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Nitrogen enrichment in runoff sediments as affected by soil texture in Beijing mountain area

Yang Yang · Zhihan Ye · Baoyuan Liu ·
Xianqin Zeng · Suhua Fu · Bingjun Lu

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Abstract Enrichment ratio (ER) is widely used in non-point source pollution models to estimate the nutrient loss associated with soil erosion. The objective of this study was to determine the ER of total nitrogen (ER_N) in the sediments eroded from the typical soils with varying soil textures in Beijing mountain area. Each of the four soils was packed into a 40 by 30 by 15 cm soil pan and received 40-min simulated rainfalls at the intensity of 90 mm h^{-1} on five slopes. ER_N for most sediments were above unity, indicating the common occurrence of nitrogen enrichment accompanied with soil erosion in Beijing mountain area. Soil texture was not the only factor that influenced N enrichment in this experiment since the ER_N for the two fine-textured soils were not always lower. Soil properties such as soil structure might exert a more important influence in some circumstances. The selective erosion of clay particles was the main reason for N enrichment, as implied by the significant positive correlation between the ER of total nitrogen and clay fraction in eroded sediments. Significant regression equations between ER_N and sediment yield were obtained for two pairs of soils, which were artificially categorized by soil texture. The one for fine-textured soils had greater intercept and more negative slope. Thus, the initially higher ER_N would be lower than that for the other two soils with coarser texture once the sediment yield exceeded 629 kg ha^{-1}.

Keywords Enrichment ratio · Total nitrogen · Soil texture · Beijing mountain area

Introduction

According to the First China Pollution Source Census (MEP et al. 2010), agricultural activities are major sources of contaminants in surface and subsurface water, contributing 57.2 % of the nitrogen (N) and 67.4 % of the phosphorus (P), respectively. For a long time, soluble forms of nutrients such as nitrate N (NO_3^--N), ammonium N (NH_4^+-N), and dissolved P have been routinely monitored in streams and lakes and widely researched in many soil erosion studies (Heathwaite and Johnes 1996). That is mostly because they are readily available to algae and other aquatic organisms (Oenema and Roest 1998), which could thereby deplete dissolved oxygen in water bodies and cause eutrophication as well as other environmental problems quickly.

Y. Yang · B. Liu (✉) · X. Zeng · S. Fu
State Key Laboratory of Earth Surface Processes and Resource Ecology, School of Geography, Beijing Normal University, Beijing 100875, China
e-mail: baoyuan@bnu.edu.cn

Y. Yang
Department of Plant and Soil Sciences, University of Kentucky, Lexington, KY 40546, USA

Z. Ye
Beijing Hydraulic Research Institute, Beijing 100044, China

B. Lu
Beijing Water and Soil Conservation Center,
Beijing 100038, China

However, serving as the long-term sources in aquatic ecosystems, sediment-bound nutrients, or in other words, particulate nutrients are very important as well. First, they account for most of the total nutrient loss in runoff. Based on the monitoring data of 20 agricultural watersheds in the Southern Plains from 1977 to 1984, Sharpley et al. (1987) found that sediments contributed average 64 % of N and 75 % of P in surface runoff. Chen and Zhang (1991) observed even greater proportions of N and P in particulate form. For all the plots established on four loess tillage slopes, above 70 % of N and 99 % of P were transported with sediments. Second, particulate nutrients can be transformed to soluble, bioavailable ones in aquatic ecosystems, depending on their relative concentrations, water temperature, and dissolved oxygen (Sharpley and Withers 1994; Heathwaite and Johnes 1996). More important, soil erosion is a size-selective process and fine particles which are usually rich in nutrients due to their large specific surface areas are easily detached and transported (Sharpley 1985; Quinton et al. 2001), resulting in greater N and P concentrations in eroded sediments than in source soil (Rogers 1941; Knoblauch et al. 1942). The enrichment ratio (ER), defined as the ratio of nutrient concentration in the eroded sediment to that in the source soil, has been introduced to quantify this phenomenon (Massey and Jackson 1952).

Stoltenberg and White (1953) proposed two principles that affect erosion selectivity and enrichment ratio. One is the energy limitations of rainfall (Palis et al. 1990a; Ghadiri and Rose 1991b) and runoff (Sharpley 1980). At a low rainfall intensity and/or runoff rate, the kinetic energy is not enough to remove proportionate large particles (i.e., sand) with clay and silt, resulting in the enrichment of fine particles in eroded sediments and the ER of associated nutrient above unity (Young et al. 1986). As energy increases and soil erosion becomes more intensive, large particles could be detached and transported as well as fines and the value of ER approaches one. Quinton et al. (2001) examined the soil erosion events on the eight plots at Woburn Experimental Farm (Bedfordshire, UK) from 1988 to 1994 and found that the enrichments of clay and P particularly occurred in the small ones with a soil loss less than 100 kg. In the rainfall simulation experiments conducted by Schiettecatte et al. (2008), the enrichment ratio of organic carbon decreased from 2.6 towards 1 as the sediment discharge rate increased. Therefore, factors affecting the kinetic energy of runoff and rainfall, such as soil slope and surface cover, usually play an important role in soil erosion and nutrient enrichment (Sharpley 1980; Palis et al. 1990b; Zhang et al. 2004).

The first principle basically leads to a general observation of inverse correlation between ER and sediment yield (Massey and Jackson 1952). Actually, in early 1930s, Middleton et al. (1934) already realized that slight erosion might be more detrimental to soil fertility. The equation widely used to describe the relationship between ER and sediment yield is (Menzel 1980):

$$ln(ER) = a + b\ln(SED) \qquad (1)$$

Where sediment yield SED is the sediment yield in kg ha^{-1}, a and b are regression intercept and slope, respectively. Based on a number of published data, Menzel (1980) concluded a general equation which held for a wide range of soil and vegetative conditions and was adopted in the CREAMS model:

$$\ln(ER) = 2 - 0.2\ln(SED) \qquad (2)$$

The other principle is the availability of particular soil fractions to erosion (Stoltenberg and White 1953). Intensive nutrient enrichment and great ER usually occur in the sediments eroded from the soil with high sand content (Menzel 1980; Sharpley 1980). Stoltenberg and White (1953) attributed this effect of soil texture on nutrient enrichment to the preferential detachment and transport of fine particles over sand (Young et al. 1986). Having coarser texture in the source soil, the enrichment of fines during erosion is greater, which thereby causes the more distinct contrast in the nutrient concentration between source soil and eroded sediment (Zhang et al. 2004). Foster et al. (1985) considered the two forms clay particles exist in the soil, i.e., primary clay and aggregates; and regarded deposition selectivity as the key. The soil high in sand is usually poorly aggregated, and most of the clay is in primary form, which is not readily deposited during erosion. The elevated clay content in the eroded sediments leads to a high ER. On the contrary, in the soil high in clay, much clay present in aggregates in addition to primary form tends to deposit with large particles like sand when sediment load exceeds the transport capacity of runoff (Ghadiri and Rose 1991b). Thus, only a slight enrichment is resulted. Palis et al. (1997) observed similar change in the ER of total N (ER_N) with soil texture when conducting a rainfall simulation on a soil slope of 3 %. However, when the slope was decreased to 0.1 % where rainfall detachment was believed to be the only erosion process, a higher ER_N was obtained for the clay soil rather than the coarser sandy clay loam. Given all this, the influence of soil texture on nutrient enrichment in eroded sediments can vary in different situations and the related mechanisms deserve further exploration.

In light of the uncertain but undoubtedly important role soil texture plays in erosion selectivity and nutrient enrichment, a correction factor for soil texture, T_f, has been introduced in the calculation of ER in the AGNPS model (Young et al. 1989). The related equation is:

$$ER = 7.4(SED)^{-0.2}T_f \tag{3}$$

After natural logarithmic (ln) transformation, a negative linear relationship between ln(ER) and ln(SED) similar with Eq. (2) is revealed:

$$\ln(ER) = 2 + \ln\left(T_f\right) - 0.2\ln(SED) \tag{4}$$

Equation (4) suggests an impact of soil texture on the intercept rather than the slope. However, in two rainfall simulation experiments conducted by Sharpley (1980, 1985), similar intercepts and slopes were obtained in the significant regression equations between ln(ER) and ln(SED) for the soils ranging in texture from sandy loam to clay. In the investigation by Menzel (1980), ER corresponded with sandy soil was found to be relatively constant between 1 and 5, but not applied to the inverse correlation with SED.

Beijing is one of the largest cities in the world facing serious water shortage and water environment deterioration (Wei 2005). In the mountain area where the major surface water sources are located, e.g., Miyun Reservoir, agricultural nonpoint source pollution associated with soil erosion is the main cause for water quality degradation (Wang et al. 2001). Thus, it is of vital importance to develop the relationship between ER and SED, which is useful in predicting the nonpoint source pollution (Sharpley 1980; Ghadiri and Rose 1991b) and has rarely been done in this area. In the present study, N enrichment was investigated in the soil erosion events occurring on four different typical soils in Beijing mountain area under simulated rainfalls. The authors aimed to analyze the effect of soil texture on the enrichment of total N (TN) in runoff sediments as well as on the relationship between ln(ER) and ln(SED).

Materials and methods

Landscape of Beijing consists of three main parts: mountain, plain, and urban area. Mountains, mainly distributed in the north and the west, cover about 62 % of the total area in Beijing; the urban area is located in the south center, and between these two is the so-called "Beijing Plain," which surrounds the urban area. The soils subject to rainfall simulation were collected from four different counties or districts. They were mountain brown earth (MBE) from Mentougou District located at southwest Beijing, cinnamon soil (CS) from Yangqing County at northwest, skeletal cinnamon soil (SCS) from Miyun County at northeast, and eluvial cinnamon soil (ECS) from Huairou District at north. The particle size distributions determined by the pipette method (Gee and Bauder 1986) for these four soils are presented in Table 1.

Each soil was passed through a 4 mm sieve and packed into a 40 cm in length by 30 cm in width by 15 cm in depth laboratory soil pan which allowed free drainage at the bottom. The bulk density of the repacked soil was controlled at the same level of corresponding field soil (Table 1), and the soil water was maintained at around 15 %. Five slope treatments were used, which were 5°, 10°, 15°, 20°, and 25°. With each slope, a 40-min simulated rainfall at the intensity of 90 mm h^{-1} was applied on each soil pan, resulting in a total rainfall amount of 60 mm. This relatively high rainfall intensity in soil erosion research using rainfall simulation (Meyer and Harmon 1989) corresponds with an average recurrence interval of 10 years in Beijing. The 20 rainfalls in total were conducted by a Norton rainfall simulator.

Before each rainfall simulation, three samples randomly collected from the top 1-cm soil were mixed and air-dried for TN analysis. Total runoff sample of each rainfall event was collected for the measurement of runoff volume first, and then separated into two subsamples. One was oven-dried to measure sediment concentration and thereby to estimate sediment yield. The other was filtered, and the sediment sample obtained was thereafter air-dried for the analyses of particle size distribution and TN. The particle size distribution was determined by the pipette method (Gee and

Table 1 Particle size distributions of the four experimental soils

Soil Type	Location	Texture class	Bulk density (g cm^{-3})	Particle size (%)		
				Sand (0.05–2 mm)	Silt (0.002–0.05 mm)	Clay (<0.002 mm)
Mountain brown earth (MBE)	Mengtougou	Silt loam	0.94	17.7	66.5	15.8
Cinnamon soil (CS)	Yanqing	Silt loam	1.30	22.2	61.5	16.3
Skeletal cinnamon soil (SCS)	Miyun	Sandy loam	1.40	63.7	24.9	11.4
Eluvial cinnamon soil (ECS)	Huairou	Loam	1.29	34.5	48.1	17.4

Bauder 1986) and TN by a semi-micro Kjeldahl apparatus (Bremner 1996).

Results and discussions

The sediment yield and nitrogen enrichment (ER_N) for each soil erosion event are displayed in Fig. 1. More soil losses were observed in the rainfall simulations conducted on the two soils with coarser textures, i.e., SCS and ECS no matter at which slope. However, the effect of soil texture on the values of ER_N was not that explicit. The MBE with the least sand content among the four soils had the lowest ER_N, which were close to one, indicating slight or no enrichment of TN in the eroded sediments. Yet, the ER_N for another silt loam, i.e., CS, were not significantly different from the ones for the coarse SCS and ECS. At the slope of 5°, the ER_N for CS was 1.66, which was much higher than the others. These results suggested that factors other than soil texture might exert a greater influence on N enrichment, such as soil structure. Ghadiri and Rose (1991a, b) have proposed a plausible mechanism in which the enrichment was caused by the gradual raindrop stripping from the outer layers of aggregate where the nutrient was more concentrated than the inner core. In this experiment, the least runoff was observed in the rainfall event for CS at each slope (data not shown). The role of rainfall detachment became more important for CS compared to the other soils. It was possible that only a thin layer of N-concentrated soil was peeled by the rainfall, resulting in the least soil loss but the most intensive TN enrichment in the sediments eroded from the CS, especially at the flattest slope (Fig. 1).

Figure 1 also reveals the influence of soil slope on N enrichment. In general, as the slope increased, the sediment yield for each soil increased as well, while the value of ER_N decreased. This result was consistent with other studies (Sharpley 1980; Palis et al. 1997; Zhang et al. 2004) in which the change in the runoff energy with slope was regarded as the reason. On a steeper slope, runoff with greater energy is more able to remove the soil materials, especially the coarse ones. As a result, the selective erosion of clay particles, which is widely acknowledged as the main cause for sediment-bound nutrient enrichment, is slighter.

This explanation was verified by the ER of clay fraction (ER_{Clay}), which was estimated based on the particle size distribution of the eroded sediment. Owing to the least soil loss on CS (Fig. 1), the sediment samples collected were not enough for this analysis. The results for the other three soils are presented in Fig. 2. Similar with ER_N, the value of ER_{Clay} generally decreased with soil slope, indicating that the disproportionate erosion between coarse and fine particles could be alleviated by increasing the slope. At the same time, the correlation between ER_N and ER_{Clay} were examined. For SCS and ECS, the correlation coefficients were 0.896 and 0.926, both of which were significant at the level of 0.05. For MBE, the correlation coefficient was 0.843, which was, to a less extent, only significant at the level of 0.10. It was implied in these positive correlations that the enrichment of clay particles was the main reason leading to TN enrichment, at least for these three soils, which was in agreement with Zhang et al. (2004). However, this mechanism might be less prevailing for the soils with finer texture in light of the smaller correlation coefficient at a lower level of significance obtained for MBE.

Both ER_N and SED were ln-transformed and plotted in Fig. 3 thereafter. A general decrease in $\ln(ER_N)$ was observed with ln(SED) no matter for which soil. The inverse relationships for the soils with similar textures,

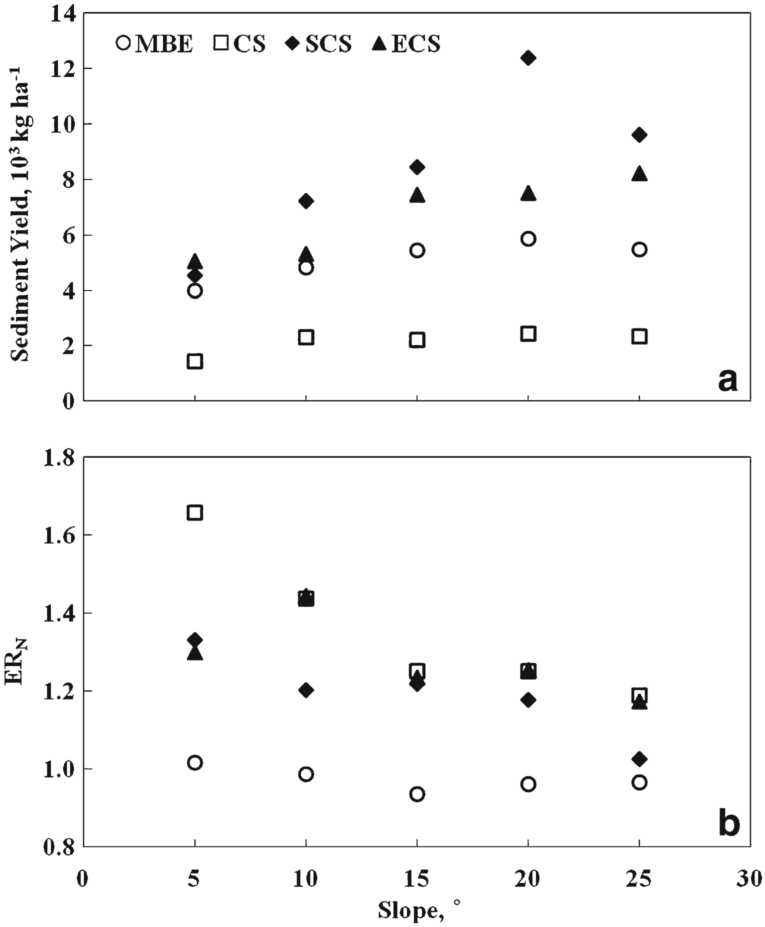


Fig. 1 Changes in **a** sediment yield and **b** ER_N with slope for the four soils: mountain brown earth (MBE), cinnamon soil (CS), skeletal cinnamon soil (SCS), and eluvial cinnamon soil (ECS)

i.e., MBE and CS with fine textures and SCS and ECS with coarse textures, appeared alike, although single statistical comparison of relationships was improbable. Thus, two regression equations for the coarse- and fine-

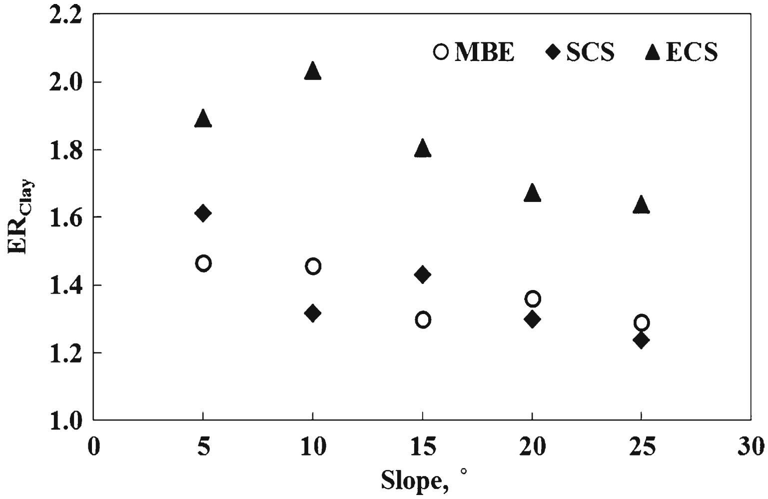
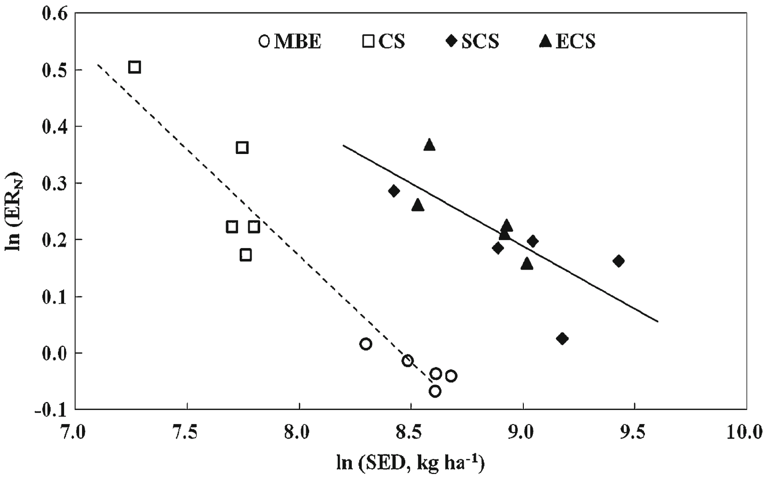


Fig. 2 Changes in ER_{Clay} with slope for mountain brown earth (MBE), skeletal cinnamon soil (SCS), and eluvial cinnamon soil (ECS)

Fig. 3 Changes in $\ln(ER_N)$ with ln(SED) for the four soils: mountain brown earth (MBE), cinnamon soil (CS), skeletal cinnamon soil (SCS), and eluvial cinnamon soil (ECS)



textured soils were generated and presented as Eqs. (5) and (6), respectively.

$$\ln(ER_{\mathrm{N}}) = 2.18 - 0.22\ln(SED) \tag{5}$$

$$\ln(ER_{\mathrm{N}}) = 3.16 - 0.37\ln(SED) \tag{6}$$

The determination coefficients for these two equations were 0.52 and 0.90, respectively, both of which were significant at the level of 0.05. With a greater intercept, Eq. (6) indicated more intensive TN enrichment in the early stage of soil erosion on fine-textured soil, especially when little runoff was initiated and rainfall stripping on aggregates was the dominant erosion process (Palis et al. 1997). As the sediment yield increased, ER_N would decrease very soon implied by a more negative slope than that in the Eq. (5) for the two soils with coarser textures. When sediment yield exceeded 629 kg ha^{-1}, ER_N was estimated to be higher for the two coarse-textured soils in this experiment.

Comparing to the general Eq. (2) developed by Menzel (1980), the absolute values of intercepts and slopes were higher in these two regression equations. It was probably due to the small size of soil pans adopted in this rainfall simulation experiment, on which hardly could rill erosion be initiated, especially for the fine-textured soil with greater cohesion (Loch 1996). The experiments by Alberts et al. (1980) and Schiettecatte et al. (2008) to some extent support this reasoning in which interrill sediments were found to be enriched with clay particles and nutrients, while no selectivity was observed during rill erosion owing to the high transport capacity of rill flow. The non-selective characteristic indicates that the ER values of clay and nutrients for rill sediments are not significantly different from one and are not prone to change with SED. Therefore, the occurrence of rill erosion would not only decrease the values of ER but also impair its relationship with SED. On the contrary, without the development of rills, the ER values are relatively high and decrease rapidly as erosion proceeds.

Conclusions

To evaluate the effect of soil texture on nitrogen enrichment in runoff sediments, four soils representing the typical soils in Beijing mountain area were packed in laboratory soil pans and subject to rainfall simulations. Soil losses in the erosions occurring on the two soils with finer textures were generally smaller, but the values of ER_N were not always lower. Factors other than soil texture, such as soil structure, might influence N enrichment in certain circumstance. The total nitrogen enrichment in the eroded sediments was mainly resulted from the enrichment of clay particles, especially for the coarse-textured soil, as revealed in the significant positive correlations between ER_N and ER_{Clay}.

The relationship between ER_N and SED was affected by soil texture. Two distinct regression equations were obtained for two pairs of soils, which were artificially categorized based on soil texture. With finer soil texture, the enrichment of N was expected to be stronger when soil erosion initiated, as indicated by the higher intercept in the corresponding Eq. (6). However, as the erosion proceeded and more soil materials were eroded, ER_N would decreased more rapidly. Once the sediment yield exceeded 629 kg ha^{-1}, N enrichment in the eroded sediments from the two coarse-textured soils in this study would be more intensive.

While the size of the soil pans used in this experiment was small and the rill development was to some extent limited, the resulting regression equations, especially the one for fine-textured soils, were slightly different from the general equation concluded by Menzel (1980). More observations on the nutrient enrichment at a larger scale under both natural and simulated rainfalls are suggested in further analysis.

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