

Characteristics of Runoff Nutrient Loss and Particle Size Distribution of Eroded Sediment under Varied Rainfall Intensities

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Abstract. Soil erosion is a serious problem of worldwide concern. Rainfall intensity is an important factor affecting soil erosion and the resulting nutrients loss. Field experiments were conducted to investigate the effect of rainfall intensity (60, 100 and 140 mm/h) on runoff nutrients loss and sediment particles size distribution under simulated rainfall conditions. The results showed that rainfall intensity had a significant effect on runoff, sediment and the associated nutrients loss. In general, higher rainfall intensity led to higher runoff nutrients loss. Furthermore, the nutrients mostly lost through sediment instead of runoff water. Inorganic nitrogen loss was mainly due to runoff, primarily in the form of $\text{NO}_3\text{-N}$. Positive linear relationships existed between soil loss and nutrients loss. Rainfall intensity had more significant effects on enrichment ratio of nitrogen (ER_N) than that of organic matter (ER_OM) and phosphorus (ER_P). Compared with the original surface soil, the sediment contained more fine particles ($<20\mu\text{m}$). The clay content significantly decreased with increasing rainfall intensity ($p<0.05$). ER of sediment-bound nutrients was positively correlated with ER of particles smaller than $2\mu\text{m}$. This suggested that the clay fraction ($<2\mu\text{m}$) was preferentially eroded and soil nutrients were mainly adsorbed on or contained within this part of particles.

Introduction

Soil erosion is a serious eco-environmental problem of worldwide concern. It not only causes on-site loss of topsoil and reduces the land productivity, but also brings about major off-site environmental effects such as water body pollution and eutrophication [1, 2, 3]. This is especially true on the Loess Plateau of China.

Rainfall is the dynamic factor for soil erosion and is mainly shown in several aspects: precipitation, rainfall intensity, rainfall spatial and temporal distribution, rainfall energy, etc. Among which, rainfall intensity is the most important one [4, 5]. Kang [6] and Zhang [7] reported that rainfall intensity, especially short duration rainstorms with higher intensity, was the key factor causing soil erosion and the related nutrients loss on the Chinese Loess Plateau.

Soil fine particles were easily transported by runoff [8]. Soil erosion led to the enrichment of fine particles and chemical elements in sediments [9], which in turn caused the changes in particle size distribution (PSD) of the eroded sediments. Furthermore, Water erosion may cause a redistribution of the soil particles in the surface soil layer and, by modifying the soil texture, can significantly contribute to a deterioration of soil properties [10]. It is important to study the particle size composition of eroded sediment because the properties of sediment eroded from interrill area provides basic information on erosion process and may suggest measures for controlling the off-site effects of sediment in surface waters [11]. In addition, information on eroded sediments is needed for calibrating and verifying erosion models to predict soil losses and sediment quality and therefore implement practices to reduce erosion [12, 13, 14].

The objective of the present study was to explore the effect of rainfall intensity on runoff, sediment, nutrients loss, and sediment PSD, as well as their relationships. The findings can offer useful insights into the characteristics of runoff, sediment and the associated nutrients loss, and provide scientific guidance for construction of soil and water conservation measures.

Materials and Methods

Study area. The study was conducted on field plots at the Ansai Research Station of Soil and Water Conservation from June to September 2008. The experimental station, which belongs to the Chinese Academy of Science, is located 35 km north of Yan'an City in northern Shaanxi Province, China (108°51'–109°26'E, 36°30'–37°39'N; average elevation: 1060 m a.s.l.). With a typical temperate continental semiarid monsoon climate, this area has a mean annual precipitation of 530 mm that occurs mostly between July and September during summer wet season. Summer rains are characterized by high intensity and short duration; these storms produce significant volumes of surface runoff. Mean annual temperature is 8.8°C. The soil is classified as a typical loessial soil, representing the most common soil type in the hilly-gully region of the Loess Plateau. Soil in this region is susceptible to erosion and the erosion modulus is more than 10000 t km⁻²·yr⁻¹. A variety of soil properties were measured for the experimental plot and the average values are listed in Table 1.

Table 1 Physical-chemical properties of Surface soil (0–5 cm) in the experiment site (Mean ± Std)

Nutrients content (g/kg)			Bulk density g/cm ³	Porosity %	Soil particle composition (%)		
Organic matter	TN	TP			<0.002 mm	0.002–0.02 mm	0.02–0.2 mm
7.95±2.87	0.54±0.17	0.61±0.012	1.28±0.025	51.7±0.01	6.14±0.52	26.17±3.12	67.13±3.83

Rainfall simulator set-up. Four side-sprinkle simulators manufactured by the Institute of Soil and Water Conservation, Chinese Academy of Science and Ministry of Water Resources were used in this experiment. Rainfall height was 5.5 m and simulated storm with uniformity of above 85% is similar to natural rainfall in raindrop distribution, raindrop size and terminal velocity. Rainfall intensities can be precisely adjusted through the aperture of nozzle orifice and water pressure. The aperture ranges from 3 mm to 13 mm which can produce rainfall intensities of 30–165 mm/h.

Plot characteristics, experimental design and sampling. The experiments were carried out on 8.5×2.5 m plots with the same slope gradient of 15°. Concrete flumes at the bottom of each plot collected runoff and sediment, and metal troughs at the outlet point of the flume directed runoff into collection containers.

On the Loess Hilly Region, rainfall is concentrated in summer period with high rainfall intensity and short duration typically occurring. Therefore, we designed three representative high rainfall intensity levels in our study: 60 mm/h, 100 mm/h and 140 mm/h, respectively.

Experiments were conducted on dry, windless days to minimize the influence of weather and each rainfall simulation test lasted for 60 min. Before each rainfall simulation test, soil surface samples (0–5cm) were collected using a soil auger (20mm in diameter), and then analyzed to determine soil water content, PSD, and different nutrients content. For each test, the time to initiate runoff was recorded. The collection containers at the flume outlets were changed periodically and the time was noted. After the rainfall event was over, the amount of runoff in each collection container was measured. The containers were allowed to stand so that suspended sediment could settle out, then runoff samples were collected from the supernatant using polyethylene bottles and preserved in a refrigerator at 4°C until nutrient analysis could be conducted. The supernatant that remained in the collection containers 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, especially the antecedent soil moisture. We waited several days until the soil moisture content in each plot returned to the level it was at before the first simulated rainfall event and then repeated the process. All treatments had three replicates.

Measurements. In the laboratory, runoff water samples were filtered through 0.45µm glass fiber filters. The filtered runoff water was analyzed for total dissolved nitrogen (DN) and phosphorus (DP), NO₃-N and NH₄-N. Sediment samples were analyzed for organic matter (OM), total particulate nitrogen (PN) and phosphorus (PP), NO₃-N and NH₄-N. DN and PN were measured using the alkaline potassium persulfate oxidation-UV spectrophotometric method and the

semi-micro Kjeldahl method, respectively. Both $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ were determined with a continuous flow analyzer. Soil organic matter was measured using Potassium dichromate oxidation method. Total N loss was recorded as the sum of their respective dissolved form in runoff water and the amount of particulate form in sediments. Nutrients background values in the applied rainfall water were subtracted from their contents in the runoff water. The main nutrients parameters calculated for each simulated rainfall event was summarized in Table 2. Texture analysis (International System) was done using laser diffraction method (Malvern Mastersizer 2000 with a Hydro G sample dispersion unit). 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 of the sediment. The enrichment ratio (ER) is the concentration of a soil constituent in eroded sediment to that of the original soil from which the sediment originates.

Table 2 Explanatory variables

Variable	Abbreviation
Organic matter	OM
Total phosphorus	TP
Total nitrogen	TN
Ammonium nitrogen	$\text{NH}_4\text{-N}$
Nitrate nitrogen	$\text{NO}_3\text{-N}$
Mineral/inorganic/organic nitrogen	MN /IN/ON
Particulate (Dissolved) phosphorus	PP(DP)
Particulate (Dissolved) nitrogen	PN (DN)
Particulate (Dissolved)organic nitrogen	PON(DON)
Particulate (Dissolved) mineral/inorganic nitrogen	PMN (DMN) /PIN (DIN)

Data analysis. An analysis of variance (ANOVA) 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 calculated to verify interactions between nutrients loss and soil and water loss, as well as between enrichment ratio of nutrients and enrichment ratio of sediment particle with different diameter. Statistical procedures were carried out with the software package SPSS 13.0 for Windows.

Results

Hydrological and erosive response. Runoff and sediments collected from different rainfall simulation tests can be an indication of total soil and water losses caused by rainsplash and runoff-driven processes. As can be seen from Table 3, high rainfall intensity events led to high runoff and sediment parameters. Statistically significant differences were found in the hydrological and erosive results. Average runoff ranged from 628.58 L for 60mm/h to 777.33 L for 140mm/h, increased by 23.66%. Runoff rate ranged from 0.51 mm min^{-1} for 60mm/h to 0.62 mm min^{-1} for 140mm/h. No significant differences were detected between 60mm/h and 100mm/h for the hydrological response. Likewise, average sediment yield increased with increasing rainfall intensity. Average erosion rate were 2.50, 6.65 and $8.05 \text{ g m}^{-2}\text{min}^{-1}$ for the three treatments, respectively. Mean sediment concentrations in the 100mm/h and 140mm/h treatments were 12.33 and 12.82 g/L, respectively, which were 2.5 times of that in 60mm/h treatment. There were no pronounced differences in erosive results between 100mm/h treatment and 140mm/h treatment. Our findings were in agreement with other reports that showed that major runoff and soil loss appear to be result of rainfall intensity [15, 16, 17, 18].

Table 3 Hydrological and erosive results under different rainfall intensities

Rainfall intensity (mm h ⁻¹)	Runoff (L)	Runoff rate (mm min ⁻¹)	Sediment (g m ⁻²)	Erosion rate (g m ⁻² min ⁻¹)	Sediment concentration (g L ⁻¹)
60	628.58a	0.51a	145.00a	2.50a	4.94a
100	671.29a	0.54a	389.03b	6.65b	12.33b
140	777.33b	0.62b	472.00b	8.05b	12.82b

Means within a column followed by the same letter are not significantly different at 0.05 levels using the least significant difference (LSD) method

Nutrients loss. Along with soil erosion, nutrients were lost also. Taking into account the amount of runoff, sediment and the average nutrients concentration, the total losses of nutrients in each rainfall simulation test were calculated (Table 4). Nutrients losses increased with the increase of rainfall intensity. OM, TP and TN losses under 140mm/h were 4, 2.5 and 3 times of the value under 60mm/h condition, respectively. In terms of different N forms, total N was mainly lost through the sediment rather than runoff water. Particulate N, which was 2 to 7 times of dissolved N, takes 68–88% of the total N loss. Organic N was 3 to 8 times of the inorganic N (mineral N) in the total N loss. Total inorganic N loss ranged between 41.87 and 54.71 mg m⁻². In contrast to total N loss, inorganic N loss was mainly through runoff water instead of runoff sediment, and the former was almost 5 to 15 times of the latter; NO₃-N loss was obviously higher than NH₄-N loss and occupied 71–75% of total inorganic N loss.

The following results can be obtained based on the analysis of Table 4: runoff sediment was the primary pathway for the nutrients loss; particulate N, especially its organic form, was the major form of N loss; soluble NO₃-N and NH₄-N were also the important forms of inorganic N loss; though organic N comprised the largest proportion of total N loss, the mineral N loss was indispensable.

Table 4 Nutrients loss under different rainfall intensities

Rainfall intensity (mm/h)	OM (g/m ²)	TP ^a (mg/m ²)	TN (mg/m ²)	N loss in sediments(mg/m ²)					N loss in runoff water(mg/m ²)				
				PN	NH ₄ -N	NO ₃ -N	MN	ON	DN	NH ₄ -N	NO ₃ -N	MN	ON
60	0.89	119.93	155.22	106.36	1.42	1.12	2.53	103.83	48.86	9.17	30.17	39.34	9.52
100	2.11	233.23	243.60	191.45	3.20	3.24	6.44	185.01	52.15	10.05	30.31	40.36	11.79
140	3.54	303.69	485.24	425.45	4.83	3.99	8.82	416.62	59.79	10.97	34.91	45.89	13.91

^a Dissolved phosphorus contents were below the detectable level for most of the runoff samples, hence, here TP also refers to particulate phosphorus

Components of the nutrients viz. organic matter, total N, total P and total K are basic constituents of the soil medium which undergoes erosion due to the action of rainfall and runoff. The amount of nutrient loss therefore, is directly proportional to the amount of soil erosion [19]. Linear regression analysis between nutrients loss and soil erosion indeed indicated significant coefficients of determination (Table 5). This finding is in agreement with Kothyari [19] who reported linear relationships among rainfall, runoff, sediment, and nutrients load under different land uses in Bhetagad watershed of Central Himalaya and is also consistent with Ramos and Martínez-Casasnovas [20] who found higher correlation coefficient between N, P losses and soil losses in vineyards of the Penedés area (north-eastern Spain).

The average ER of different nutrient species was in the order of ER_N (1.6) > ER_{OM} (1.2) > ER_P (1.1) (Fig. 2). ANOVA showed that effect of rainfall intensity on ER_N was significantly different at 0.01 levels. For ER_{OM} and ER_P, the effects were not so pronounced in comparison to ER_N, which can also be seen from Fig. 2.

Table 5 Correlation analysis between nutrients loss and runoff, sediment loss

Regression function	R^2	Regression function	R^2
OM=0.0067S-0.0704	0.7922	PN=0.7666S-15.986	0.7162
PP=0.578S+25.114	0.9499	DN=0.087R-5.8837	0.9823

S: sediment; R: runoff

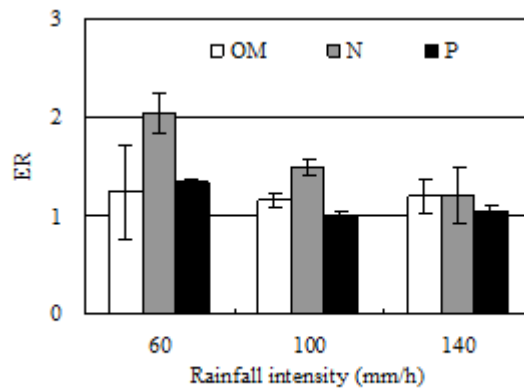
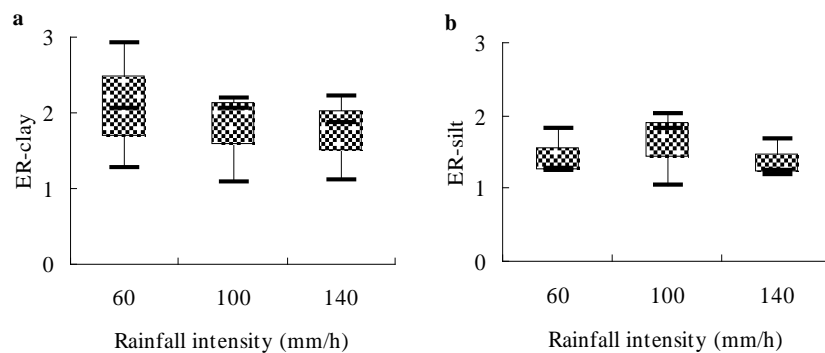


Fig.2 Enrichment ratios (ER) of sediment-associated nutrients

Effect of rainfall intensity on sediment particle size distribution. Compared to the original soil, runoff sediment contained considerably more clay (<2 μ m) and silt (2–20 μ m) (Table 6). Less fine sand (20–200 μ m) was observed in sediments in comparison to original surface soil. The percentage of clay significantly decreased with increasing rainfall intensity ($p<0.05$). The clay (<2 μ m) fraction of the sediment in runoff had an enrichment ratio of clay between 1.7 and 2.1 followed by silt (0.002–0.02 mm) fraction with an ER ranging from 1.4 to 1.6. This implies that these fractions were more represented in the eroded sediments than in the original soil (Fig. 3).

Table 6 Sediment particle size distribution

Rainfall intensity mm/h	Particle size distribution (μ m)/%			
	<2 /Clay	2–20/Silt	20–200/Fine sand	200–2000 /Coarse sand
60	11.92	38.84	46.38	2.86
100	10.31	37.97	51.07	0.66
140	9.38	34.40	55.65	0.56



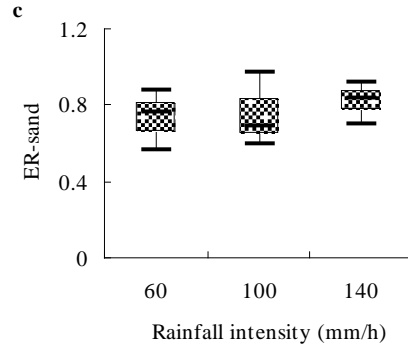


Fig.3 Box-plots for the enrichment ratios (ER) of sediment particles

Fig.4 depicts the relationship between ER of clay and sediment-associated nutrients. Positive linear relationships were identified between ER of the clay (<2 μ m) and ER of sediment-associated nutrients. There was no clear relationship between ER of silt and ER of the nutrients.

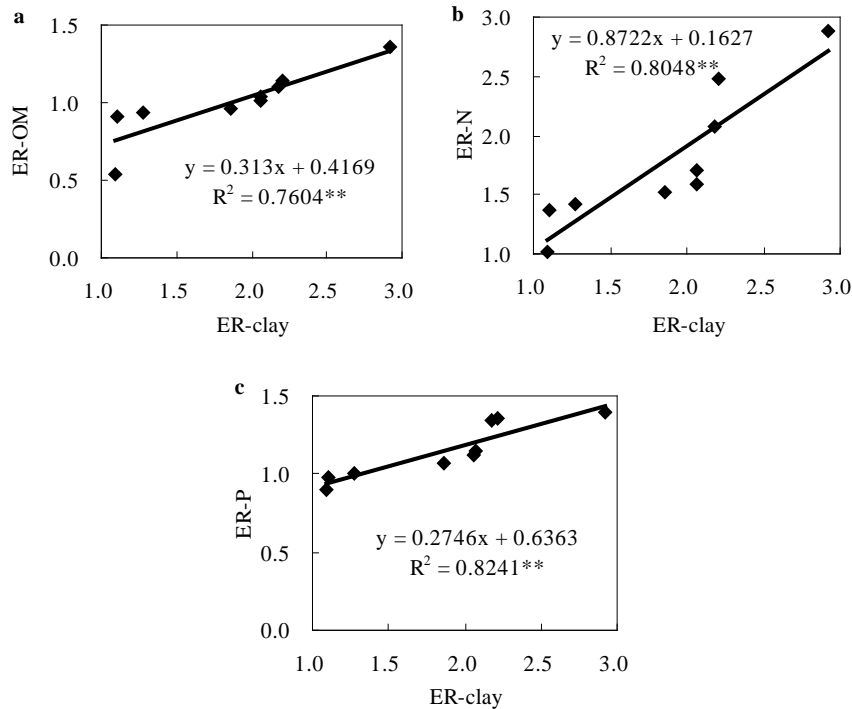


Fig.4 Relationships between ER of clay and sediment-associated nutrients

Discussion

The present study showed that rainfall intensity had important effect on soil erosion and the related nutrients loss. As concurs with many previous studies [15, 21, 22, 23], high rainfall intensity favors more soil and nutrients loss. In addition, regression analysis demonstrated significantly positive linear relationships between nutrients loss and runoff, sediment loss.

Soil nutrients loss by slope runoff mainly behaved in two ways: runoff sediment and runoff water, and both played different leading role according to the surface condition [24]. In agriculture slope land, the eroded sediment was the primary pathway for soil nutrients loss [25]. Hamilton [26] also reported that in Loess Plateau of China, 98% of nutrients loss was through sediment. We got the similar result that in our experiment conditions, P totally lost through sediment and sediment-associated N accounted for 69–88% of TN loss. However, Ma et al. [27] found that for the red soil, soil nutrients loss mainly via sediment under higher rainfall intensity; under lower rainfall intensity, the dissolved nutrients in runoff water occupied a higher proportion. The differences may be attributed to the soil type and the selection of rainfall intensity.

It is well known that fine particles are generally preferentially eroded compared with coarse ones. The significant increase in fine fractions ($<20\mu\text{m}$) in the sediment in our study means that for this sandy loam soil with nearly 70% sand, particles smaller than $20\mu\text{m}$ are susceptible to selective erosion, while higher rainfall intensity and amount of rainfall and subsequent higher runoff might be required to move the larger sand particles. Jin et al. [28] also found similar findings in this respect. However, there were inconsistent view points on the size distribution of the primary particles of the eroded sediment. Rhoton et al. [29] suggested that the clay fraction ($<2\mu\text{m}$) was preferentially eroded, while Stone and Walling [30] concluded that selective mobilization meant that clay ($<2\mu\text{m}$) and silt-sized material ($2\text{--}63\mu\text{m}$) were eroded preferentially and that the majority of the sand-sized material was not mobilized. Basic et al. [31] also stated that eroded sediment was generally richer in silt and clay compared with the original soil. Ghadiri and Rose [32] found that the proportion of large aggregates in the eroded sediment was less than in the original soil, and the intermediate size fractions remained unchanged.

The significantly positive correlations between ER of clay fraction and nutrients in the sediment implied that nutrients were mainly adsorbed on or contained within small-sized particles ($<2\mu\text{m}$). This result has also been examined by other researchers [32, 33, 34], which further confirmed our results of nutrients enrichment in sediments. Jolivet et al. [35] found that the amounts of soil organic matter and soil fertility are positively correlated with the clay and the silt fractions. Moreover, the transport of nutrient-enriched particles may result in the pollution of water bodies such as groundwater, rivers and lakes [10]. From these two respects, the loss of clay and silt in our experiments implies that the soil is experiencing quality deterioration.

Conclusions

Field simulated rainfall experiments were conducted to explore the influence of rainfall intensity on runoff, sediment yield and nutrients loss, as well as the characteristics of sediment particle size distribution. The results showed that runoff, sediment and nutrients loss increased with the increasing of rainfall intensity. The nutrients mainly lost through runoff sediment. Inorganic N loss was mainly in runoff water and primarily consisted of $\text{NO}_3\text{-N}$. The analysis of the sediment particle size distribution revealed that compared with the original surface soil, the sediment contained more fine particles ($<20\mu\text{m}$); the dominant particle size fractions that were removed by erosion were comprised in the clay ($<2\mu\text{m}$). Enrichment ratios for organic matter, N and P were positively correlated with enrichment ratio of particles smaller than $2\mu\text{m}$, and this implies that a large portion of soil nutrients were selectively transported. These results are important for understanding the soil particle distribution and losses resulting from soil erosion and deposition.

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