably diminished slope erosion throughout the Loess Plateau, although erosion in gullies remains poorly understood. In this paper, a composite fingerprinting approach was employed to assess the relative importance of the erosion of gully and slope soils within a typical dam-controlled catchment of the Loess Plateau. A total of 23 couplets were identified based on the deposited layer thicknesses and extreme rainfall event records along the sediment profile. The results suggest that gullies contributed 71% to the overall sediment proportion, and those sediments had an increased tendency to accumulate during 2010–2016 under the ‘Grain for Green’ project. The sediment inputs from slope areas were predicted to be 29%. The eroded gullies materials mainly consisted of silt-sized particles, which dominated the eroded sediment. Silt particles with sizes of 0.02–0.05 mm constituted the main particles in both deposit sediments and gully materials, whereas the slope areas mainly contained particle sizes of <0.01 mm. The check dam proved to be effective at trapping coarse silt with 27–42% of the total sediment content. This study presents reliable information on the importance of gullies as sediment source materials and verifies the applicability of tracing procedures for collecting information on sediment effluxes from both slopes and gullies.

KEYWORDS
check dam, sediment fingerprinting, gully, Loess Plateau, sediment, soil erosion

1 | INTRODUCTION

Soil erosion constitutes a critical environmental problem (Hou et al., 2016). In particular, intense erosion of the soil can cause a decline in soil fertility (Jien & Wang, 2013) and a loss of agronomic production (Lal, 1998) in addition to widespread land degradation (Higgitt, 1993). Furthermore, long-term land quality degradation results in reduced agricultural and economic growth (L. Wang, Dalabay, Lu, & Wu, 2017; Y. Wang, Kang et al., 2017; Y. X. Wang, Fang et al., 2017). Accordingly, better knowledge regarding sediment sources and soil erosion processes could serve as an important tool for coping with problems related to soil erosion (G. J. Zhao, Mu et al., 2017; T. Y. Zhao, Yang et al., 2017).

The Loess Plateau is well known for its extreme soil erosion (Fu et al., 2011; Hou et al., 2016), and it is considered an important sediment source to the Yellow River due to a combination of unique soil properties and intense anthropogenic pressures (Ni, Li, & Borthwick, 2008). More than 60% of the land in the Loess Plateau suffers from accelerated soil erosion, seriously influencing the river siltation conditions and social economy in the lower Yellow River (Wei et al., 2016). To address these challenges, the Chinese central government initiated the ‘Green for Grain’ project, which increased the vegetation cover on
the Loess Plateau from 31.6% in 1999 to 59.6% in 2013 (Y. P. Chen et al., 2015; L. Wang, Dalabay et al., 2017; Y. Wang, Kang et al., 2017; Y. X. Wang, Fang et al., 2017). In addition, steep slopes in the Loess Plateau were converted into fallow grassland (19%), shrubs (13%), terraced farms (7%), and fallow forest (5%) between 1990 and 2000 (Feng, Wang, Chen, Fu, & Bai, 2010). As a result of these restoration efforts, the yearly sediment discharge of the Yellow River has been reduced by approximately 2 billion tons (Y. P. Chen et al., 2015). Appropriately, because vegetation cover plays a significant role in controlling soil erosion, the relationship between vegetation and soil erosion has received increasing attention from researchers worldwide (Hou et al., 2016).

Early studies on the Loess Plateau usually focused on slope erosion (Bissonnais, Renaux, & Delouche, 1995; Sun, Shao, Liu, & Zhai, 2014; Xiong, Tang, Li, Yuan, & Lu, 2014; Xu, 2005; J. Zhou et al., 2016; Z. C. Zhou & Shangguan, 2007). Consequently, few attempts have been made to compare the sediment contributions from slopes and gullies in response to changes in the vegetation cover. Before the 1990s, approximately 400 million tons of sediment was deposited downstream of the Yellow River annually, of which 280 million tons consisted of coarse sediment with particle sizes coarser than 0.05 mm (Jin & Chen, 1986); such coarse sediment mainly originates from fragile parent materials or bedrock in gullies. In contrast, due to the ‘Grain for Green’ project, topsoil erosion throughout the Loess Plateau was reported to have significantly decreased in recent years (Fu et al., 2011). Therefore, because a better understanding of the changes in soil sources with variations in the vegetation cover is important for the construction of catchment controls and the assessment of soil conservation measurements on the Loess Plateau (Xu, Hu, & Chen, 2009), further research on the coarse sediment in the gullies throughout the Loess Plateau is essential.

Fingerprinting techniques offer a potentially valuable way of successfully recording sediment provenances at the catchment scale in a location of concern (Collins et al., 2012; Walling, 2005; Walling, Owens, & Leeks, 2015). For example, Collins, Zhang, Walling, Grenfell, and Smith (2010) used a sediment tracing procedure to quantitatively investigate the apportionment of sediments exported from pastureland, cropland, and channel banks and concluded that pastureland is the leading source of material found in the upstream region of the River Piddle. Similarly, by applying a fingerprinting approach, Walling, Collins, and Stroud (2008) assessed the importance of sediment-contributed nutrients and contaminants related to agricultural activities. Furthermore, F. X. Chen, Fang, Wang, Tong, and Shi (2017) used tracing procedures to successfully identify sediment sources over a longer timeframe in a basic agricultural catchment on the Loess Plateau. As is evident, the fingerprinting approach is being used in a rapidly increasing number of studies (Stone, Collins, Silins, Emelko, & Zhang, 2014). However, this efficient approach has not yet been thoroughly applied to trace sediments back to slopes and gullies following the implementation of vegetation restoration measures on the Loess Plateau.

Check damming constitutes an effective soil conservation engineering measure, and it is widely used throughout the Loess Plateau (X. B. Zhang, Wen, Feng, Yang, & Zheng, 2007). As of 2013, approximately 58,446 check-dams had been constructed, and they remain intact to this day, thereby allowing for the silting of approximately 5.7 billion m$^3$ of sediment (Ministry of Water Resource of PR China (CMWR), 2014). On the Loess Plateau, severe erosion is commonly caused by a few flood events (Yang & Xu, 2010); the sediments deposited in check-dams during these floods exhibit a distinct sedimentary sequence, and the thickness of each couplet normally lies in the range of a few centimeters to several decimeters (L. Wang, Dalabay et al., 2017; Y. Wang, Kang et al., 2017; Y. X. Wang, Fang et al., 2017; X. Zhang et al., 2006). Sediment sequences in check-dams provide deep insight into the long-term sediment deposition processes within catchment ecosystems (F. X. Chen et al., 2017). Accordingly, check-dams enable research to be conducted on soil erosion in ungaged catchments. Therefore, based on the above discussion, the specific intentions of this study were (a) to use sediment source tracking techniques to quantify the relative allocation of sediment provenances in a small catchment of the Loess Plateau and (b) to reveal the impacts of vegetation restoration on changes in sediment sources in a small catchment on the Loess Plateau under the background of the ‘Grain for Green’ project.

2 | MATERIALS AND METHODS

2.1 | Study area

This study was performed on the Washuta Catchment (36°43′ N to 36°45′ N, 109°14′ E to 109°15′ E) located in the Yanhe River Basin, which is the main contributor of coarse sediment to the Yellow River (Figure 1). The Washuta Catchment is characterized by a continental monsoon climate, and it has a total area of 4.7 km$^2$. The elevation within the catchment spans from 1,129 to 1,406 m. The slope gradient varies from 0° to 38°, and the gully density is 3.8 km km$^{-2}$. Furthermore, the annual mean precipitation of this region ranges from 300 to 500 mm, over half of which primarily occurs as high-intensity rainfall between June and October. Based on the different geomorphological units, the landforms in the Washuta Catchment can be subdivided into slope surfaces covered by loess and gullies that deeply dissect the bedrock. The bedrock and parent materials in the gullies mainly include sandstone, shale, and mudstone in addition to Pleistocene Wucheng loess (i.e., old loess; H. Li, An, & Wang, 1982). A check-dam without a spillway was constructed in 1988 in the Washuta Catchment outlet. To date, the check-dam has never been destroyed, and nearly no sediment has been lost. Therefore, the trap efficiency of the check-dam over the past few decades can be considered to be 1.0 (M. Li et al., 2017). A land use map was constructed using Quick Bird imagery, and reconnaissance field surveys were completed in 2016. Fallow forest covers 32% of the study area, and fallow grassland, farmland, gullies, and residential areas cover respectively 31%, 11%, 10%, and 14% of the study area (Figure 1). The vegetation coverage reaches 63% on the loess slope of the Washuta Catchment. All slopes with a gradient exceeding 25° were converted into grassland and forest following the initiation of the ‘Grain for Green’ project.

2.2 | Soil sample collection

Representative samples including both source materials and sediment deposit profiles were collected in July 2016. Field investigations found...
that the primary sediment source materials were derived from slopes and gullies. Moreover, three different landform units composed the slope surfaces, namely, fallow forest, fallow grassland, and farmland. Thus, four primary potential sediment source types were identified. The source materials were sampled in a 5 × 5 m² grid along transects, and every sample from an eroding area was split into five subsamples that were deployed at depths from 0 to 10 cm within the surface soil. In total, 112 soil samples were collected from the source area, 27 of which were from fallow forest, 27 were from fallow grass, 42 were from farmland, and 16 were from gullies (Figure 1). The sampling was carefully carried out using a stainless-steel spatula to avoid disturbing the soil surface structure.

2.3 | Flood couplets and chronology

Sediment profiling samples were collected from the head of the check-dam to a vertical depth of 7.16 m. A total of 23 couplets were identified based on the thicknesses of the deposited layers and extreme rainfall event records (F. X. Chen, Zhang, Fang, & Shi, 2016; L. Wang, Dalabay et al., 2017; Y. Wang, Kang et al., 2017; Y. X. Wang, Fang et al., 2017; Wei et al., 2016). First, the profiles were sectioned carefully using a stainless-steel spatula to reveal the flood couplets (Figure 2e and 3f). The boundary of each flood couplet was easily distinguished based on a fine clay layer at the top and a coarse sand layer on the bottom (Figure 3; L. Wang, Dalabay et al., 2017; Y. Wang, Kang et al., 2017; Y. X. Wang, Fang et al., 2017). The couplet thicknesses varied from 2 to 150 cm. During the fieldwork, not every flood couplet consisted of one clay layer following one sand layer; instead, some flood couplets exhibited mixed layers (Figure 3).

Second, according to the definition of an erosive rainfall event in the Chinese Loess Plateau (Xie, Liu, & Zhang, 2000), we selected all rainfall events with daily precipitation greater than 10 mm, an average rainfall intensity standard ($I_{30}$) of 0.03 mm min$^{-1}$, and break point standards of 30 min ($I_{30}$) greater than 0.13 mm min$^{-1}$ from 1988 to 2016 at the Washuta station (Figure 3) on the basis of the dates on which the check-dam was built and used. The precipitation associated with the 23 couplets was determined according to careful interpretations of rainfall data. The profile contained a 7-year time sequence, the top and bottom couplets of which occurred in 2010 and 2016, respectively (without cultivation layer, Figure 3). Couplets associated with extreme rainstorms with high sediment deposition values were analyzed in 2013, 2014, and 2016. The small flood couplets identified between these large flood events were connected with smaller amounts of rainfall. For example, the heaviest storm produced approximately 83 mm of rainfall on December 7, 2013, and the second heaviest rainfall event produced 82 mm on July 9, 2014 (Figure 3).

2.4 | Laboratory analysis

The collected samples were kept in a well-ventilated room and allowed to dry naturally for a week until they reached a constant weight. Artificial disaggregation was completed using a rubber-tipped mortar and pestle. The samples were sieved at 2 mm to remove litter, residue, and other coarse fragments prior to further analysis.

According to prior geochemical information related to geological variations, we applied geochemical elements as fingerprinting tracers. To analyze the concentrations of different elements, subsamples consisting of 0.2 g were taken from each sediment layer and homogenized using a 0.01 mm sieve (Collins et al., 2016). Then, samples were digested by boiling in nitrohydrochloric acid until a clear solution was obtained; this solution was then diluted 1,000-times and filtered, and
finally, inductively coupled plasma mass spectrometry (Agilent Technologies Inc., United States) was used to measure various element concentrations. A total of 23 elements (Li, Al, Mg, Ca, K, Na, Fe, Cr, Co, Mn, Ni, Cu, Ag, Ga, Zn, Sr, Cd, Ba, Bi, Pb, In, and Tl) were identified and measured.

2.5 | Sediment fingerprinting procedure

Geochemical fingerprints enable discrimination between source materials. A three-stage statistical procedure was applied to confirm the source apportionment. First, a mass conservation assessment, which is important to the efficient utility of sediment tracing (Stone et al., 2014), was used to initially screen tracers regarding nonconservative behaviors (Koiter, Owens, Petticrew, & Lobb, 2013). The conservation test, which was bounded by the highest and lowest median fingerprint property values measured for the spatial sources (Collins et al., 2013; Collins et al., 2016), was based on a fundamental assumption that selected signatures remain constant during the sediment cycle. Furthermore, the concentration and coefficient tracer variations from sediment samples must lie within the source material range, and only those properties located within the corresponding parameter space were selected for further analysis. Second, the nonparametric Kruskal–Wallis test was used to examine the normality of the tracers for each spatial source (Collins, Walling, & Leeks, 1996). This test was applied to ascertain the power of individual tracers under scrutiny in the multivariate mixing model for a potential sediment source discrimination (Collins, Walling, Webb, & King, 2010). Each individual property used to discriminate among the source types had to pass the Kruskal–Wallis test to ensure that the tracer signal exhibited obvious differences between individual sources. Properties that returned a $p$ value $> 0.05$ were excluded (Franz, Makeschin, Weiss, & Lorz, 2014). Discriminant function analysis was used to ensure optimal composite fingerprints and their discriminatory power by minimizing Wilks’ lambda during stepwise selection (Collins, Walling, & Leeks, 1997b; Collins, Zhang, et al., 2010). Third, a multivariate mixing model was applied to determine the individual spatial source unit contributions (Walling, 2005). The multivariate mixing model equation is as follows:

$$f = \sum_{i=1}^{n} \left( \left( 1 - \frac{\left( \sum_{s} S_{s} / C_{i} \right) \cdot P_{s}}{S_{s}} \right) \right)^{2},$$

where $f$ is the minimum of the sum of the squares of the relative errors, $C_{i}$ is the concentration of each fingerprint property ($i$) in the
collected check-dam sediment, $P_i$ is the optimized percentage contribution from source category (s), $S_i$ represents the mean concentration of the fingerprint property (i) in the source category (s), $n$ represents the number of fingerprint properties that compose the optimal composite fingerprint, and $m$ represents the number of sediment source categories (Collins, Walling, & Leeks, 1997a). The model must satisfy two constraints: First, the contribution from each individual source must vary from 0 to 1; second, the total contribution rate from all sources is 1 (Walling et al., 2015). The model assumes that the linear system in Equation (1) is optimized when $f$ is a minimum (Motha, Wallbrink, Hairsine, & Grayson, 2003).

The uncertainties related to source materials that influence the final source discrimination results have attracted increasing attention over the last decade (Collins & Walling, 2007; Collins, Walling, et al., 2010). The inclusion of an explicit assessment of the uncertainties in the model represents the within-source fingerprint property variability and the individual source contribution variations. This uncertainty associated with the application of the multivariate mixing model was estimated by using a Monte Carlo approach (Collins et al., 2016). Accordingly, the mixing model is capable of precisely assessing the uncertainties related to samples from both source and sediment materials. The statistical goodness of fit was used to explicitly account for the efficiency of the model by comparing the actual fingerprint property concentrations in the sediment samples with the corresponding values predicted by the mixing model (Walling, 2005).

### 3 | RESULTS

#### 3.1 | Particle size distributions

The profile distributions of the particle size are shown in Figure 4. The sizes of the sediments were classified as clay (<0.002 mm), fine silt (0.002–0.02 mm), coarse silt (0.02–0.05 mm), fine sand (0.05–0.25 mm), and coarse sand (>0.25 mm; Shi et al., 2012). The check-dam proved to be effective at trapping coarse silt, which represented 27–42% of the total sediment. The amount of clay and fine silt showed nearly the same tendency in the deposit profile with contents of 10–21% and 17–40%, respectively. The quantity of coarse sand was the lowest among the five size classes and was found only in a few layers of sediment with a content that varied over a narrow range (approximately 0.02–0.09%). The fine sand content ranged approximately from 8% to 45%. The amounts of clay, fine silt, coarse silt, and fine sand particles changed greatly at depths of 460–680 cm.

Comparisons of the particle size distribution of sediments from the slope, gully, and check-dam are presented in Figure 5. The sediment size distribution from the bedrock and the dam showed a sharp increase in the range of 0.02–0.05 mm and then a rapid decrease, whereas the sediment from the gully contained more coarse silt and fine sand than the slope. In contrast, the sediment from the slope was dominated by soil composed of clay and fine silt. The coarse sand content was the lowest among all size classes from the different land
3.2 | Optimal combination of fingerprints

All 23 fingerprint factors were evaluated by mass conservation. Table 1 represents the total number of discrete signatures that passed the primary screening test. The four factors that failed the assessment were Ca, Mn, Cu, and Pb. The mean concentrations of Ca, Mn, and Pb in the sediment sample mix were larger than those in the source samples. These three elements did not maintain conservative behaviors during the deposition process. As a result, the variation coefficient of Cu was not in the range of the source samples, indicating that it changed drastically during the process of sediment transportation; Fe was also excluded because the digging tool was a stainless-steel spatula.

Based on the Kruskal–Wallis H test and discriminant function analysis, the remaining signatures were sorted statistically. Table 2 indicates that a majority of the fingerprinting signatures for each individual source category passed the Kruskal–Wallis H test. However, the test resulted in the exclusion of Li and Zn with p values of 0.989 and 0.250, respectively, confirming that both datasets exhibited non-uniform distributions. In total, 16 properties retained p values < 0.05 from the Kruskal–Wallis H test, and the H-value ranged from 0.125 to 69.196.

On the basis of the results from the Kruskal–Wallis H test, we used Fisher’s discriminant to select the optimal fingerprint combination. The results indicate that the final combination was composed of four individual constituents (Mg, Al, Co, and Bi), and 93.6% of the samples were successfully distinguished (Table 3). The depth concentrations of the optimal composite fingerprints (Mg, Al, Co, and Bi) are shown in Figure 3.

3.3 | Sediment source apportionment

The details regarding the sediment contribution to each flood couplet from the potential sediment source types are clearly shown in Figure 6. The geochemical properties indicate that gully materials represented the most significant source for all flood couplets. The contributions originating from gullies were assessed to be 71% with a relative
importance varying from 31% to 100%. In contrast, for the slope surfaces, the average median relative contribution from farmland was 22%, and those from fallow forest and grassland were 4% and 3%, respectively; the corresponding ranges were estimated to be 0–95%, 0–45%, and 0–14%. The average mean contributions from individual source types generated using repeated sets of data were within a 95% confidence limit, which indicates the conjunction of the model solutions with a reproducibility within ±5%. The average model goodness of fit was 0.86, indicating that the model results are meaningful (Mckinley, Radcliffe, & Mukundan, 2013).

### TABLE 1  Geochemical soil source tracers that passed the conservation test

<table>
<thead>
<tr>
<th>Source samples (n = 112)</th>
<th>Sediment samples (n = 23)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracer property</td>
<td>Mean (ppb)</td>
</tr>
<tr>
<td>Li</td>
<td>1.63</td>
</tr>
<tr>
<td>B</td>
<td>117.47</td>
</tr>
<tr>
<td>Na</td>
<td>41.39</td>
</tr>
<tr>
<td>Mg</td>
<td>462.70</td>
</tr>
<tr>
<td>Al</td>
<td>1,506.10</td>
</tr>
<tr>
<td>K</td>
<td>188.60</td>
</tr>
<tr>
<td>Cr</td>
<td>1.74</td>
</tr>
<tr>
<td>Fe</td>
<td>1,669.09</td>
</tr>
<tr>
<td>Co</td>
<td>0.76</td>
</tr>
<tr>
<td>Ni</td>
<td>2.84</td>
</tr>
<tr>
<td>Zn</td>
<td>32.19</td>
</tr>
<tr>
<td>Ga</td>
<td>0.78</td>
</tr>
<tr>
<td>Sr</td>
<td>29.60</td>
</tr>
<tr>
<td>Ag</td>
<td>0.33</td>
</tr>
<tr>
<td>Cd</td>
<td>0.51</td>
</tr>
<tr>
<td>In</td>
<td>1.83</td>
</tr>
<tr>
<td>Ba</td>
<td>201.40</td>
</tr>
<tr>
<td>Tl</td>
<td>0.27</td>
</tr>
<tr>
<td>Bi</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Note. Sample size collected from the source area: n = 112. Sample size collected from the sediment area: n = 23.

### TABLE 2  Results of the normality test of the tracers for each spatial source using the nonparametric Kruskal–Wallis H test

<table>
<thead>
<tr>
<th>Tracer property</th>
<th>H-value</th>
<th>p-value</th>
<th>Tracer property</th>
<th>H-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>0.125</td>
<td>0.989</td>
<td>Co</td>
<td>30.388</td>
<td>0.000*</td>
</tr>
<tr>
<td>B</td>
<td>31.759</td>
<td>0.000*</td>
<td>Ni</td>
<td>10.999</td>
<td>0.012*</td>
</tr>
<tr>
<td>Na</td>
<td>8.496</td>
<td>0.037*</td>
<td>Zn</td>
<td>4.106</td>
<td>0.250</td>
</tr>
<tr>
<td>Mg</td>
<td>9.917</td>
<td>0.019*</td>
<td>Ga</td>
<td>17.997</td>
<td>0.000*</td>
</tr>
<tr>
<td>Al</td>
<td>69.196</td>
<td>0.000*</td>
<td>Sr</td>
<td>10.289</td>
<td>0.016*</td>
</tr>
<tr>
<td>K</td>
<td>26.147</td>
<td>0.000*</td>
<td>Ag</td>
<td>37.431</td>
<td>0.000*</td>
</tr>
<tr>
<td>Cr</td>
<td>17.644</td>
<td>0.001*</td>
<td>Cd</td>
<td>8.071</td>
<td>0.045*</td>
</tr>
<tr>
<td>Tl</td>
<td>23.073</td>
<td>0.000*</td>
<td>In</td>
<td>51.516</td>
<td>0.000*</td>
</tr>
<tr>
<td>Bi</td>
<td>56.454</td>
<td>0.000*</td>
<td>Ba</td>
<td>11.247</td>
<td>0.010*</td>
</tr>
</tbody>
</table>

*Statistically significant values at p ≤ 0.05.

### TABLE 3  Optimal combination of fingerprints for discriminating individual sediment source types

<table>
<thead>
<tr>
<th>Step</th>
<th>Tracer property</th>
<th>Cumulative classified correctly (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mg</td>
<td>52.6</td>
</tr>
<tr>
<td>2</td>
<td>Mg + Al</td>
<td>70.4</td>
</tr>
<tr>
<td>3</td>
<td>Mg + Al + Bi</td>
<td>86.9</td>
</tr>
<tr>
<td>4</td>
<td>Mg + Al + Bi + Co</td>
<td>93.9</td>
</tr>
</tbody>
</table>

FIGURE 6  Sediment contribution details for each flood couplet

95% confidence limit, which indicates the conjunction of the model solutions with a reproducibility within ±5%. The average model goodness of fit was 0.86, indicating that the model results are meaningful (Mckinley, Radcliffe, & Mukundan, 2013).

### DISCUSSION

#### 4.1 The applicability of geochemical fingerprinting in small catchments

The final composite fingerprint, which included Mg, Al, Co, and Bi, successfully provided a discriminatory efficiency of 93.9% (Table 3). F. X.
Chen et al. (2017) highlighted that geochemical tracers cannot always provide a robust discrimination among land use erosion sources within a small study area; this may be caused by selectivity problems or the biogeochemical alteration of land use histories associated with field rotation (Blake, Ficken, Taylor, Russell, & Walling, 2012; Collins et al., 2016). Thus, the source signals among different types of land use become less distinct. Franz, Makeschin, Weiß, and Lorz (2013) successfully discriminated sources depending on geological zones based on their soil geochemistry signatures. Fortunately, in the study catchment, the land use histories and geological conditions between the gullies and the slopes are completely different. Moreover, Smith and Blake (2014) reported that geochemical properties can be used to discriminate among different source materials due to differences in the geology, soil type, and weathering gradients. Sediments eroded from rock-derived soils normally preserve these recognizable geochemical signatures during sediment mobilization and delivery (Haddadchi, Olley, & Laceby, 2014; Hughes, Olley, Croke, & Mckergow, 2008).

4.2 | Temporal shifts in predominant sediment source

The results presented in this paper indicate that gullies were the primary source of sediments with a contribution of 71%, and their contribution increased during the 2010–2016 rainstorm events (Figure 5). However, numerous studies have concluded that slope areas constituted the main sediment contributors on the Loess Plateau prior to vegetation restoration efforts. For example, Jiao (1992) reported that sediment contributions caused by slope runoff account for approximately 70% of the total sediment contents in hilly and gully areas of the Loess Plateau. H. Chen (1999) also showed that slope areas contributed more than half of the total amount of sediment in the basic catchment of the middle reaches of the Yellow River. However, the vegetation coverage and corresponding spatial–temporal changes significantly affect hydrological, sediment transport, and soil erosion processes (Xu, 2005). Nevertheless, field monitoring confirmed that the ‘Green for Grain’ project significantly reduced soil erosion on slope areas (Fu et al., 2011); similar results were also found in other studies. Regardless, F. X. Chen et al. (2016) reported that gullies have remained the main source of sediments in the basic catchment of the Loess Plateau after the initiation of the ‘Grain for Green’ project. J. Q. Zhang et al. (2017) also suggested that gully collapses were responsible for a large proportion of soil erosion throughout the Loess Plateau. This is likely because the materials in gullies are particularly susceptible to collapse and are vulnerable to transport during a rainstorm (Yang, Tian, & Liu, 2006).

Our study area is characterized by gullies that are deeply incised into the bedrock. However, the study conducted by Yang and Xu (2010) revealed that only 33.7% of all sediment was contributed from gullies. This difference might imply that gullies characterized by bedrock and old loess are topographically prone to erosion. Our data showed that the sediments from gullies mainly consisted of silt-sized particles. Many studies have found that silt-sized particles are readily dispersed (L. Wang & Shi, 2015) and are commonly prominent in eroded sediment (Rienzi, Fox, Grove, & Mataocha, 2013; L. Wang et al., 2014). Correspondingly, the slope soils in our study area were dominated by particles smaller than 0.005 mm (Figure 5), and soils with high clay contents exhibit a lower erodibility than those with high silt contents (Gumiere, Le Bissonnais, & Raclot, 2009). Similarly, our results also suggest that the sediment trapped in the check-dam had a lower clay content than a silty soil (Figure 5) and that the silt particle content from the slope areas was significantly lower than that from the gullies (Figure 5). We believe that the gullies materials distributed widely throughout the study area produced an unstable situation that made the gullies more erodible than the slope areas within the background of the ‘Grain for Green’ project. Accordingly, the particle size distribution is helpful for understanding the potential for gully erosion in a basic catchment (Vaezi, Abbasia, Keesstra, & Cerda, 2017).

4.3 | Influence of land use on the sediment source

Some research conducted in recent years has revealed that soil erosion is significantly related to land use (Sharma, Tiwari, & Bhadoria, 2011; Sun et al., 2014). The farmland in the slope area was approximated to have dominated the sediment efflux with a relative importance of 22%, indicating that a vulnerable slope without adaptive strategies for protecting soil and water will still constitute the leading land use source of erosion. This finding has since been accepted by the scientific community (Z. J. Wang, Jiao, Rayburg, Wang, & Su, 2016). In addition, crops are usually harvested in the autumn when the soil is damp and easily compressed by large harvesting machinery; therefore, farmland, which is often left barren until the following spring, has become a major contributor to soil loss (Walling, 2005). In contrast, fallow grassland and fallow forest contributed 4% and 3%, respectively, to soil erosion. Moreover, Al-Seekh and Mohammad (2009) proposed that the lack of vegetation cover and the detachment of soil particles cause farmland to exhibit greater soil loss than fallow vegetation areas. Appropriately, revegetation has played a significant role in helping to conserve the soils in hilly regions by reducing slope soil erosion, which is consistent with previous observations (Cao, Chen, Xu, & Liu, 2007; J. Zhou et al., 2016). Additionally, the high contribution to erosion from gullies also indicates that the sole use of vegetation-based measures cannot effectively control soil erosion on the Loess Plateau. Thus, additional engineering measures, such as check-dams and sediment trapping through reservoirs, are required (Xu, 2005).

4.4 | Influence of effective management strategies

Rustomji, Caitechon, and Hairsine (2008) revealed that 70% of the reduction of soil erosion was due to effective management strategies. In contrast, the reduction in soil erosion due to vegetation cover was less than 14%, and the reduction reached 44% in combination with check-dams in southeastern Spain (Quiñones-Rubio, Nadeu, Boix-Fayos, & Vente, 2016). In the Huangfuchuan tributary of the Loess Plateau, 92% of the sediment in areas with little vegetation cover originated from bedrock in gullies, and the sediment reduction from the installation of check-dams accounted for 57.8% of the total (G. Zhao et al., 2015). Thus, this strategy is particularly applicable in the Loess Plateau (J. Q. Zhang et al., 2017; G. J. Zhao, Mu et al., 2017; T. Y. Zhao, Yang et al., 2017).
5 | CONCLUSIONS

In this study, a geochemical sediment source fingerprinting technique was applied to predict the relative importance of gullies as a contemporary sediment source in response to land use change in the Washuta Catchment of the Loess Plateau. Our results indicate that gullies constituted the principal erosional source with an overall sediment contribution of 71%, whereas slope loess accounted for 29%. In addition, the proportion of silt-sized particles, which usually dominated the eroded soils, from slopes was significantly lower than that from gullies.

Land use changes have resulted in a reduction of loess on catchment slopes, whereas bedrock material and old loess erosion in gullies have become increasingly apparent in recent years. This study quantitatively revealed the importance of gully erosion, which has important implications for the corresponding implementation of rational conservation measures. The construction of appropriate biological barriers and geotechnical facilities should be considered to acquire direct bedrock measurements in gully areas. Overall, our results provide useful information regarding gully and slope loess yields relative to vegetation cover changes on the Loess Plateau that have largely been unreported in the literature.

ACKNOWLEDGEMENTS

Financial support for this research was provided by the National Natural Science Foundation of China (41671282 and 41525003) and the National Key Research and Development Program of China (2016YFC0402401).

ORCID

Nufang Fang http://orcid.org/0000-0001-8157-0256

REFERENCES


