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Effects of Vegetation Cover and Rainfall Intensity on Sediment-Bound Nutrient Loss, Size Composition and Volume Fractal Dimension of Sediment Particles*1

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ABSTRACT

Vegetation and rainfall are two important factors affecting soil erosion and thus resulting in nutrient loss in the Chinese Loess Plateau. A field experiment was conducted to investigate the effects of rainfall intensities (60, 100 and 140 mm h^{-1}) and vegetation (*Caragana korshinskii*) coverages (0%, 30% and 80%) on soil loss, nutrient loss, and the composition and volume fractal dimension of eroded sediment particles under simulated rainfall conditions. The results showed that vegetation cover, rainfall intensity and their interaction all had significant effects on sediment transport and the sediment-bound nutrient loss. Higher rainfall intensity and lower coverage led to higher sediment and nutrient losses. Positive linear relationships were observed between soil loss and nutrient loss. The treatments showed more significant effects on the enrichment ratio (ER) of nitrogen (ER_N) than organic matter (ER_{OM}) and phosphorus (ER_P). Compared with the original surface soil, the eroded sediment contained more fine particles. Under the same coverage, the clay content significantly decreased with increasing rainfall intensity. The ER of sediment-bound nutrients was positively correlated with that of clay, suggesting that the clay fraction was preferentially eroded and soil nutrients were mainly adsorbed onto or contained within this fraction. There were increments in the fractal dimension of the sediment particles compared to that of the original surface soil. Moreover, the fractal dimension was positively correlated with clay, silt, and sediment-bound OM, N, and P contents, whereas it was negatively correlated with sand content. This study demonstrated that fractal dimension analysis can be used to characterize differences in particle-size distribution and nutrient loss associated with soil erosion.

Key Words: fractal features, Loess Plateau, particle-size distribution, runoff nutrients, simulated rainfall

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INTRODUCTION

Soil erosion has become a global environmental problem of growing concern. It not only causes on-site loss of topsoil and reduces the productivity of cropland, but it can also cause major off-site environmental effects such as water pollution and eutrophication (He *et al.*, 2003; Zheng *et al.*, 2005). This is especially true on the Loess Plateau of China.

Many factors affect soil erosion, such as rainfall, topography, land use or vegetation cover, and anthropogenic factors, among which rainfall is the most important and also the most dynamic factor with rainfall intensity playing a particularly prominent role (García-Rodeja and Gil-Sotres, 1997). Kang *et al.* (1999) and Zhang (2001) reported that rainfall intensity, especially in short-duration rainstorms, was the key factor causing soil erosion and nutrient loss in the Chinese Loess Plateau. Vegetation cover is one of the main measures of soil and water conservation and ecological improve-

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ment (Yu *et al.*, 1997; Li *et al.*, 2009). During the last two decades, numerous studies have been conducted to examine the fluxes of runoff, sediment yield and the sediment-bound nutrient loss in small plots (Schlesinger *et al.*, 2000) or in small watersheds (Correll *et al.*, 1999; Girmay *et al.*, 2009). Field or indoor simulated rainfall experiments under different vegetation coverages (Zhang *et al.*, 2000; Pan and Shangguan, 2006) or different rainfall intensities (Zhang *et al.*, 2004; Wu *et al.*, 2007) have also been extensively performed. However, both vegetation coverage and rainfall intensity have often been studied in an isolated way, and their interaction effects are seldom mentioned.

Fractal theory has been increasingly used in soil science since its first publication (Mandelbrot, 1979). It has been possible to characterize particle-size distribution (PSD), pore-size distribution, aggregate-size distribution and soil-water-retention curves using fractal theory (Tyler and Wheatcraft, 1992; Lipiec *et al.*, 1998; Millán and Orellana, 2001; Huang *et al.*, 2006), and the results have shown that fractal theory is a useful tool in quantifying soil structure, soil erodibility, and soil permeability (Rieu and Sposito, 1991; Perfect and Kay, 1995; Huang and Zhan, 2002). A mass fractal model was proposed based on the hypothesis that soil particles of different sizes have the same density (Tyler and Wheatcraft, 1992). Due to this unreasonable hypothesis, it was later challenged by some scholars (Martín and Montero, 2002). In recent years, laser diffraction (LD) techniques have been rapidly developed. Many studies have shown that LD can achieve precise estimations of volume information in PSDs (Dur *et al.*, 2004; Pieri *et al.*, 2006). The volume fractal model of soil particles was developed on this basis (Wang *et al.*, 2005). This model does not require the hypothesis of “density resemblances”, so it is more realistic than the mass fractal model.

Fine soil particles are readily transported by runoff (McIsaac *et al.*, 1991). Soil erosion leads to the enrichment of fine particles in sediments (Catroux and Schnitzer, 1987), causing changes in sediment PSD. Su *et al.* (2004) reported that the fractal dimension of a PSD is a useful parameter for monitoring soil degradation and estimating the degree of soil desertification. Although many findings with respect to fractal dimensions of PSDs have been obtained, little attention has been paid to the fractal features of sediment generated by soil erosion.

The objective of this study was to explore the effects of vegetation cover and rainfall intensity on sediment yield, sediment-bound nutrient loss, and the volume fractal dimensions of sediment PSDs and their relationships. Additionally, the possibility that the fractal dimension of a PSD can be used as an integrating index for quantifying soil degradation due to soil erosion was evaluated.

MATERIALS AND METHODS

Site description

This research was conducted on field plots at the Ansai Research Station of Soil and Water Conservation, Chinese Academy of Sciences from June to September, 2008. The experimental station is located 35 km north of Yan’an City in northern Shaanxi Province, China (108° 51′–109° 26′ E, 36° 30′–37° 39′ N; 1 060 m a.s.l.). This area has a semiarid, continental monsoon climate with a mean annual precipitation of 530 mm that occurs mostly between June and September during the wet summer season. Summer rains are characterized by high intensity and short duration, which can produce large volumes of runoff. The mean annual temperature is 8.8 °C and monthly mean temperatures range from −7.2 °C in January to 22.8 °C in July. The soil is classified as a typical loessial soil, representing the most common soil type on the Loess Plateau. The soil in this region is highly susceptible to erosion; the erosion rate is over 10 000 t km^{-2} year^{-1}. A variety of soil properties were measured for each plot, and the average values are listed in Table I.

Rainfall simulator setup

Four side-sprinkle simulators manufactured by the Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources were used in this experiment. Rainfall height was 5.5 m, and the simulated storm, with uniformity above 85%, was similar to natural rainfall in raindrop distribution, raindrop size and terminal velocity. Rainfall intensities were precisely adjusted through the aperture of nozzle and water pressure.

Plot characteristics, experimental design and sampling

Each runoff plot was 8.5 m long (downslope) and 2.5 m wide with the same gradient of 15°. Runoff flowed into a rectangular cement trough at the bottom of each plot and was then directed to the outlet point and collected. On the Loess Plateau, rainfall is

TABLE I

Selected physicochemical properties of the surface soil (0–5 cm) in the test plots

Nutrient content			Bulk density	Porosity	Particle-size distribution			Fractal dimension
Organic matter	Nitrogen	Phosphorus			Clay	Silt	Sand	
	$g\ kg^{-1}$		$g\ cm^{-3}$	%		$g\ kg^{-1}$		
7.95±2.87[a)]	0.54±0.17	0.61±0.012	1.28±0.025	51.7±0.01	61.4±5.2	674.7±49.6	263.9±52.0	2.534±0.015

[a)]Means ± standard deviations.

concentrated in the summer, typically in high-intensity and short-duration rainstorms, which are primarily responsible for soil erosion. Therefore, we designed three high rainfall intensities in this study: 60, 100, and 140 mm h^{-1}. Additionally, we selected three runoff plots with different vegetation (*Caragana korshinskii*) coverages: 0% (bare plot), 30%, and 80%. Vegetation coverage was measured using vertical and aerial photographs taken with a high-resolution digital camera and empirical estimation by visual inspection.

The experiment was conducted on rainless, windless days (mostly in the morning) to minimize the influence of weather. Each rainfall simulation test lasted for 60 min. Before each rainfall test, surface soil samples (0–5 cm) were collected using a soil auger (20 mm in diameter). A total of five samples were taken in an "S" pattern along the slope and analyzed to determine soil water content using an oven-drying method at 105 °C. Another three soil cores distributed up-, mid- and downslope were taken and thoroughly mixed to obtain a single, composite sample for each plot. The composite samples were then air dried and sieved (2 mm) to determine the nutrient contents and PSDs. Cutting rings (100 cm^3) were also used to take soil samples for bulk density measurements.

The time to initial runoff was recorded during each rainfall; plastic runoff-collection buckets at the plot outlet were changed periodically, and the times were noted. After each rainfall, the amount of runoff in each bucket was weighed on a balance. The buckets were then allowed to stand so that the suspended sediment could settle out. Runoff samples were collected from the supernatant using polyethylene bottles and preserved in a refrigerator at 4 °C until the nutrient analysis could be conducted. The supernatant remaining in the bucket was discarded, and the sediment was air dried, weighed, and sampled. Soil samples were transported in plastic bags to the laboratory for chemical analysis and PSD determination. Rainfall interval was determined according to the initial condition of the plot, particularly the initial soil moisture. It should be several days until the soil water content in each plot returned to the same level as before the first simulated rainfall event and then repeated the process. During the experiment, the soil moisture before each rainfall test was within the dry range of 6%–11%, which was assumed to be uniform. All treatments were conducted in three replicates.

Measurements

In the laboratory, the sediment samples were analyzed to determine soil organic matter (OM) (potassium dichromate oxidation method), total N (semimicro Kjeldahl method) and total P (colorimetric analysis) (Liu, 1996). Textural analysis (USDA System) was performed using a laser-diffraction method (Mastersizer 2000, Malvern, UK). Similarly, soil samples from each runoff plot collected before each rainfall-simulation test were analyzed for the same nutrients following the same procedures described above to determine the enrichment ratio (ER) of the sediment. The ER is defined as the concentration of a soil constituent in an eroded sediment to that in the parent soil from which the sediment originated. The volume fractal dimensions (D) of soil PSDs were determined using the following expression (Wang *et al.*, 2005):

$$\frac{V(r < R_i)}{V_{\mathrm{T}}} = \left(\frac{R_i}{\lambda_v}\right)^{3-D} \tag{1}$$

where $V(r < R_i)$ is the cumulative volume of particles of ith size r less than R_i, V_{T} is the total volume, R_i is the particle diameter (mm) of the ith size class, and λ_v is the diameter of the largest particle.

Taking the logarithm of both sides in Eq. 1, we performed linear regression analysis between $\log(R_i/\lambda_v)$ (as the independent variable) and $\log[V(r < R_i)/V_{\mathrm{T}}]$ (as the dependent variable). D was determined by subtracting the slope of the above derived regression equation from the number 3. According to USDA taxonomy, soil particles were classified into seven grades: 0–0.002, 0.002–0.05, 0.05–0.1, 0.1–0.25, 0.25–0.5, 0.5–1, and 1–2 mm.

Data analysis

An analysis of variance (ANOVA) or general linear model, univariate, was used to detect the treatment effects on measured variables. If significant treatment effects were revealed ($P < 0.05$), the least significant difference (LSD) was used to test comparisons among treatment means. Regression analyses were performed to verify the interactions between nutrient loss and sediment yield and between the ER of nutrients and the ER of different sizes particles. Statistical procedures were performed with the SPSS 13.0 for Windows software package.

RESULTS AND DISCUSSION

Effects of vegetation cover and rainfall intensity on sediment yield and nutrient loss

Mean sediment yield ranged from 76 to 472 g m^{-2} (Fig. 1). The ANOVA showed that vegetation cover, rainfall intensity and their interaction all had significant effects on sediment yield. Compared with the bare plots, sediment yields in the vegetation-covered plots decreased by 30%–80%, which may be ascribed to rainfall interception and runoff retardation by plant shoots and slope stabilization by plant roots. Average sediment yields for simulated rainfalls of 100 and 140 mm h^{-1} were approximately 2 and 2.5 times the value for 60 mm h^{-1}, respectively, due to the higher rainfall erosivity produced. The results are in agreement with many studies pertaining to the impacts of vegetation (Braud *et al.*, 2001; Casermeiro *et al.*, 2004; Marques *et al.*, 2007) or rainfall (Kleinman *et al.*, 2006; Shigaki *et al.*, 2007) on soil erosion.

Along with soil erosion and water loss, nutrients bound with runoff and sediment were also transported. The total nutrient losses in each simulation test were calculated from the sediment amounts and the concentrations of OM, N, and P (Fig. 1). The patterns of the sediment-bound nutrient loads were similar to those of the sediment loads. OM, N, and P losses decreased with increasing *Caragana korshinskii* coverage and increased with increasing rainfall intensity. Average OM loss ranged from 0.7 to 3.5 g m^{-2}, N loss from 65 to 425 mg m^{-2}, and P loss from 55 to 303 mg m^{-2}. These findings are similar to those obtained by prior researchers (Zobisch *et al.*, 1995; Owino *et al.*, 2006), who reported that the reduction in nutrient loss was not the result of changes in nutrient concentration in the runoff but rather depended on runoff volume.

The analyzed nutrient components, *i.e.*, OM, N, P, and K, are basic constituents of soil media undergoing erosion due to the action of rainfall and runoff. The amount of nutrient loss is, therefore, directly proportional to the amount of soil loss (Kothyari *et al.*, 2004; Ramos and Martínez-Casasnovas, 2006). The data analysis indicated a strong ($P < 0.05$) linear relationship between soil loss and sediment-bound nutrient loss (Fig. 2). This relationship displayed the same trend for soil and nutrient load and explained how higher levels of soil loss tended to lead to elevated levels of nutrient loss.

Both vegetation cover and rainfall intensity had significant effects on the ER of N (ER_N) (Table II). Low rainfall intensity and dense plant cover contributed to higher ER_N. For ERs of OM (ER_{OM}) and P (ER_P), the effects were not as pronounced (Fig. 3). The mean values of the ERs were in the following order: ER_N (1.8) > ER_{OM} (1.3) > ER_P (1.1). One possible

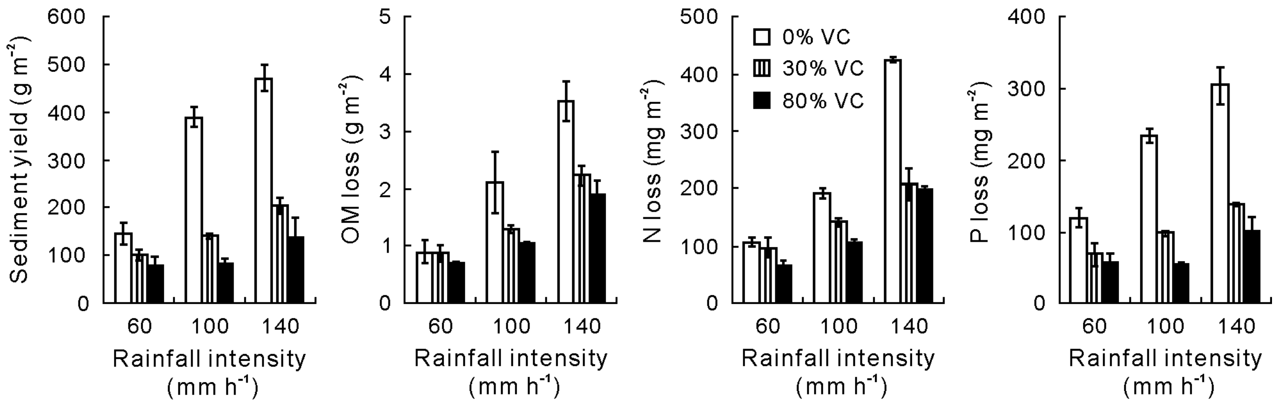

Fig. 1 Sediment yields and the bound organic matter (OM), nitrogen (N) and phosphorus (P) losses under different rainfall intensities and vegetation coverages (VC).

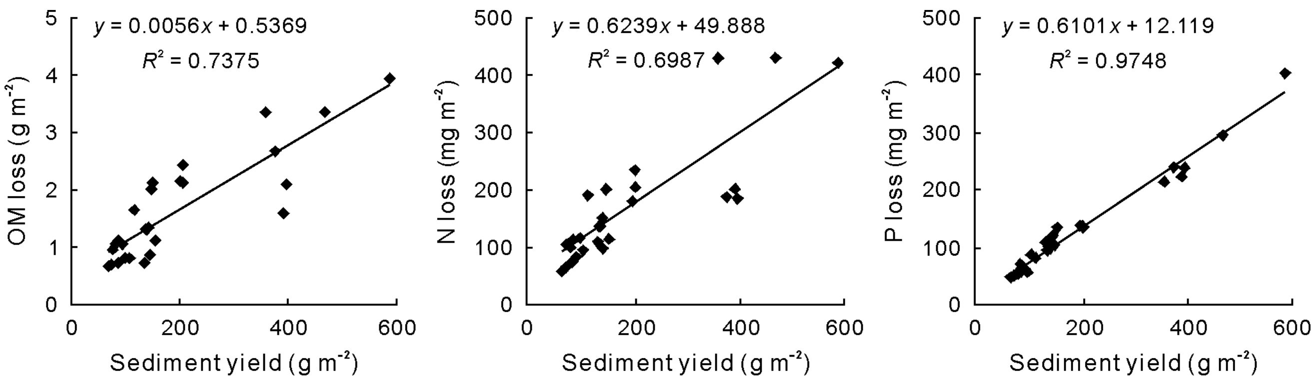

Fig. 2 Relationships between organic matter (OM), nitrogen (N), and phosphorus (P) losses and sediment yield.

TABLE II

Analysis of variance for the effects of rainfall intensity, vegetation coverage and their interaction on sediment yield, nutrient loss, enrichment ratio (ER), particle-size distributions and fractal dimension

Item	Vegetation coverage (VC)	Rainfall intensity (RI)	Interaction (VC × RI)
Sediment yield	< 0.001**	< 0.001**	< 0.001**
Organic matter (OM) loss	< 0.001**	< 0.001**	0.001**
Nitrogen (N) loss	< 0.001**	< 0.001**	< 0.001**
Phosphorus (P) loss	< 0.001**	< 0.001**	0.015*
ER_{OM}	0.008**	0.153	0.556
ER_N	0.005**	0.001**	0.001**
ER_P	0.165	0.012*	0.014*
Clay	0.068	0.036*	0.963
Silt	0.361	0.324	0.279
Sand	0.054	0.131	0.191
Fractal dimension	0.052	0.074	0.988

*, **Significant at $P = 0.05$ and $P = 0.01$ levels, respectively.

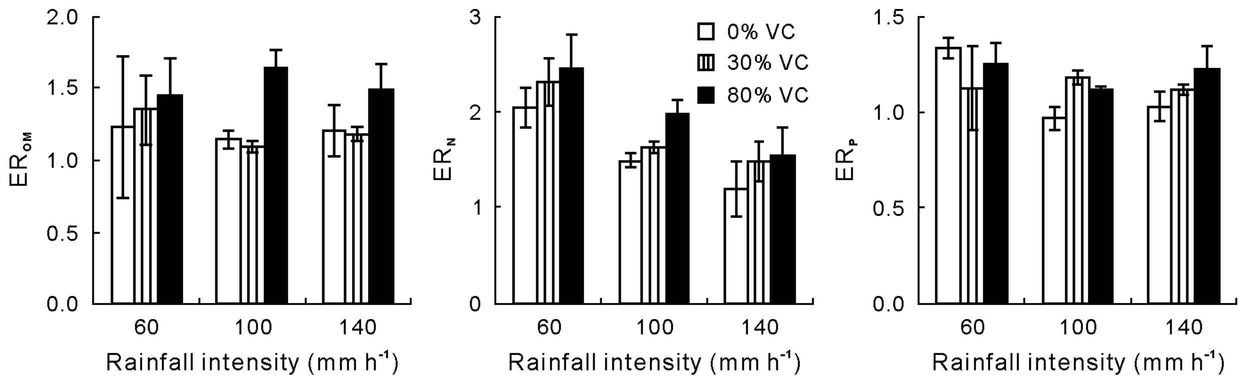

Fig. 3 Enrichment ratios (ERs) of sediment organic matter (OM), nitrogen (N), and phosphorus (P) under different rainfall intensities and vegetation coverages (VC).

reason for the lower ER_P is that sediment from high-intensity rainfall events tends to contain larger, less P-enriched particles (Panuska and Karthikeyan, 2010). Another explanation offered by Flanagan and Nearing (2000) suggests that when conditions are appropriate for selective deposition of coarser sediment particles, lower ER_P can occur in soils having large fractions of primary silt.

Effects of vegetation cover and rainfall intensity on compositions and fractal dimensions of sediment particles

To date, it has been widely accepted that smaller and less dense particles are generally preferentially eroded over larger and denser ones. In the current study, the eroded sediment contained higher clay and silt fractions compared with the original surface soil, with an increase in clay content by 5%–8% and silt content by 3%–10% (Table III). Less fine sand (0.05–1 mm) was observed in the sediments, decreased by 8%–18%. Under the same cover conditions, the clay content significantly ($P < 0.05$) decreased with increasing rainfall intensity. Moreover, the clay fraction in the sediment had an ER of 1.3–2.9, followed by the silt fraction, with an ER ranging from 1.0 to 1.3. The sand fraction had an ER value of < 0.8. This implies that clay and silt fractions were more represented in the eroded sediments than in the original surface soil, in accordance with the results of Basic *et al.* (2002). However, there is some disagreement in field on the dominant eroded particles. Rhoton *et al.* (1979) suggested that the clay fraction (< 2 μm) was more readily eroded, while Stone and Walling (1996) concluded that clay (< 2 μm) and silt-sized material (2–63 μm) were eroded preferentially and that the majority of the sand-sized material was not mobilized. Ghadiri and Rose (1991) found that the proportion of large aggregates in the eroded sediment was less than that in the original soil, and that the intermediate size fractions remained unchanged. This discrepancy may be attributable to differing soil textures and properties, climate conditions, topography, and experimental treatments in the various studies.

Linear relationships were observed between the ER of clay and ER of sediment-bound nutrients (Fig. 4). However, no clear relationship was noted between the ER of silt and ER of the nutrients (Fig. 4), thus indicating that nutrients were mainly adsorbed onto or contained within the clay fraction. Similar re-

TABLE III

Compositions and fractal dimensions of sediment particles under different vegetation coverages and rainfall intensities

Vegetation cover	Rainfall intensity	Particle size (mm)						Fractal dimension	$R^{2a)}$
		0–0.002	0.002–0.05	0.05–0.1	0.1–0.25	0.25–0.5	0.5–1		
%	mm h^{-1}	g kg^{-1}							
0	60	119.2c$^{b)}$	700.8a	126.9a	29.5a	7.6c	16.0b	2.647a	0.821a
	100	103.1b	740.9b	126.6a	24.1a	4.1b	1.2a	2.626a	0.808a
	140	93.8a	733.8b	140.4b	27.0a	1.5a	3.4a	2.610a	0.811a
30	60	139.6c	773.4b	72.5a	14.5a	0.0a	0.0a	2.679a	0.792a
	100	116.8b	720.6a	99.2b	32.0b	12.1b	19.3b	2.651a	0.817a
	140	112.4a	759.4b	92.2b	22.9a	12.6b	0.6a	2.644a	0.804a
80	60	150.2c	748.5b	90.8a	10.4a	0.1a	0.0a	2.689a	0.797a
	100	130.8b	712.0a	100.6b	28.8b	6.2b	18.2b	2.672a	0.816a
	140	111.7a	762.5b	80.9a	24.3b	4.3b	16.1b	2.643a	0.803a

a)Coefficient of determination.
b)Means followed by the same letter within each column for the same vegetation coverage are not significantly different at $P < 0.05$.

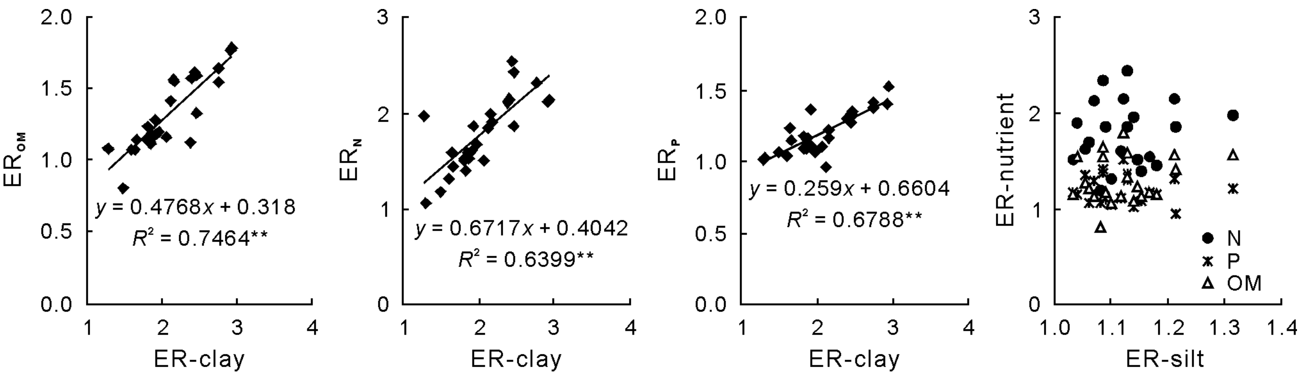

Fig. 4 Correlations between enrichment ratios (ERs) of clay (0–2 μm) and silt (2–50 μm) and ERs of sediment-bound organic matter (OM), nitrogen (N), and phosphorus (P).

sults have also been reported by other researchers (Quinton *et al.*, 2001; Sharpley and Kleinman 2003; Jacinthe *et al.*, 2004) in different landscapes and under contrasting climate conditions.

As shown in Table III, the mean values of D ranged from 2.610 to 2.689. The coefficients of determination (R^2) of the linear regressions were high ($P < 0.01$), ranging from 0.792 to 0.821, indicating the goodness of fit for the volume-based fractal model. Similar to the changes in clay content, the mean values of D increased by 0.1166 compared with the original soil and were greater in higher vegetation coverage and lower rainfall intensity (Table III). The regression analysis showed that D was positively correlated with the clay and silt contents and negatively correlated with the sand content (Table IV); logarithmic functions best fitted their relationships ($P < 0.05$). Furthermore, D had a positive correlation with the concentrations of sediment-bound nutrients following a linear trend ($P < 0.05$). Thus, based on the regression analysis, soils with higher silt and clay contents and lower sand contents have higher D values. Our findings are in line with Wang *et al.* (2005) but in disagreement with Su *et al.* (2004) and Liu *et al.* (2009), who found linear relationships between fractal dimension and soil PSD, as well as Liu *et al.* (2002) who reported power-law relationships between fractal dimension and soil features.

TABLE IV

Correlation analysis between volume fractal dimension of sediment particles (y) and sediment characteristics (x)

x	Regression function	R^2
Clay	$y = 0.1652\ln x + 2.2444$	0.9975**
Silt	$y = 0.3818\ln x + 0.9924$	0.1931*
Sand	$y = 0.0573\ln x + 2.8002$	0.2153*
Organic matter	$y = 0.0091x + 2.5665$	0.4736*
Nitrogen	$y = 0.0897x + 2.5637$	0.6905**
Phosphorus	$y = 0.3086x + 2.4362$	0.7551**

*, **Significant at $P = 0.05$ and $P = 0.01$ levels, respectively.

As an additional parameter to describe soil properties in several aspects, the fractal dimension of PSD reflects selective soil erosion based on the distribution of eroded sediment particles. In other words, a smaller sediment particle diameter (*i.e.*, clay, silt, and organic matter) leads to a coarser original surface soil after erosion occurs, which corresponds to higher D values of sediment PSD. In addition, the higher degree of aggregation among finer soil particles results in an increase of nutrient adsorption and transfer, thereby reducing soil quality and increasing the possibility of eutrophication in the receiving water body. Based on the results of this study, the fractal dimension is applicable to characterizing land degradation and nutrient loss induced by slope soil erosion through modeling the fractal behavior of PSDs.

CONCLUSIONS

The roles of rainfall and vegetation cover in soil erosion and nutrient loss were studied in field plots using rainfall simulators. The results indicated that plant cover was an effective method of preventing soil and nutrient loss. The sediment production and sediment-bound nutrient export increased with increasing rainfall intensity between 60 and 140 mm h^{-1} and decreased with increasing vegetation coverage. A high correlation between sediment and nutrient loss indicated that nutrient loss was driven by soil loss. The analysis of the sediment PSD revealed that the dominant particle-size fractions in the eroded material were clay and silt (< 50 μm). The ERs for organic matter, N, and P were positively correlated with the ER of clay, indicating that large portions of these soil nutrients were selectively transported. The fractal dimension had a positive logarithmic correlation with clay content and positive linear correlations with the concentrations of sediment-bound nutrients, implying that fractal-dimension analysis of sediment PSD could offer a useful approach to quantifying and assessing the degree of soil degradation due to soil erosion.

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REFERENCES

Basic, F., Kisic, I., Nestroy, O., Mesic, M. and Butorac, A. 2002. Particle size distribution (texture) of eroded soil material. *J. Agron. Crop Sci.* **188**(5): 311–322.

Braud, I., Vich, A. I. J., Zuluaga, J., Fornero, L. and Pedrani, A. 2001. Vegetation influence on runoff and sediment yield in the Andes region: observation and modeling. *J. Hydrol.* **254**(1–4): 124–144.

Casermeiro, M. A., Molina, J. A., de la Cruz Caravaca, M. T., Hernando Costa, J., Hernando Massanet, M. I.

and Moreno, P. S. 2004. Influence of scrubs on runoff and sediment loss in soils of Mediterranean climate. *Catena*. **57**(1): 91–107.

Catroux, G. and Schnitzer, M. 1987. Chemical, spectroscopic, and biological characteristics of the organic matter in particle size fractions separated from an Aquoll. *Soil Sci. Soc. Am. J.* **51**(5): 1200–1207.

Correll, D. L., Jordan, T. E. and Weller, D. E. 1999. Precipitation effects on sediment and associated nutrient discharges from Rhode River watersheds. *J. Environ. Qual.* **28**(6): 1897–1907.

Dur, J. C., Elsass, F., Chaplain, V. and Tessier, D. 2004. The relationship between particle size distribution by laser granulometry and image analysis by transmission electron microscopy in a soil clay fraction. *Eur. J. Soil Sci.* **55**(2): 265–270.

Flanagan, D. C. and Nearing, M. A. 2000. Sediment particle sorting on hillslope profiles in the WEPP model. *T. ASAE.* **43**(3): 573–583.

García-Rodeja, I. and Gil-Sotres, F. 1997. Prediction of parameters describing phosphorus-desorption kinetics in soils of Galicia (northwest Spain). *J. Environ. Qual.* **26**(5): 1363–1369.

Ghadiri, H. and Rose, C. W. 1991. Sorbed chemical transport in overland flow: 1. A nutrient and pesticide enrichment mechanism. *J. Environ. Qual.* **20**(3): 628–633.

Girmay, G., Singh, B. R., Nyssen, J. and Borrosen, T. 2009. Runoff and sediment-associated nutrient losses under different land uses in Tigray, Northern Ethiopia. *J. Hydrol.* **376**(1–2): 70–80.

He, X., Li, Z., Hao, M., Tang, K. and Zheng, F. 2003. Down-scale analysis for water scarcity in response to soil-water conservation on Loess Plateau of China. *Agr. Ecosyst. Environ.* **94**(3): 355–361.

Huang, G. H. and Zhan, W. H. 2002. Fractal property of soil particle-size distribution and its application. *Acta Pedol. Sin.* (in Chinese). **39**(4): 490–497.

Huang, G. H., Zhang, R. D. and Huang, Q. Z. 2006. Modeling soil water retention curve with a fractal method. *Pedosphere.* **16**(2): 137–146.

Jacinthe, P. A., Lal, R., Owens, L. B. and Hothem, D. L. 2004. Transport of labile carbon in runoff as affected by land use and rainfall characteristics. *Soil Till. Res.* **77**(2): 111–123.

Kang, L. L., Zhu, X. Y., Wang, Y. Z., Wu, Q. and Wei, Y. C. 1999. Research on nutrient loss from a loessial soil under different rainfall intensities. *Acta Pedol. Sin.* (in Chinese). **36**(4): 536–543.

Kleinman, P. J. A., Srinivasan, M. S., Dell, C. J., Schmidt, J. P., Sharpley, A. N. and Bryant, R. B. 2006. Role of rainfall intensity and hydrology in nutrient transport *via* surface runoff. *J. Environ. Qual.* **35**(1): 1248–1259.

Kothyari, B. P., Verma, P. K., Joshi, B. K. and Kothyari, U. C. 2004. Rainfall-runoff-soil and nutrient loss relationships for plot size areas of Bhetagad watershed in Central Himalaya, India. *J. Hydrol.* **293**(1–4): 137–150.

Li, M., Yao, W. Y., Ding, W. F., Yang, J. F. and Chen, J. N. 2009. Effect of grass coverage on sediment yield in the hillslope-gully side erosion system. *J. Geogr. Sci.* **19**(3): 321–330

Lipiec, J., Hatano, R. and Slowinska-Jurkiewicz, A. 1998. The fractal dimension of pore distribution patterns in variously-compacted soil. *Soil Till. Res.* **47**(1–2): 61–66.

Liu, G. S. 1996. Soil Physical and Chemical Analysis and Profile Description (in Chinese). Chinese Standard Press, Beijing.

Liu, J. F., Hong, W. and Wu, C. Z. 2002. Fractal features of soil clusters under some precious hardwood stands in the central subtropical region, China. *Acta Ecol. Sin.* (in Chinese). **22**(2): 197–205.

Liu, X., Zhang, G. C., Heathman, G. C., Wang, Y. Q. and Huang, C. H. 2009. Fractal features of soil particle-size distribution as affected by plant communities in the forested region of Mountain Yimeng, China. *Geoderma.* **154**(1–2): 123–130.

Mandelbrot, B. B. 1979. The Fractal Geometry of Nature. W. H. Freeman and Company, San Francisco.

Marques, M. J., Bienes, R., Jiménez, L. and Pérez-Rodríguez, R. 2007. Effect of vegetal cover on runoff and soil erosion under light intensity events. Rainfall simulation over USLE plots. *Sci. Total Environ.* **378**(1–2): 161–165.

Martín, M. A. and Montero, E. 2002. Laser diffraction and multifractal analysis for the characterization of dry soil volume size distributions. *Soil Till. Res.* **64**(1–2): 113–123.

McIsaac, G. F., Hirschi, M. C. and Mitchell, J. K. 1991. Nitrogen and phosphorus in eroded sediment from corn and soybean tillage system. *J. Environ. Qual.* **20**(3): 663–670.

Millán, H. and Orellana, R. 2001. Mass fractal dimensions of soil aggregates from different depths of a compacted Vertisol. *Geoderma.* **101**(3–4): 65–76.

Owino, J. O., Owido, S. F. O. and Chemelil, M. C. 2006. Nutrients in runoff from a clay loam soil protected by narrow grass strips. *Soil Till. Res.* **88**(1–2): 116–122.

Pan, C. Z. and Shangguan, Z. P. 2006. Runoff hydraulic characteristics and sediment generation in sloped grassplots under simulated rainfall conditions. *J. Hydrol.* **331**(1–2): 178–185.

Panuska, J. C. and Karthikeyan, K. G. 2010. Phosphorus and organic matter enrichment in snowmelt and rainfall-runoff from three corn management systems. *Geoderma.* **154**(3–4): 253–260.

Perfect, E. and Kay, B. D. 1995. Applications of fractals in soil and tillage research: a review. *Soil Till. Res.* **36**(1–2): 1–20.

Pieri, L., Bittelli, M. and Pisa, P. R. 2006. Laser diffraction, transmission electron microscopy and image analysis to evaluate a bimodal Gaussian model for particle size distribution in soils. *Geoderma*. **135**: 118–132.

Quinton, J. N., Catt, J. A. and Hess, T. M. 2001. The selective removal of phosphorus from soil: is event size important? *J. Environ. Qual.* **30**(2): 538–545.

Ramos, M. C. and Martínez-Casasnovas, J. A. 2006. Nutrient losses by runoff in vineyards of the Mediterranean Alt Penedès region (NE Spain). *Agr. Ecosyst. Environ.* **113**(1–4): 356–363.

Rhoton, F. E., Smeck, N. E. and Wilding, L. P. 1979. Preferential clay mineral erosion from watersheds in the Maumee River basin. *J. Environ. Qual.* **8**(4): 547–550.

Rieu, M. and Sposito, G. 1991. Fractal fragmentation, soil porosity and soil water properties: II. Applications. *Soil Sci. Soc. Am. J.* **55**: 1239–1244.

Schlesinger, W. H., Ward, T. J. and Anderson, J. 2000. Nutrient losses in runoff from grassland and shrubland habitats in southern New Mexico: II. Field plots. *Biogeochemistry*. **49**: 69–86.

Sharpley, A. N. and Kleinman, P. 2003. Effect of rainfall simulator and plot scale on overland flow and phosphorus transport. *J. Environ. Qual.* **32**(6): 2172–2179.

Shigaki, F., Sharpley, A. N. and Prochnow, L. I. 2007. Rainfall intensity and phosphorus source effects on phosphorus transport in surface runoff from soil trays. *Sci. Total Environ.* **373**(1): 334–343.

Stone, P. M. and Walling, D. E. 1996. The particle-size selectivity of sediment mobilization from Devon hillslopes. *In* Anderson, M. G. and Brooks, S. M. (eds.) Advances in Hillslope Processes. Vol. 1. John Wiley and Sons, Chichester. pp. 507–527.

Su, Y. Z., Zhao, H. L., Zhao, W. Z. and Zhang, T. H. 2004. Fractal features of soil particle-size distribution and the implication for indicating desertification. *Geoderma*. **122**(1): 43–49.

Tyler, S. W. and Wheatcraft, S. W. 1992. Fractal scaling of soil particle-size distribution: analysis and limitations. *Soil Sci. Soc. Am. J.* **56**(2): 362–369.

Wang, G. L., Zhou, S. L. and Zhao, Q. G. 2005. Volume fractal dimension of soil particles and its application to land use. *Acta Pedol. Sin.* (in Chinese). **42**(4): 545–550.

Wu, X. Y., Zhang, L. P., Zhang, M. X., Ni, H. B. and Wang, H. 2007. Research on characteristics of nitrogen loss in sloping land under different rainfall intensities. *Acta Ecol. Sin.* (in Chinese). **27**(11): 4576–4582.

Yu, X. X., Bi, H. X., Zhu, J. Z. and Wu, B. 1997. Soil and water conservation by forest vegetation in loess area. *Acta Phytoecol. Sin.* (in Chinese). **21**(5): 433–440.

Zhang, X. C., Liu, G. B. and Fu, H. F. 2000. Soil nitrogen losses of catchment by water erosion as affected by vegetation coverage. *Environ. Sci.* (in Chinese). **21**(6): 16–19.

Zhang, Y. 2001. Research advance on soil erosion in loess hilly-gully region. *J. Soil Water Conserv.* (in Chinese). **15**(2): 121–128.

Zhang, Y. L., Zhang, X. C., Shao, M. A. and Li, S. Q. 2004. Impact of rainfall intensity on soil mineral nitrogen loss by runoff on loess slope. *T. CSAE* (in Chinese). **20**(3): 55–58.

Zheng, F. L., He, X. B., Gao, X. T., Zhang, C. E. and Tang, K. L. 2005. Effects of erosion patterns on nutrient loss following deforestation on the Loess Plateau of China. *Agr. Ecosyst. Environ.* **108**: 85–97.

Zobisch, M. A., Richter, C., Heiligtag, B. and Schlott, R. 1995. Nutrient losses from cropland in central highlands of Kenya due to surface runoff and soil erosion. *Soil Till. Res.* **33**(2): 109–116.