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Degradation of soil physicochemical quality by ephemeral gully erosion on sloping cropland of the hilly Loess Plateau, China

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ABSTRACT

Ephemeral gully erosion (EGE) is a common type of shallow linear erosion that exerts a major threat to the productivity and sustainability of agricultural systems. The objective of this study was to evaluate the impact of EGE on soil physicochemical properties that determine soil quality. It was hypothesized that sites with EGE exhibit significant changes in soil physiochemical properties compared with sites without EGE. This study used a paired sampling method to compare the soil physiochemical properties of soil at 0–2, 2–5, and 5–10 cm depth of ephemeral gully bottoms to inter-gully areas (CK) in croplands of the hilly Loess Plateau of China. The results showed that EGE posed a threat to soil physicochemical properties and thus the soil quality index was progressively reduced as EGE increased. Reductions in soil quality index were observed as stages of EGE (depth of gully) increased. Three critical EGE stages were defined by $<$10 cm and $\geq$30 cm depths of gully where the soil quality index decreased significantly. Compared with the CK, the 0–2 cm depth of the gully bottom was essentially a net soil deposition layer, especially for the first erosion stage (gully $<$ 10 cm deep). Soil nutrient loss was greatest in the 2–5 cm depth. Soil physical properties were more susceptible and fragile to EGE than soil nutrients. Degradation of soil physical-dominated properties occurred in the first erosion stage, with key factors being erodibility (K value), silt content, specific surface area (SSA) and mean weight diameter of aggregates (MWD), whereas soil degradation was mainly caused by losses of soil available nutrients during the subsequent erosion stages. This approach of combining field ground-truth survey with laboratory analysis to study the in-situ impact of ephemeral gully erosion on soil physicochemical properties aids in understanding the features of soil degradation caused by EGE.

1. Introduction

Soil erosion has been recognized as the major cause of land degradation and a threat to the sustainability of agricultural ecosystems worldwide. There are three general types of water erosion: sheet erosion, rill erosion and gully erosion (Wischmeier and Smith, 1978). Ephemeral gully erosion (EGE) is a kind of gully erosion whereby a small channel eroded by concentrated flow can be easily filled by normal tillage, only to reform again in the same location by additional runoff events (Laflen et al., 1986). Gully erosion is often the dominant source of sediment transport in cultivated catchments (De Vente et al., 2005; Valentin et al., 2005). Vandaele and Poesen (1995) found that the mean, annual ephemeral gully erosion equaled 70–75% of the mean annual rill erosion. Auzet et al. (1993) found that ephemeral gully erosion during winter equals about 80% of soil loss due to rill erosion.

Previous research on ephemeral gully erosion mainly focused on techniques for monitoring and modeling gully erosion (Poesen et al., 2003; Casalí et al., 2006; Dong et al., 2015), gully retreat rates (Vandekerckhove et al., 2003; Hu et al., 2007), topographic thresholds for gully erosion (Vandaele et al., 1996; Nachtergaele et al., 2001; Poesen et al., 2003; Maugnard et al., 2014), and contribution of gullies to soil loss and sediment yield (Auzet et al., 1993; Vandaele and Poesen, 1995; Li et al., 2003; Taguas et al., 2012). For example, Govers and Poesen (1988) discriminated the contributions of inter rill and rill erosion to total soil loss. Poesen et al. (2003) found that ephemeral gully erosion contributed from 10 to 94% of total field soil loss. Chaplot et al. (2005) quantified the

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spatial and temporal variations of linear erosion at the catchment level and found linear erosion correlating well with the catchment surface area and the mean slope gradient.

EGE usually causes serious soil degradation in arid and semiarid regions, and this kind of soil degradation may be substantially enhanced in response to climate change by increasing intensity and frequency of events (Nachtergaele et al., 2001; Maeda et al., 2010). In slope lands, gully erosion affects soil attributes through: (i) losses of soil nutrients and water storage capacity, (ii) exposure of subsoil material with low fertility and high acidity, and (iii) degradation of soil structural attributes (Smith et al., 2001; Su et al., 2010). Ephemeral gully erosion can decrease soil productivity and interfere with farming operations (Poesen et al., 2003; Liu et al., 2013). Chaplot et al. (2005) reported that linear erosion, including rilling and gullying, irreversibly damages the fertility of cropping systems by the removal of surface soil. Valentin et al. (2005) found a production loss of 37% of the original crop yield induced by gully erosion in a slash and burn system of upland rice in northern Laos. Research from the black soil region of northeast China demonstrated that every 1 cm decrease in soil depth in areas adjacent to ephemeral gullies due to infilling activities resulted in a 2% decrease in yield (Liu et al., 2013). Recent studies have indicated that EGE-induced soil degradation was a gradual process, in which subsurface soil was ploughed up by tillage and mixed with the eroded surface soil year by year. However, the use of cultivars and fertilisers masked the short-term effect of soil erosion (Wang et al., 2009; Su et al., 2010). As a result of several cycles of EGE followed by tillage in-filling, the nutrient-rich topsoil decreases progressively with proximity to the channel. Over the long-term, removal of the topsoil degrades the soil physicochemical properties, thereby creating a nutrient imbalance (Yan and Yue, 2010). For example, Wang et al. (2009) adopted an innovative simulated desurfacing method to evaluate the impact of soil erosion on soil properties, and found that the silt content decreased from 46.5% to 33.6% and thus the nutrient pool reduced to different degrees with erosion depth from 0 cm to 70 cm. However, research on the in-situ effects of ephemeral gully erosion on soil quality is relatively scarce. There has not been a consensus on EGE progression and its subsequent effect on soil quality (i.e., soil properties). The lack of investigations on the impact of EGE on soil quality may exist because, generally speaking, EGE does not affect how the farmer manages the land nor does it lead to sufficient removal or burial of the crop to affect farm profitability in the short term. The in-situ effects of EGE on soil properties, soil quality degradation process and key soil quality factors influenced by EGE are still unclear even with the abundance of research that has been conducted on soil erosion and soil quality.

The Loess Plateau in the northwestern part of China is susceptible to water erosion and the resulting environmental problems occurring for this type of soil are far-reaching (Cai, 2001). The 400–500 mm precipitation belt of the Loess Plateau is characterized by frequent natural disasters of flash floods and landslide/mudflows. More than 70% of the inter gully areas could be impacted by ephemeral gully erosion, which contributed 35–85% of the total soil loss from the slope in the region (Qin et al., 2010; Tang, 2004). The excessive erosion is in response to infrequent intensive rainfalls, steep slopes, and intensively tilled small-scale subsistence farming, combined with the nature of the loess soil (low organic matter content, poor nutrient content and weak soil structure). These factors cause this region to be very prone to ephemeral gully generation, which has selectively deprived the soil of fine particles and posed a threat to soil quality (Su et al., 2010).

The objective of this study was to (1) evaluate the in-situ impact of EGE on soil physicochemical properties in cultivated slope lands of the Loess Plateau, China and (2) link ephemeral gully erosion with soil quality degradation. It was hypothesized that EGE exhibits significant changes in soil physiochemical properties in comparison with inter-gully sites and that the soil quality decreases as EGE depth increases.

2. Materials and methods

2.1. Study area

The study was conducted within the 400–500 mm rainfall zone of the central Loess Plateau (Fig. 1). This region features low-frequency, high-magnitude rainfall and hilly steep slopes. These factors often cause a large amount of overland flow and high rates of soil erosion in the region. Annually, over 60% of the arable land suffers from various degrees of soil erosion, with rill and EGE as the most common types of erosion on the Loess Plateau (He et al., 2006). The average density of erosion gullies is approximately 0.062 km ha^{-1}, with an erosion modulus of 21.8 t ha^{-1} y^{-1} and a sediment load of 1.6 billion tons detected in a headwater catchment of 75.2 million hectare (Zhang et al., 1997; He et al., 2006). As a result, losses of soil organic matter, total nitrogen and total phosphorus could be up to 216 kg ha^{-1} y^{-1}, 118 kg ha^{-1} y^{-1} and 255 kg ha^{-1} y^{-1}, respectively (Li and Pang, 2008). Therefore, the 400–500 mm precipitation zone of Loess Plateau is an optimal site for studying the relationship between EGE and soil quality.

2.2. Field survey and soil sampling

Paired sampling was chosen as the appropriate experimental technique to address differences in soil physical and chemical qualities between ephemeral gully and inter-gully locations (Stavi and Lal, 2011). At each selected site, samples were collected at a single representative gully bottom and a single location adjacent to the gully that was far enough away to be representative of the inter-gully condition. In August 2009, a field ground-truth survey was conducted in which a total of 64 representative soil profiles were identified at 13 sites in the study area (Table 1). The sites selected for sampling were located in different basins but had similar tillage practice (contour tillage), residue management (residue removed), slopes, and fertilization systems. The soil type was loess soil (Entisols in the USDA classification system), which was characterized by silt loams in texture with low organic matter content of 6.15 ± 2.4 g kg^{-1} (Xu et al., 2006).

The ephemeral gully (EG) dimensions, such as ephemeral gully width including the top and bottom width and erosion depth (H in Fig. 2), were measured manually using a steel tape to quantify the erosion volume (Prasuhn, 2011). At each site, multiple profiles were selected for sampling (Table 1). For each profile, three bulk soil samples were collected at the gully bottom in depths of 0–2, 2–5, and 5–10 cm (Fig. 2) and combined to form a composite sample for each depth increment. For comparison, composite bulk soil samples were also taken outside the gully at a minimum distance of 10–15 m from the gully edge to represent the inter-gully soil properties. The soil bulk density was also sampled by collecting undisturbed soil cores (stainless steel cylinders with a diameter and a height of 5 cm each) and composite bulk samples in the middle of the 0–10 cm depth increment. Land degradation was determined based upon 17 selected soil physicochemical indicators (Li et al., 2013) that are commonly used to evaluate soil quality (Table 2).

2.3. Soil properties measurement and data analysis

The bulk soil samples were taken to the laboratory, and miscellany materials such as roots and small stones were removed.

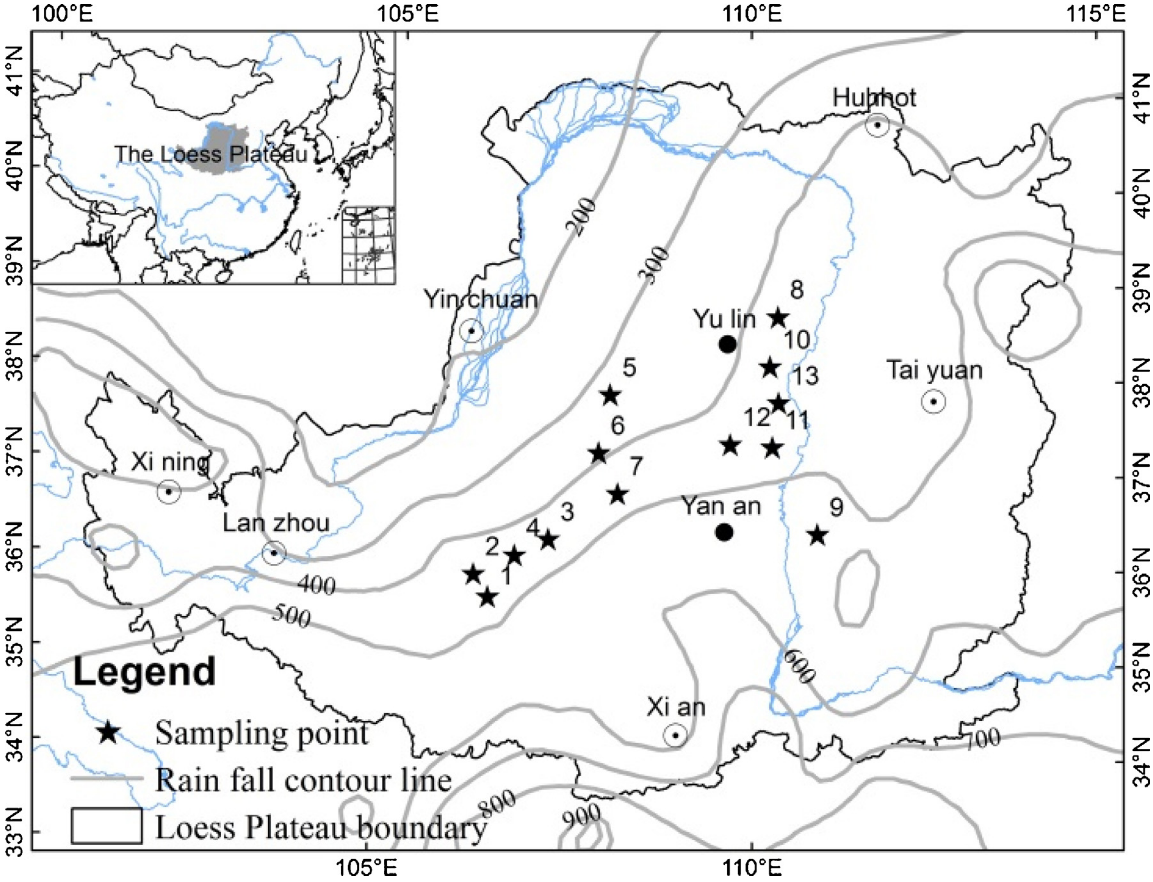


Fig. 1. Location of sampling sites in the central Loess Plateau.

Samples were air-dried then sieved through 1-mm and 0.25-mm mesh screen. Sand (S), silt (Si), and clay (C) contents were determined by the Malvern MS2000 method (Malvern Company, Britain). Soil aggregation was determined by a conventional wet sieving method (Yoder, 1936). Specific surface area (SSA (cm^2/g)) was calculated by Eq. (1):

$$C_{SSA} = 0.05(\text{S percent}) + 4.0(\text{Si percent}) + 20(\text{C percent}) \quad (1)$$

where S, Si, and C are percent sand (>50 μm), silt (50–2 μm), and clay (<2 μm) contents, respectively (Foster et al., 1985). Soil mean weight diameter (MWD) was calculated by Eq. (2):

$$\text{MWD} = \sum_{i=1}^{n} R_i \times W_i \quad (2)$$

where R_i and W_i represent the average diameter of class i of soil aggregate and the percent of class i in the bulk soil, respectively. Soil erodibility coefficient (K), which was used for evaluating vulnerability to erosion, was calculated using Eq. (3) proposed by Williams et al. (1983):

$$\begin{aligned} K_{\text{epic}} = {} & \{0.2 + 0.3\exp[-0.0256\text{S}(1 - \text{S}_i/100)]\} \times \left(\frac{\text{S}_i}{\text{C} + \text{S}_i}\right)^{0.3} \\ & \times \left[1.0 - \frac{0.25\text{SOC}}{\text{SOC} + \exp(3.72 - 2.95\text{SOC})}\right] \\ & \times \left[1.0 - \frac{0.7\text{SN}_1}{\text{SN}_1 + \exp(-5.51 + 22.9\text{SN}_1)}\right] \end{aligned} \quad (3)$$

Table 1
Basic characteristics of sampling sites including site locations, number of profiles described at each site and general description.

Sampling time	Sampling sites	Profiles described	Coordinates	Sampling sites description[a]
2009–2007	Guyuan, Ningxia	1	36°01.118′N 106°25.220′E	Gully slope, shady slope, up, SL 21°, barley
2009–2007	Zhaike, Ningxia	7	36°02.119′N 106°14.945′E	Gentle slope, sunny slope, mid, SL 15°, potato
2009–2007	Guyuan, Ningxia	6	36°03.262′N 106°26.840′E	Gully slope, semi-sunny slope, down, SL 23°, potato
2009–2007	Guyuan, Ningxia	2	36°11.192′N 106°22.149′E	Gully slope, semi-sunny slope, up, SL 20°, potato
2009–2007	Dingbian, Shaanxi	6	37°50.188′N 107°28.941′E	Gully slope, semi-sunny slope, up, SL 17°, buckwheat
2009–2007	Dingbian, Shaanxi	11	37°20.840′N 107°54.301′E	Gully slope, semi-sunny slope, up, SL 24°, buckwheat
2009–2007	Wuqi, Shaanxi	3	36°55.352′N 108°10.332′E	Gentle slope, semi-sunny slope, mid, SL 23°, potato
2009–2007	Shenmu, Shaanxi	3	38°47.723′N 110°22.043′E	Gully slope, shady slope, up, SL 20°, potato
2009–2008	Wucheng, Shanxi	4	36°29.953′N 110°53.478′E	Gully slope, semi-sunny slope, up, SL 20°, soybean
2009–2008	Zizhou, Shaanxi	7	37°38.258′N 109°45.545′E	Gully slope, sunny slope, mid, SL 17°, potato
2009–2008	Zizhou, Shaanxi	5	37°38.339′N 109°45.524′E	Gully slope, semi-sunny slope, up, SL 20°, soybean
2009–2008	Zizhou, Shaanxi	6	37°39.104′N 109°46.112′E	Gully slope, shady slope, up, SL 15°, potato
2009–2008	Zizhou, Shaanxi	3	37°39.033′N 109°46.326′E	Gully slope, sunny slope, mid, SL 22°, potato

[a] Up, mid, down stand for the position of the gully on the hillslope being up, middle, or down slope position, respectively, and SL stands for the gradient.

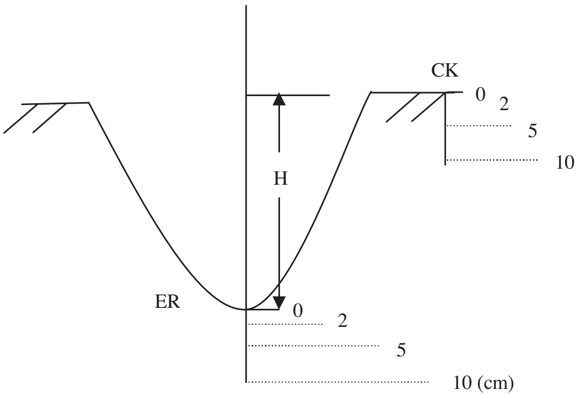


Fig. 2. Sketch map of sampling.
CK: inter-gully site; ER: ephemeral gully bottom and H-ephemeral gully depth which defines the stage of gully erosion.

where SOC is the percent soil organic carbon, SN_1 is 1-S. Subsequently, a modified Eq. (4):

$$K = -0.01383 + 0.51575K_{epic} \quad (4)$$

was proposed by Zhang et al. (2008) and applied in many studies of the Loess Plateau (Gao et al., 2013; Pang et al., 2013). Soil pH was determined in 1:2.5 soil:water suspensions with an automatic acid–base titrator. Soil organic matter (SOM) was determined by the modified Walkley–Black method. Total nitrogen (TN) and available nitrogen (AN) were determined using the Kjeldahl method and available potassium permanganate distillation, respectively. Total phosphorus (TP) was determined using a molybdate-based colorimetric assay and available phosphorus (AP) was determined by extracting samples with 0.5 M $NaHCO_3$. CEC was measured by the sodium saturation method (Nelson and Sommers, 1982).

To better understand how the relative contributions of soil properties to soil degradation change as ephemeral gullies evolve, we analyzed the impact of EGE on soil physiochemical properties with depth at three stages of gully development. Given that these loess soils did not contain a non-erodible layer to restrict the vertical progression of the gullies, the stage of gully evolution was defined by the depth of the gully: stage 1 was 0–10 cm, stage 2 was 10–30 cm, and stage 3 was 30–50 cm deep. The impact of EGE at each stage was determined by the percent change using:

$$\text{Percent change} = \frac{ER - CK}{CK} \times 100\% \quad (5)$$

where ER and CK were the soil attribute values of eroded (gully bottom) and CK (inter-gully) sites, respectively.

2.4. Establishment of soil quality index (SQI)

Principal component analysis (PCA) was used to calculate the SQI in three steps: (i) selection of the critical parameters, (ii) conversion of indicator values into non-dimensional scores (0–1) based on critical values, and (iii) integration of the indicator scores into a single SQI (Xu et al., 2006). In our study, the critical values for each soil indicator were set according to the range of values from the CK soils. Specifically, the critical values were the maximum (b) or minimum (a) of the soil attributes of CK and the turning point a_2 (b_1) was the mean value of soil attributes in CK soils (Table 3). To detect the factors affecting soil quality in different erosion stages, each indicator was scored by the equations in Fig. 3. As a result, three types of standardized functions were generated: (1) 'S' curve or 'more is better', (2) 'reverse S' shape or 'less is better' and (3) trapezoid shape or 'optimum'.

A technically sound scientific method of soil quality assessment should consider both the effect of the weight of each soil indicator on the results of the soil quality assessment and the interactions among parameters. According to Xu et al. (2006) and Romina et al. (2011), the following weighted method (Eq. (6)) was employed in this study:

$$SQI = \sum_{i=1}^{n} K_i \times C_i \quad (6)$$

where C_i is the membership value, K_i is the PCA weight factor and n is parameter number. The equation was used to calculate the SQI weighted by sampling depth and then normalized to obtain a maximum SQI value of one. Using SOM as an example, the SOM content (C_{SOM}) was calculated according to Eq. (6) as:

$$SQI_{SOM} = C_{0-2cm} \times \frac{2}{10} + C_{2-5cm} \times \frac{3}{10} + C_{5-10cm} \times \frac{5}{10} \quad (7)$$

where the C_{0-2cm} is the SOM content of 0–2 cm soil, etc.

Table 2
Soil properties of the cultivated slope land in the studied area.

Soil indicators[a]	Maximum	Minimum	Mean	Std.[b]	C.V.[c] (%)	Sensitivity[d]	Fluvial terrace[e]
Bulk density ($g\,cm^{-3}$)	1.22	1.07	1.15	0.06	5.22	NS	1.30
Porosity (%)	58.20	52.34	55.12	3.68	6.68	NS	50.94
Aggregate content ($g\,kg^{-1}$)	178.0	94.9	147.9	32.9	22.24	LS	460.1
MWD (mm)	0.92	0.31	0.47	0.52	26.96	LS	1.38
Clay content (%)	12.57	5.25	7.92	2.14	27.02	LS	10.26
Silt content (%)	63.19	53.45	57.67	3.49	6.05	NS	65.73
Sand content (%)	39.14	24.24	34.17	4.50	13.17	LS	24.01
SSA ($cm^2\,g^{-1}$)	505.3	340.7	390.7	48.29	12.36	LS	469.3
Erodibility coefficient	0.24	0.08	0.19	0.03	14.29	NS	0.19
Soil organic matter ($g\,kg^{-1}$)	10.8	3.7	7.9	1.02	12.91	LS	14.48
Total nitrogen ($g\,kg^{-1}$)	0.69	0.19	0.45	0.04	8.89	NS	0.80
Total phosphorus ($g\,kg^{-1}$)	0.52	0.38	0.46	0.05	10.87	LS	0.65
Available nitrogen ($mg\,kg^{-1}$)	36.89	15.23	25.64	7.52	29.33	LS	61.13
Available phosphorus ($mg\,kg^{-1}$)	5.65	2.77	3.93	1.00	25.45	LS	15.32
Available potassium ($mg\,kg^{-1}$)	143.4	51.3	78.7	6.04	7.67	NS	136.6
CEC ($cmol\,kg^{-1}$)	6.25	5.10	5.60	0.43	7.68	NS	6.88
pH	8.85	8.67	8.76	0.06	0.68	NS	8.64

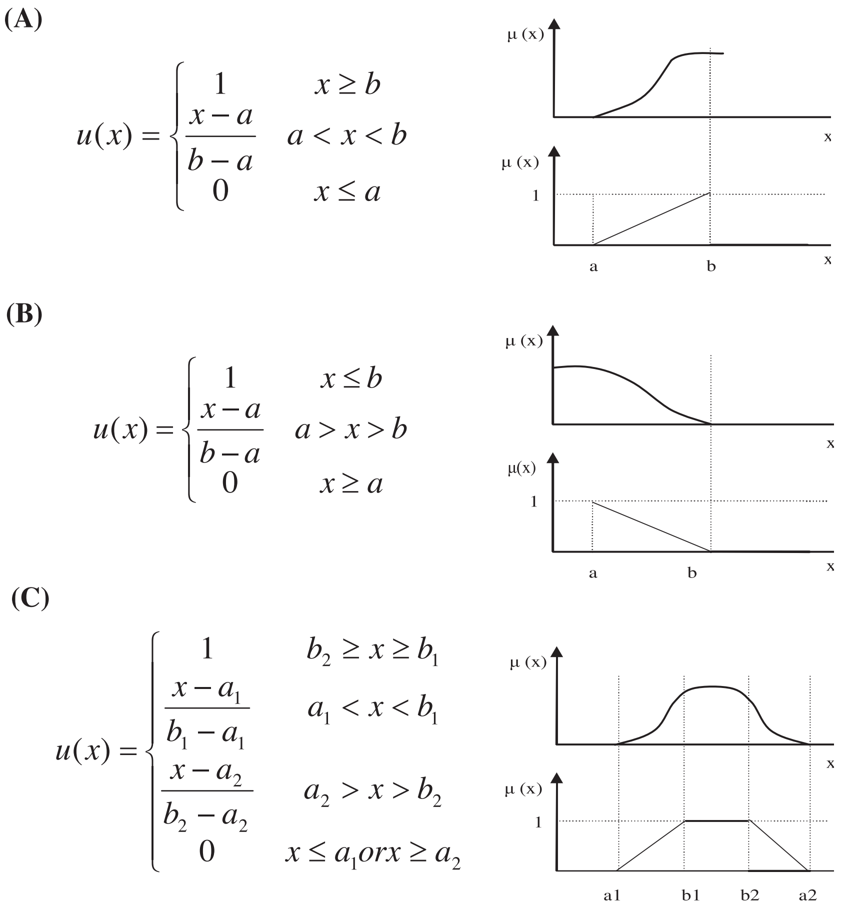
[a] MWD: mean weight diameter; CEC: cation exchange capacity; SSA: specific surface area.
[b] Std.: standard derivation.
[c] C.V.: coefficient of variation.
[d] No sensitivity (NS): C.V. ≤ 10%; low sensitivity (LS): C.V. 40–10%; medium sensitivity: C.V. 100–40% and high sensitivity: C.V. ≥ 100%.
[e] Soil properties of fluvial terrace in the research region, unpublished data.

Table 3
The relationship between erosion stage and soil physical properties.

Indicators	Soil layers (cm)	Erosion stages[a]			
		First stage	Second stage	Last stage	Mean value[a]
Bulk density	0–10	5.8 (0.28)	6.1* (0.22)	6.5* (0.39)	6.1
Aggregate	0–10	−6.4 (0.75)	−7.6* (1.18)	−14.3* (2.71)	−9.4
MWD	0–10	3.6 (0.38)	−12.4* (2.20)	−27.6* (3.32)	−12.1
Clay content	0–2	19.9* (3.90)	3.6 (0.17)	5.9 (1.00)	16.5
	2–5	−0.3 (0.08)	−6.8* (0.14)	−12.2* (1.41)	−6.4
	5–10	6.4 (1.12)	−2.7 (0.18)	−1.5 (0.19)	0.7
Silt content	0–2	0.9 (0.06)	2.6 (0.17)	−1.9 (0.11)	0.5
	2–5	−6.8* (0.12)	−0.4 (0.06)	−4.0 (1.04)	−3.7
	5–10	−2.5 (0.17)	7.0 (0.13)	0.8 (0.09)	1.8
Sand content	0–2	−10.0* (0.58)	1.8 (0.09)	−5.7* (0.19)	−2.0
	2–5	2.5 (0.18)	2.0* (0.12)	4.4 (0.19)	3.0
	5–10	−1.3 (0.11)	−0.8 (0.07)	1.8 (0.17)	−0.1
SSA	0–2	12.9* (0.62)	2.7 (0.12)	3.7 (0.12)	6.4
	2–5	0.5 (0.06)	−0.2 (0.03)	−1.9 (0.07)	−0.5
	5–10	8.5* (0.14)	2.2 (0.14)	−0.3 (0.02)	3.5
K value	0–2	22.8* (2.01)	18.3* (1.19)	17.7* (0.39)	19.6
	2–5	29.0* (2.34)	17.7* (2.01)	12.4* (0.18)	19.7
	5–10	23.8* (2.07)	16.6* (1.04)	19.0* (0.19)	8.7

* indicates a significant difference at $P < 0.05$ according to a paired *t*-test. MWD: mean weight diameter; SSA: specific surface area. *K* value: soil erodibility factor. Negative (positive) value indicates EGE reduces (increases) the soil attributes value.

[a] Numbers represent mean difference, in %, between the eroded soil and CK (Eq. (5)) and SE of the mean were in parentheses.



(A)

$$u(x)=\begin{cases}1 & x\ge b\\ \dfrac{x-a}{b-a} & a<x<b\\ 0 & x\le a\end{cases}$$

(B)

$$u(x)=\begin{cases}1 & x\le b\\ \dfrac{x-a}{b-a} & a>x>b\\ 0 & x\ge a\end{cases}$$

(C)

$$u(x)=\begin{cases}1 & b_2\ge x\ge b_1\\ \dfrac{x-a_1}{b_1-a_1} & a_1<x<b_1\\ \dfrac{x-a_2}{b_2-a_2} & a_2>x>b_2\\ 0 & x\le a_1 or x\ge a_2\end{cases}$$

Fig. 3. Illustration of (A) the 'S' curve, (B) reversed 'S' curve and (C) trapezoid curve.
Note: $\mu(x)$ is the membership function; *x* is the value of the analyzed indicators in lab. Small letters *a* and *b* are the lower and upper limits of the indicator' critical value in (A) and (B) and a_1,a_2 and b_1, b_2 are the appropriate lower and upper limits in (C) above.

2.5. Statistical analysis

The Pearson correlation coefficient and a paired T test ($P < 0.05$) were used to analyze each pair of soil properties using SPSS 13.0. This assessment was conducted only between pairs of soil properties sampled at the same site and depth (i.e., ER and CK).

3. Results

3.1. Soil properties

The overall statistics for the 17 soil properties measured are presented in Table 2. The least variable properties, as expected for the loess soil, were bulk density and silt content. The greatest variability among samples over all sites was the available nitrogen, MWD, clay content and available phosphorus. Even for these, the variability was low (<40%) which is expected for loess parent material. In general all of the soil properties showed a low variation across the research region. This behavior demonstrated that the soil physiochemical properties on the sloped land in the hilly loess region was quite invariant and uniform, which was a comprehensive result of homogeneous loess parent material as well as historically similar cultivation management practices.

Compared with soil in fluvial terrace in the region (Table 2), soil in sloped land was loose with a lower bulk density and higher porosity; the soil structure was poor with lower water stable aggregate; the texture was higher in sand and silt, which could be a result of selective soil erosion. The SOM and nutrient contents in sloped land were also lower compared with fluvial terrace. As a whole, the descriptive statistics (Table 2) reflected that the soil in the sloped land was homogeneous, relatively infertile and vulnerable to erosion.

3.2. The relationship between the EGE stage and the soil physical indicators

Significant increase in soil bulk density of the EGE soils was found in comparison with the CK soils in the 0–10 cm depth when EGE was at the second and third stage of development (Table 3). The quantity of water-stable aggregates in the 0–10 cm of the gully bottom was 6.4%, 7.6% and 14.3% lower than the inter-gully locations at the three respective erosion stages (1, 2, 3) with the latter two being significantly different. Soil MWD was also significantly lower at the latter two erosion stages for the 0–10 cm depth.

Separation of the 0–10 cm zone into depth increments revealed inconsistent differences in particle size distributions (S, Si, and C) between the gully bottom and the inter-gully locations (Table 3). The clay content was significantly higher (EG vs CK) at stage 1 at the surface (0–2 cm) and still numerically higher at stages 2 and 3 but not statistically significant. However, this behavior was compensated by the observed clay content being significantly lower in the 2–5 cm increment at stages 2 and 3. No significant differences in clay content were observed in the 5–10 cm increment. The silt content did not appear to change with depth or stage of erosion with the exception of being significantly lower in the intermediate depth (2–5 cm) at stage 1. The sand content was significantly lower at the surface (0–2 cm) of the gully bottom compared to the inter-gully location for stages 1 and 3. The SSA is predominantly controlled by the clay content and as expected showed a similar trend as the clay content. The particle size distribution and SOC combined based upon Eq. (3) to produce the erodibility. As such, the erodibility (K) was significantly higher in all three depth increments at all three erosion stages in the gully bottom than the inter-gully location. This was consistent with previous studies on the loess plateau that reported that past erosion accelerates future erosion (Wang et al., 2013). This is a reflection of the nature of loess deposits that do not contain a non-erodible layer with depth that could restrict the vertical progression of gully erosion and thereby foster widening of gullies. Instead, EGs in the loess plateau tend to progressively deepen with time. It should be noted that the greatest differences in K were observed for stage 1 at all three depth increments so the soil properties alone would contribute to accelerated gully erosion but combined with enhanced networking of gullies and contributing area with stage of development an acceleration of EGE with time is likely.

3.3. The relationship between the EGE stages and soil chemical indicators

Soil nutrient loss should be correlated with erosion stages in that the greater the soil loss the greater the loss in the nutrient pool. SOM content showed insignificant differences between the gully bottom and inter-gully locations at the immediate surface (0–2 cm) (Table 4). However, there was a significant decrease in comparison with the CK soil at all three erosion stages for the 2–5 cm depth. Differences in SOM between gully and CK locations progressively increased with stage in the 5–10 cm depth to the point of being significantly different by stage 3 (Table 4). Thus, a large proportion of SOM content was lost as EGE progressed. Surprisingly, total nitrogen showed an increase at the surface (0–2 cm) with the difference between the gully and inter-gully being significant in the latter two stages. In contrast, total phosphorus showed a decrease in the gully surface compared to the inter gully surface. However, both total nitrogen and phosphorus showed significant decreases below the surface (2–5, 5–10 cm) at stage 3. The available nutrient pools for N, P, and K tended to be significantly lower in the gully bottom compared to the inter-gully locations, particularly for the 2–5 cm depth. The CEC showed no significant effect of EGE regardless of the stage of erosion. Given the increase in clay content at the gully bottom surface (0–2 cm), one would expect an increase in CEC. There was a numerical non-significant increase in 0–2 cm and 2–5 cm layers during the first stage of erosion followed by a reduction as EGE continued but the differences were not significant. Thus, the majority of loss in available nutrients occurred during the latter two stages of EGE.

3.4. Soil quality index based on PCA

Principal component analysis was conducted with these data (Table 2) to select critical parameters and turning points (Table 5) in order to convert these into non-dimensional scores. In general, behavior of K values was considered as 'reverse S' curves, BD, porosity, content of clay, silt and sand, SSA and pH were 'trapezoid shape', and the others were 'S' curves.

Soil quality index (SQI) is a sensitive indicator for reflecting the evolution of soil quality as influenced by certain external disturbances such as soil erosion, fertilization, and tillage practice (Xu et al., 2006). As shown in Fig. 4, EGE had a significant impact on SQI, and three step-like reductions in the SQI were observed as the erosion depth increased. During the first stage of EGE when the erosion depth was less than 10 cm, the SQI of the EG bottom was 0.894, and an average reduction of 10.6% was found in comparison with the CK soil. As the EGE depth increased to the range of 10–30 cm (stage 2), the SQI was between 0.698 and 0.752, with an average value of 0.723. The SQI of the gully bottom was significantly lower in stage 2 than stage 1. Similarly, when the erosion depth reached 30–50 cm (stage 3), the SQI values were between 0.624 and 0.645, with an average value of 0.634 which was significantly lower than stage 2. There was a 26.0% and 8.9%

Table 4
The relationship between the erosion stage and differences in soil chemical properties between gully and CK locations for each depth increment.

Indicators	Soil layers (cm)	Erosion stage[a]			
		First stage	Second stage	Last stage	Mean value[a]
SOM	0–2	2.4 (0.12)	2.2 (0.22)	−1.7 (0.06)	1.0
	2–5	−11.2* (1.53)	−14.4* (2.22)	−13.4* (2.19)	−13.0
	5–10	1.6 (0.14)	−3.8 (0.17)	−6.7* (0.11)	−3.0
Total nitrogen	0–2	4.3 (0.14)	16.3* (1.82)	8.5* (0.33)	9.7
	2–5	−2.8 (0.28)	2.2 (0.19)	−11.0* (1.12)	−3.9
	5–10	−3.5 (0.12)	1.4 (0.12)	1.8 (0.14)	−0.1
Total phosphorus	0–2	9.4* (0.26)	5.5 (0.17)	8.1* (0.27)	7.7
	2–5	−6.3* (0.29)	−5.9 (0.11)	−6.6* (0.14)	−6.3
	5–10	5.5 (0.12)	−0.2 (0.01)	4.1 (0.13)	3.1
Available phosphorus	0–2	3.6 (0.17)	2.2 (0.09)	2.9 (0.10)	2.9
	2–5	2.2 (0.27)	−14.3* (1.61)	−21.9* (1.47)	−11.3
	5–10	–	–	–	–
Available nitrogen	0–2	7.6* (0.13)	−5.2 (0.15)	−4.9 (0.09)	−0.8
	2–5	0.4 (0.02)	−9.4* (0.76)	−16.7* (2.32)	−8.6
	5–10	0.4 (0.07)	−2.9 (0.04)	−5.3 (0.12)	−2.6
Available potassium	0–2	8.5* (1.67)	3.1 (0.22)	−6.8* (0.84)	1.6
	2–5	−14.6* (1.43)	−10.0* (1.99)	−4.8 (0.14)	−9.8
	5–10	−3.8 (0.65)	−12.7* (1.33)	−9.3* (0.16)	−8.6
CEC	0–2	1.7 (0.37)	−3.4 (0.24)	−1.1 (0.15)	−0.9
	2–5	2.9 (0.32)	−2.6 (0.11)	−0.9 (0.17)	−0.2
	5–10	–	–	–	–

* indicates a significant difference from CK soil at $P < 0.05$ according to a paired t-test. SOM: soil organic matter; CEC: cation exchange capacity. Negative (positive) value indicates EGE reduces (increases) the soil attribute value.

[a] Numbers represent mean difference, in %, between the eroded soil and inter-gully area (Eq. (5)) and the SE of mean were in parentheses.

reduction at stage 3 from the first two erosion stages, respectively. In addition, the SQIs of the EG bottoms were 10.6, 27.7 and 36.6% less than the respective inter-gully locations for erosion stages 1, 2, and 3, respectively. The erosion depths of 10 and 30 cm were the two critical points where significant reductions in SQI occurred.

3.5. Limiting parameters in the different stages of erosion

To detect the limiting soil parameters of the SQI in different erosion stages, the soil physicochemical indicators used in the SQI were plotted using a radar diagram as presented in Fig. 5. Lines crossing the axes were the soil layers and the lines at the periphery of the web had better soil quality, whereas increased proximity to the origin indicated low soil quality. This analysis showed (Fig. 5), that the soil parameters in the 2–5 cm layer degraded more rapidly in comparison with those in the 0–2 cm and 5–10 cm layers as the erosion stage progressed (Fig. 5 from A to B and C). The K value, silt content, SSA and MWD were the limiting factors in the first erosion stage, whereas soil nutrients (including total and available nitrogen, and phosphorus) were the key contributors to the SQI. However, soil nutrients (particularly total and available nitrogen), along with BD, AGG and SSA, were limiting factors to SQI in the second erosion stage. The progression of EGE selectively deprived the soil of fine particles associated with available nutrients resulting in the key soil parameters by stage 3 being SOM, AGG, MWD which contributed to increased resistance against further erosion. As a whole, soil texture and structure were the limiting factors for SQI in the first erosion stage, then soil nutrients became the limiting factors in the second stage, and SOM and soil structure became the dominant contributors to SQI in the third erosion stage.

4. Discussion

Soil erosion is a major threat to soil quality degradation (Lal, 1998). Soil erosion could cause significant degradation of soil properties such as nutrient availability, texture, structure, and water holding capacity. Weesies et al. (1994) found that slight to

Table 5
Critical values and turning points for the metrics used in the model.

Property[a]	SOM (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})	AN (mg kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})	CEC (cmol kg^{-1})	Aggregate (g kg^{-1})	MMD (mm)	K value
Critical value	7.62	0.45	0.64	40.00	5.72	79.00	4.93	507.8	0.82	0.02

Critical[b]	BD (g/cm^3)	Porosity (%)	Clay (%)	Silt (%)	Sand (%)	SSA (cm^2/g)	pH
a_1	1.0	45	5.3	46.9	24.7	280	8.5
a_2	1.3	60	12.6	63.1	39.5	500	8.9
b_1	1.1	50	10	50	25	350	8.6
b_2	1.2	55	12	60	35	450	8.8

[a] SOM: soil organic matter; TN: total nitrogen; TP: total phosphorus; AN: available nitrogen; AP: available phosphorus; AK: available potassium; CEC: cation exchange capacity; MWD: mean weight diameter; K: erodibility value; BD: bulk density; SSA: specific surface area.

[b] a_1 and a_2 are the lower and upper limits; b_1 and b_2 are the appropriate limits for each parameter.

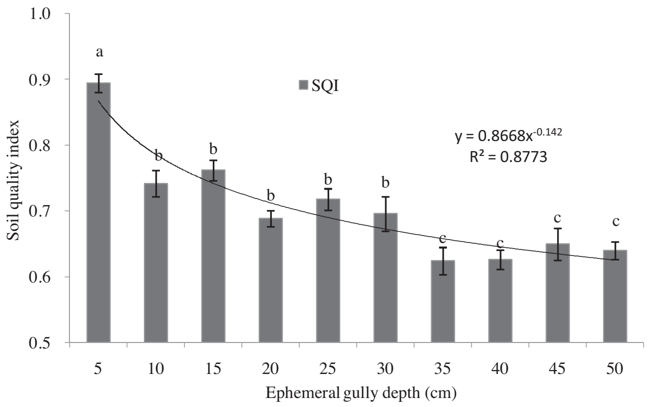


Fig. 4. Soil quality index (SQI) as a function of the ephemeral gully depth. Different letter indicate differences significant at 0.05 level.

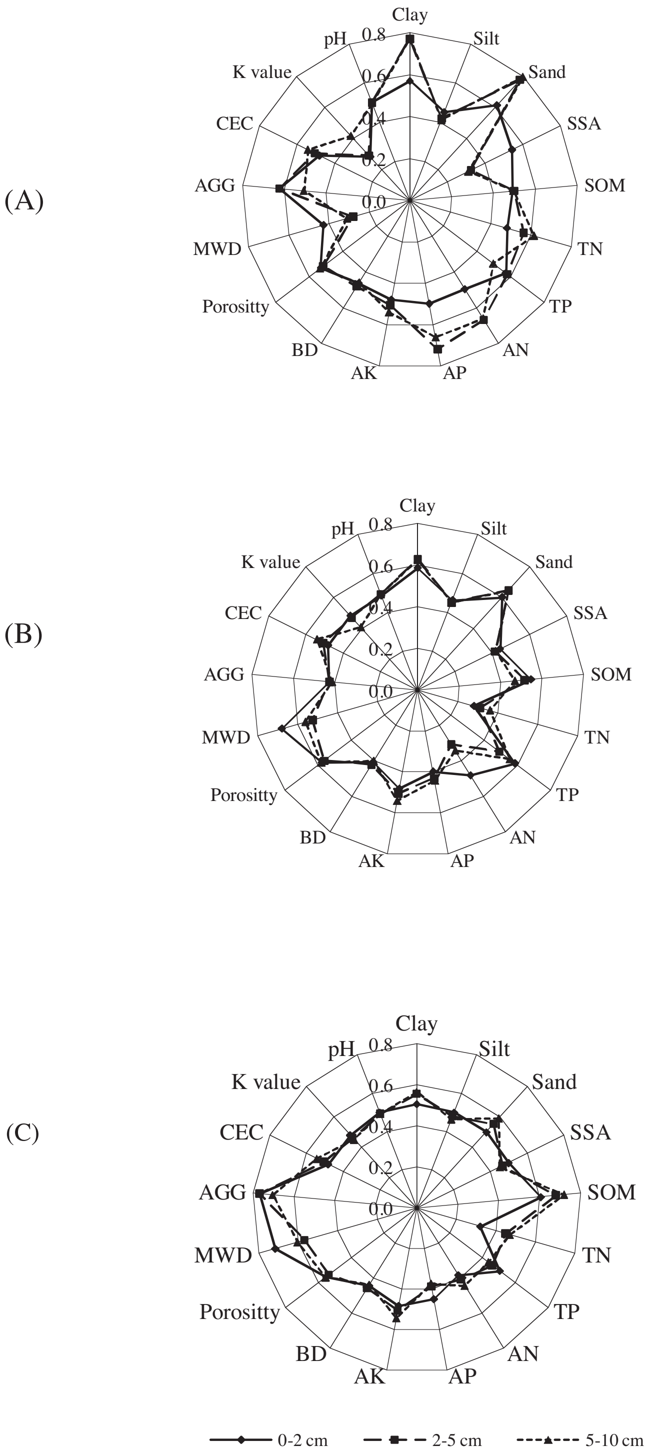


Fig. 5. Radar plots of scores in soil properties in the different erosion phases. (A) Erosion stage 1, (B) erosion stage 2 and (C) erosion stage 3; SOM: soil organic matter; TN: total nitrogen; TP: total phosphorus; AN: available nitrogen; AP: available phosphorus; AK: available potassium; AGG: aggregation; MWD: mean weight diameter; *K* value: erodibility coefficient; CEC: cation exchange capacity; BD: bulk density; SSA: specific surface area.

severe erosion could cause 16–39% decrease in SOM, 29–38% decrease in total phosphorus and 11–53% increase in clay content in three types of soils in Indiana. Fahnestock et al. (1995) reported that erosion-induced changes in soil quality of a Miamian soil in central Ohio was dramatic with 67–72% decrease in SOM, 27–30% decrease in water stable aggregates, and 20–23% increase in bulk density. Actually the effects of soil erosion on soil properties depend on soil types, soil fertility, soil and residue management, and degree of erosion among other factors (Lal, 1998). Despite the numerous publications on the effects of erosion on soil quality and productivity, limited research has been reported on soil degradation by EGE, although EGE-induced soil and nutrient loss is a worldwide matter of concern for land degradation in cultivated sloped lands.

To bridge the knowledge gap, a paired sampling method was employed to reveal the effects of EGE on soil quality. The design of the sampling could reflect the on-site effects and soil erosion–deposition impacts of EGE compared to inter-gully areas. Comparing depth incremented samples at the bottom of a gully to those outside the gully as if they were the same depth was considered a valid approach to determine the impact of EGE due to the fact that EGs by definition are ones that form, are subsequently filled-in by tillage, and formed again in the same place. Thus, the soil outside the gully has been eroded by sheet and rill erosion combined with tillage erosion (i.e., filling-in of the gully). In addition, the material in the gully may be filled-in material or natural soil depending upon the stage of development. Thus, to compare the gully properties to true inter-gully soil one would have to sample far enough away from the gully to have not been affected by these erosion processes. For this reason it was important to take samples far away from the gully edge. Research experience in black soils region of northeast China found that even samples taken 10's of meters away were still affected by the gullies (Liu et al., 2013). We took inter-gully samples about 10–15 meters away from the gullies where the micro-topography consisted of ridges along the slopes. Despite this result, the differences we observed were conservative measures of the effect of the gullies because essentially the whole area was affected by the gullies to some degree. Samples taken further away or at the earliest periods of agriculture in the region would likely show even larger differences as the inter-gully areas would be less affected by the filling-in process. The magnitude of those differences should depend upon the stage of development. Gullies in early stage would be affected by the proximity to the gully as those in later stages.

Our results demonstrated that EGE induced serious degradation of soil. The response of soil quality to EGE showed differences that were dependent upon the stage of erosion. The reduction in SQI was 10.6%, 27.7% and 36.6%, respectively, compared with the inter-gully area. In addition, the SQI decreased significantly as the depth of EGE progressed from surface soil to 10 cm and then to depths >30 cm. Generally, cultivated soil profiles consist of multiple layers including natural soil horizons and those imposed by tillage and erosion (e.g., surface crust, tillage layer, or sediment deposition layer). For the loess soil on the sloping cropland in the hilly Loess Plateau, these layers tend to be about 0–10 cm, 10–30 cm and >30 cm deep for topsoil, subsoil and parent material, respectively. When EGE occurred within the tillage layer (0–10 cm), part of the fertile soil in the tillage layer was lost with a reasonable degradation of soil quality of 10.6%. When EGE progressed to the 10–30 cm deep gully stage, soil quality decreased dramatically by 27.7% (compared with the inter-gully area) accompanied with the loss of the tillage layer. As the EGE continued to occur, soil quality decreased further by 36.6% (compared with the inter-gully area). In addition, this result suggested that soil physicochemical degradation is a process, which is closely related to the soil erosion stages and influenced by the vertical soil nutrient distribution. Soil quality degradation by EGE was the result of fertile surface soil losses as well as the dilution effects caused by infertile soil in deeper layers of the ephemeral gullies. This study provides fundamental knowledge for practical land management, such as prompt control of convergent flow into gullies during the early-stage EGE before it progresses further. Nevertheless, more studies on other soil types and soil biological properties are needed to validate this idea.

The specific response of soil physicochemical properties to EGE was different among the erosion stages and soil properties. No significant change in soil bulk density, water stable aggregate and its MWD was found in the first stage, however, with the development of EGE to second and third stages, bulk density increased and aggregate stability decreased significantly (Table 3). Soil clay content and SSA increased in the first erosion stage, which might be the result of sediment deposition as well as clay translocation from the upper soil. The decrease of clay and increase of sand content in the second and third erosion stages of EGE reflected that soil textural composition became coarser as the EGE progressed. Soil erodibility (K value, Table 3) increased significantly by 12.4–29.0% with a higher increase in the first erosion stage, which showed a comprehensive response of SOM and clay content to EGE. SOM and soil nutrients decreased obviously in the second and third erosion stages of EGE but increased in some cases in the first erosion stages as a result of sediment deposition. Mean degradation of SOM, AN, AP and AK after EGE was 4.0–6.9%, whereas the mean change of bulk density, aggregate, MWD, and K value was 6.1–14.2% (Tables 3 and 4). Comparatively, soil physical properties showed a greater change after EGE than soil nutrients. Moreover, radar plots of scores in soil properties (Fig. 5) revealed soil physical properties (erodibility, soil texture and structure) to be the limiting factors of soil quality in the first erosion stage, whereas soil nutrients were the limiting factors in the later erosion stages. This result indicated that the soil physical properties were more sensitive to erosion and more attention should be paid to the protection of these physical properties especially from the point of view that soil nutrients are easier to increase through chemical fertilizer application.

Several factors, including high variability of soil disturbance by human activity, high uncertainty regarding terrain attributes, soil nutrient removal and loss processes, and indirect, elusory relationship of EGE and crop yield are reasons for the slow advancement of EGE research (Chaplot et al., 2005; Chaplot, 2013). Perhaps that is why Knapen et al. (2007) reported in a review article that more than 90% of the papers on soil erosion do not directly address EGE, despite estimates that gullies constitute 10–94% of total erosion. In a similar fashion, the majority of research attributes soil degradation to rill or inter-rill erosion while largely ignoring the role of EGE processes, which in many cases are the dominant occurrences of erosion in extensively cultivated sloped land. This lack of information is partially because the development of EGE removes the evidence of their origin (Valentin et al., 2005) and, more importantly, because of the indirect and limited information on the effects of EGE on crop yield available to local farmers and policy-makers. As a result, most catchment-scale hydrology and soil erosion models lack adequate tools to address the initiation, development and subsequent effects of EGE on soil quality and productivity (Souchère et al., 2003; Poesen et al., 2003). The approach of this study in which field ground-truth survey of EGs is combined with laboratory analysis of samples in the gully and outside the gully demonstrated the significance of soil degradation caused by EGE. Our results regarding the three-step progression of soil quality degradation by EGE provides a reference for quantifying the impact of EGE on soil quality in other regions.

5. Conclusions

EGE caused a significant degradation of soil quality on the sloping crop land in the Loess Plateau of China. The degradation was a developing process which was closely related to the soil erosion stages and was influenced by the vertical soil nutrient distribution at soil profile scales. The response of soil quality to EGE showed a three-step process with two critical points of EGE depth of 10 cm and 30 cm where the SQI decreased significantly. The descent of SQI was 10.6%, 27.7% and 36.6%, respectively, compared with the inter-gully areas as the depth of the EGE increased from surface soil to 10 cm and then to a depth of >30 cm in the research region.

Comparatively, soil physical properties were more susceptible and fragile to EGE than soil nutrients. The soil physically-dominated degradation occurred during the first erosion stage (<10 cm gullies), with the key factors being K value, silt content, SSA and MWD, whereas further soil degradation was caused by the loss of available nutrients in the subsequent erosion stages. More attention should be paid to the protection of physical properties especially from the point of view that soil nutrients are easier to be remediated through chemical fertilizer application. These research results could provide a reference for quantifying the impact of EGE on soil quality degradation in other regions, as well as guidelines for practical land management, such as prompt control of convergent flow into gullies during the early-stages of EGE before the next erosion stage occurred. Nevertheless, more studies on other soil types and soil biological properties are needed to enrich the knowledge on the response of soil quality to EGE.

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