Research advances in nutrient runoff on sloping land in watersheds

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High nitrate and phosphorus concentrations in runoff resulting from sloping lands (especially agricultural sloping lands) have direct consequences on the aquatic environment through eutrophication of surface water. This paper details the transfer mechanism of nutrients in soil on sloping lands influenced by natural and artificial factors. Results showed that the rainfall intensity had a small influence on nutrient concentrations in runoff, but a significant influence on the runoff flow on sloping lands. The slope length influenced the nutrient loss by soil erosion on areas that receive rainfall. The slope gradient influenced the nutrient loss by runoff flux and velocity on sloping land. As the slope gradient decreased, the nutrient loss decreased because of the increase in infiltration. The soil texture, porosity, and water content influenced the motion of soil water and the transfer and form of nutrients in soil, through oxidation and deoxidation. Vegetative coverage influenced the infiltration coefficient of rainwater into subsurface soil, and thus influenced the runoff flow velocity. Therefore, different sloping lands need to be managed in different ways. To better carry out best management practices in watersheds, a new management based on sloping lands needs to be further studied, including changing fertilization quantity, improving fertilization technology, adjusting vegetation coverage, and studying cultivation systems on different sloping lands within a watershed.

Keywords: nitrogen, phosphorus, transfer, rainfall intensity, slope length and gradient

Introduction

The global intensification of sloping land (SL) use has been accompanied by water quality concerns. One of the most acute problems is the increase of nitrate and phosphorus concentrations in the surface water due to SL over-fertilization and soil erosion (Cai et al., 1996; Fu et al., 2002; Molenat et al., 2002; Richard et al., 2002; van der Valt, 2002). High nitrate and phosphorus concentrations have direct consequences on the decrease of soil fertility and loss of nutrients (Sharpley, 1985; Romano and Santini, 2000) and on the eutrophication of coastal marine ecosystems (Cai et al., 1996; Elrashidi et al., 2001; Fu et al., 2002; van der Valt, 2002). The quantity of pollutants caused by soil erosion from SLs is comparable to other diffuse source pollution in a watershed (Ma et al., 1997; Reed-Andersen et al., 2000; Elrashidi et al., 2001).

Many field experiments about transport and transformation of nutrients in soil on SLs were done because of increased public attention on diffuse pollution in watersheds (Daniel et al., 1998; Liang et al., 2002). Posthumus and Spaan (2001) analyzed the rainfall runoff relationships for different vegetative covers. Govindaraju et al. (1992) and Tayfur (2001) numerically studied runoff generation on complex surface hillslopes using 2D models. These studies indicated a limited understanding of the mechanism of nutrient transfer in surface soil on sloping lands. To reduce nutrient losses from SLs, environmentally friendly strategies of land use management have to be defined. Definitions need to be based on a good understanding

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of the main mechanisms controlling nutrient transfer within watersheds. The goal of this research was to better understand the transfer process of nitrogen (N) and phosphorus (P) on SLs and influencing factors, including rainfall intensity, slope length, and slope gradient, by using indoor experiments in a sand flume.

Materials and methods

As shown in Figure 1, nutrient transfer into downstream surface water occurs through the following three pathways (Cann, 1994; Molenat et al., 2002; Richard et al., 2002): 1) partial dissolved nutrients and fine soil particle carrying some nutrients flow downward along with surface runoff (Figure 1A); 2) partial nutrients infiltrate and move into subsurface soil along with seepage (Figure 1B); and 3) partial nutrients enter into groundwater which discharges to surface water (Figure 1C). The distribution of nutrients within the three parts is related to rainfall intensity, slope length, slope gradient, soil type and vegetation.

Some field observations corresponding to different intensities of nutrient loss were plotted (Figure 2), which illustrates a small trend of nutrient loss. According to these findings, experiments were designed under different rainfall intensity, slope length, and slope gradient. Experiments were conducted in a soil flume at the Key Laboratory of Water Resources Development (Ministry of Education) in Hohai University, Nanjing, China. The soil flume was 1200 cm long, 300 cm wide, and 150 cm deep with an adjustable slope from 0 to 30 degrees. The tested soil, as shown in Table 1, was collected from a sloping land at upstream of Taihu Lake basin. Simulated rainfall was applied to experimental treatments. During the experiment to study the effect of rainfall intensity on runoff nutrient concentrations and losses, the rainfall intensity was set at 0.58, 0.99, 1.98, 3.2, 4.1, and 4.95 mm min^{-1} and the soil surface gradient was set at 10 degree, which commonly occurs in Taihu Lake basin. When analyzing the influence of different slope lengths on runoff nutrient losses, the soil surface gradient was also fixed at 10 degree and the rainfall intensity was fixed at 2 mm min^{-1}. The experiments of influence of different land gradients on runoff nutrients were done under constant rainfall intensity 2 mm min^{-1} and constant slope length 12 m. Runoff samples were collected and total runoff volumes were recorded at 30, and 60 min. Subsamples of the runoff were analyzed for total nitrogen (TN), total Phosphorus (TP), and soil organic matter (SOM) concentrations and loads. The TN, TP and SOM concentrations are the amounts in a given volume of runoff, and loads are the total amounts of TN, TP, and SOM leaving (concentration multiplied by runoff volume).

The dry matter content of the soil was determined by drying the samples for 18 ± 24 h at 105°C. Soil organic matter content was measured as loss on ignition from the dried samples at 550°C for 4 h. Soil pH was measured in 3:5 v:v soil: H_2O suspensions. Total nitrogen was determined using an automated CHN analyzer (Leco CHN-600). Unfiltered samples were used to determine TP after persulphate digestion.

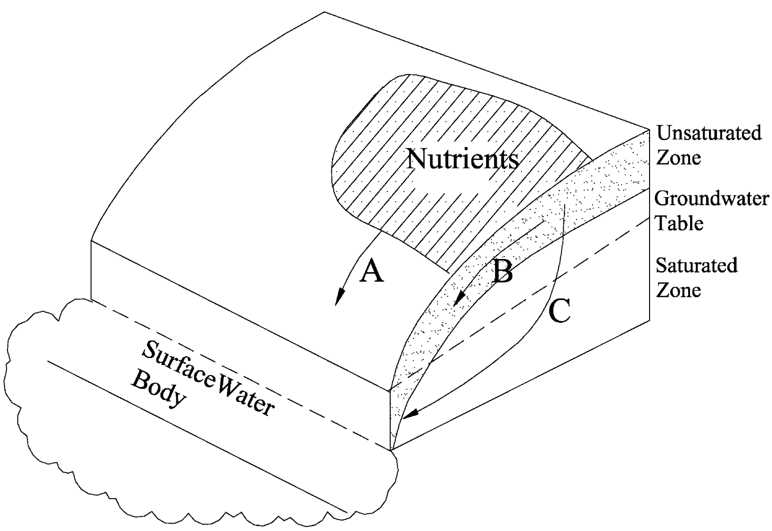

Figure 1. Potential transfer pathways of nutrients on sloping lands to surface water in watersheds: (A) surface runoff, (B) subsurface flow, and (C) groundwater.

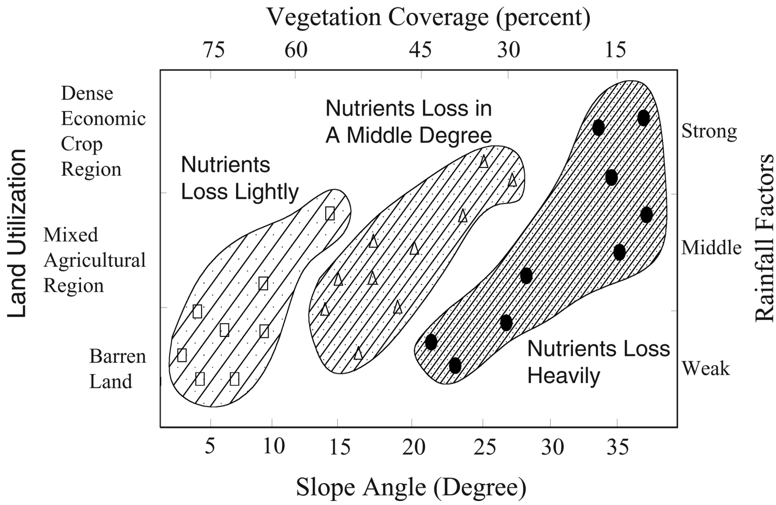

Figure 2. A sketch map of influence factors on transfer of nutrients in sloping land soil (□, △, ● represent some field experimental observations corresponding to three intensities of nutrients loss).

Results

Influence of rainfall intensity

Rainfall intensity (RI) has a remarkable influence on the loss of soil and nutrients on SL. The higher the amount or intensity of rainfall, the greater the given potential for soil erosion and thus nutrient loss. Under six levels of RI (0.58, 0.99, 1.98, 3.2, 4.1, and 4.95 mm min^{-1}), the losses of TN, TP and SOM from experimented sloping land with a constant gradient 10° were measured. As shown in Figure 3, the total losses of nutrients significantly increased with the increase of RI. As the RI increased from 0.58 mm min^{-1} to 4.95 mm min^{-1}, the loss of TN, TP and SOM increased from 8.0 μg to 42.1 μg, 5.6 μg to 35.3 μg, and 3.1 mg to 10.9 mg respectively.

When the RI increased, the nutrient concentrations increased slightly and then maintained balanced as shown in Figure 4. Therefore, the RI has a small influence on nutrient concentrations in runoff but a significant influence on the runoff flow.

In the experiments, we observed that when RI was 0.58 mm min^{-1}, the form of lost nutrients was mainly particulate; however, when RI was 4.95 mm min^{-1}, the form was primarily dissolved. Synchronously, soil mineral nitrogen diffuses into runoff under lixiviation, and the ammonia-N is absorbed on soil particles released under the flush of runoff. In the process, the main form of N is composed of organic-N eroded by runoff.

Influence of slope length

Under the same RI (1.98 mm min^{-1}) and a gradient of 10°, the nutrient loss at two slope lengths, 6 m and 12 m, were studied. The longer the slope, the larger the discharge. However, the runoff generation time increased only slightly with increasing slope length (as shown in Figure 5). The influence of slope length on nutrient loss was actually the influence of the slope area that received rainfall. When runoff was steady, the nutrient loss was positively proportional to the slope length, or the slope area.

Influence of slope gradient

The slope gradient (SG) influences the loss of SL nutrients by influencing on SL runoff. The SG influences the runoff velocity and thus influences the initiation of soil particles, and nutrient loss. For a uniform

Table 1. Physical and chemical properties of tested soil from a sloping land in Taihu Lake basin.

Fine gravel (%)	Sand (%)	Silt (%)	Clay (%)	Organic matter (%)	Water content (%)	Specific gravity ($g{\cdot}cm^{-3}$)	PH	TN (%)	TP (%)
9	30	39	22	2.27	26	1.55	6.8	0.18	0.06

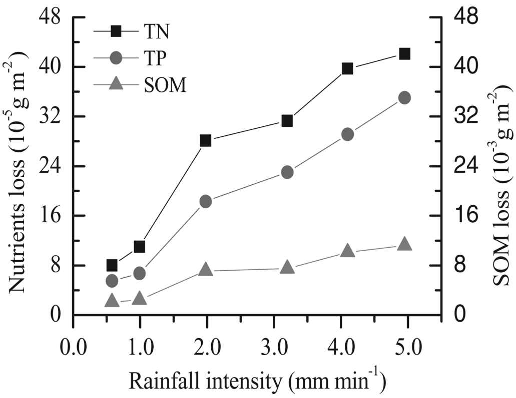

Figure 3. Experimental results of the nutrients loss (TN, TP and SOM) on a sloping land with 10° gradient under different rainfall intensity.

rainfall intensity (1.98 mm min^{-1}) and a constant slope length (12 m), nutrient loss was measured for 6 slope gradients, 5°, 10°, 15°, 20°, 25° and 30°. The results are illustrated in Figure 6. The greater the SG, the earlier the runoff occurred. For steady runoff, the unit loss of nutrients generally increases as the SG decreases because of the increasing area of rainfall. As the SG decreases to some small value, the proportion nutrient loss decreases because of the increase in infiltration. As a result, the depth that seepage reaches increases with the decreasing SG. At the same time, we found that the form of P in runoff, with fewer particles, was mainly dissolved at a 5° gradient due to the long residence time of rainwater on surface soils. Nevertheless, at 30°, the particulate forms were the majority. At a 15° gradient, two forms were both present.

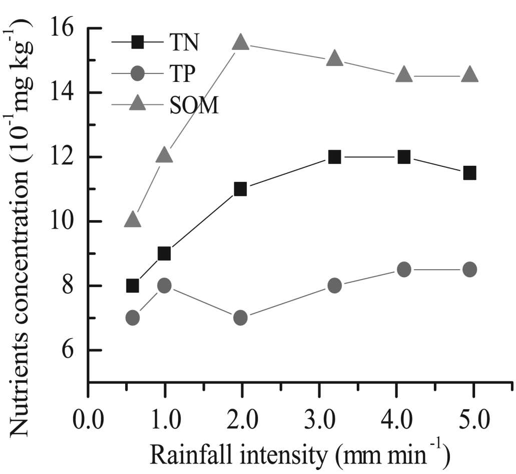

Figure 4. Experimental results of nutrient concentrations (TN, TP and SOM) in runoff with 10° gradient under different rainfall intensity.

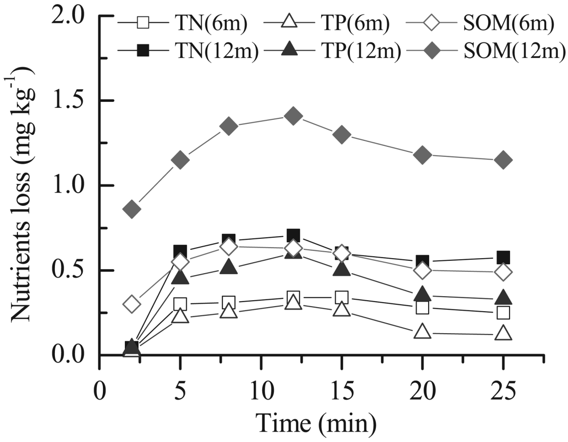

Figure 5. Experimental results of the nutrients loss (TN, TP and SOM) on a sloping land with 10° gradient and constant RI (RI = 2 mm min^{-1}) at different slope length (6 m and 12 m).

Discussion

Fu et al. (2002) studied the nutrient losses of lime soil in the reservoir area of Three-Gorges. A positive regressive relationship between nutrient loss and RI was obtained. Chen et al. (1999) also found that the loss of P has a strongly positive relationship with RI. Gburek and Sharpley (1998) found that the P-loads leaving from two small drainage basins with 3 to 17% and 1 to 20% of gradient respectively were positively proportional to the RI.

Ma et al. (2002) also found that the soil nutrients in particle form were leached primarily along with mud and sand when RI was high or in dissolved form when RI was low on a red-soil sloping land.

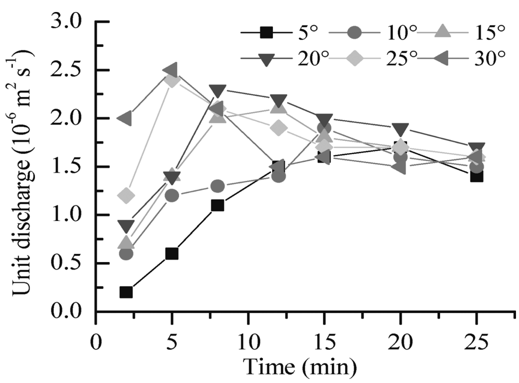

Figure 6. Experimental results of the unit discharge on a sloping land under constant RI (2 mm min^{-1}) and slope length (12 m) with different gradient.

The slope length influences the nutrient loss on SL by influencing the soil erosion area receiving rainfall. Rainfall intensity influences erosion, which is changed on slope length (Toy, 1997).

Wang and Liu (1999) studied a small catchment of loess upland and found that the loss of SOM was strongly correlative with SG in an exponential functional relationship: $N_S = a_2 \exp(b_2 \cdot x)$, N_S = nutrient loss quantity; x = SG; a_2 and b_2 are exponent parameters, $a_2 > 0$ and $b_2 > 0$). Peng et al. (2002) constructed a simulation experiment of flushing on different gradients SLs. Their results also showed that the concentration of potassium ion with runoff increases with increasing SG in an exponential fashion. However, Liu and Li (1995) found that the loss of nutrients increased with SG as a power function is suitable when SG is more than 12°, but as a linear relation when SG is less than 12°. The difference may be due to the different soil properties, rainfall intensity or other influences.

Soil texture directly influences the infiltration coefficient of rainwater into subsurface soil, and then influences the runoff generation velocity and runoff discharge. TP loss from SLs is not large and depends greatly on sediment amounts carried off the lands. Clay particles may contain more than 1400 mg kg^{-1} of TP while TP in sand can be as low as 450 mg kg^{-1} (Aase et al., 2003). Tightly bound clay has a much lower erodibility factor and thus is more resistant to the external forces favoring erosion than a sandy soil. Good structure soil has high porosity and is well permeated. In this way, soil water can infiltrate soil and reduces the surface runoff. The soil density also affects the infiltration velocity and stabilization time of seepage, which will influence transport of nutrients in SL surface soils. Influence of water content or porosity of soil on transfer of TP is mainly due to the balance between aeration, which diminishes with water content and favorable humid conditions for microbial biomass (Porporato et al., 2003). High water content in soil favors diffusibility of nutrients. Generally, as water content increases, the quantity of capillary water increases and the diffusion coefficient becomes larger (Cai et al., 1996). In this way, the runoff would have a larger flushing action on surface soils and lead to more soil erosion and nutrient loss. Conversely, soil erosion is bigger when weak rainfall. The nitrate loss will increase proportionately as the increment of water content (Porporato et al., 2003). The nutrient loss is also correlative to the nutrient content in soil. As soil-P increases the particulate and dissolved forms of P, along with runoff, will increase (Sharpley, 1985; Pote et al., 1996).

Rainfall will cause different effects on the transfer of nutrients on SL with different vegetation coverage (VC) (Yan and Chen, 1998). Under certain RI and SG, high VC can accelerate the subsurface flow and decelerate surface runoff. With a high intensity rainfall, an uncovered SL is prone to form a soil-water membrane, which restrains water infiltrating in soil, leading to runoff when soil is still not saturated (Cai et al., 1996). The root systems of plants facilitate infiltration and may reduce nutrient loss by adhering soil particles and blocking surface runoff on SL. Branches and leaves decrease the influence of raindrops on the initiator of the erosion process. Therefore, the subsurface flux in slope soil covered with vegetation is more than uncovered. In other words, the VC decreases the runoff output. The higher the coverage, the less the soil erosion or nutrient loss.

Zhang and Wang (1996) monitored the SL in the Three-Gorge region of the Yangtze River basin. They found that soil erosion (or nutrient loss) increased quickly with increasing SG when the VC ratio was less than 0.60 and increased slowly when the VC ratio was between 0.60 and 0.80. However, SG will not affect the soil erosion in general when the VC ratio was more than 0.80. Shan and Yin (2001) studied the transport of P in different VC-ratio SL in the Chao Lake basin (China) after rainfall. Results showed that the concentration and output load of TP from SL covered vegetation was observably less than that from barren SL. Zhang and Shao (2003) studied the loss of nitrogen on SL with different VC ratios. Results showed that the losses of soil ammonium-N were 87.08, 44.31, 25.16 and 13.71 kg km^{-2}, corresponding to 0%, 20%, 40% and 60% VC ratios respectively. Nitrate-N and TN losses were 85.50, 74.05, 63.95, 56.23 kg km^{-2} and 180, 1180, 1980, and 7510 kg km^{-2} respectively.

Conclusions

The following conclusions were drawn from this study: 1) The rainfall intensity (RI) has a remarkable influence on the loss of soil and nutrients on SL, but a small influence on nutrient concentrations in runoff and a significant influence mainly on the runoff flow. 2) The slope length influences the nutrient loss on SL by affecting the soil erosion area that receives rainfall. 3) The SG influences the loss of nutrients by runoff flux and velocity on sloping lands. As SG decreases to some small value, the nutrient loss decreases because of the increase in infiltration. 4) The soil properties such as influence the motion of soil water and the transfer and form of nutrients in soil by influencing oxidation and deoxidation directly as well as the infiltration coefficient. 5) Different sloping lands need to be managed in different ways. In order to carry out the best management practices of watershed land, a new management mode based on the basic knowledge of sloping lands should be allowed. Changing fertilization, improving fertilization technology, adjusting vegetation coverage, and cultivation systems of arable land on different sloping lands within a watershed need to be further studied.

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