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ORIGINAL PAPER

The role of soil surface water regimes and raindrop impact on hillslope soil erosion and nutrient losses

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Abstract Few investigations have addressed the interaction between soil surface water regimes and raindrop impact on nutrient losses, especially under artesian seepage condition. A simulation study was conducted to examine the effects on nitrogen and phosphorus losses. Four soil surface water regimes were designed: free drainage, saturation with rainfall, artesian seepage without rainfall, and artesian seepage with rainfall. These water regimes were subjected to two surface treatments: with and without raindrop impact through placing nylon net over soil pan. The results showed saturation and seepage with rainfall conditions induced greater soil loss and nutrient losses than free drainage condition. Nutrient concentrations in runoff from artesian seepage without rainfall condition were 7.3–228.7 times those from free drainage condition. Nutrient losses by runoff from saturation and seepage with rainfall conditions increased by factors of 1.30–9.38 and 2.81–40.11 times, and the corresponding losses with eroded sediment by 1.37–7.67 and 1.75–9.0 times, respectively, relative to those from free drainage condition. Regardless of different soil surface water regimes, raindrop impact increased 20.90–94.0 % nutrient losses with eroded sediment by promoting soil loss, but it only significantly enhanced nutrient transport to runoff under free drainage condition.

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1 Introduction

Current nonpoint source (NPS) pollution is one of the major environmental concerns in the world. About 30–50 % of the world's land has been affected by NPS pollution (Dennis and Corwin 1998). Agricultural activities, especially the excessive use of nitrogen (N) and phosphorus (P), are recognized as an important cause of NPS pollution (Pimentel 1993; Tsihrintzis and Hamid 1997). So, minimizing N and P losses from agricultural land is necessary to protect receiving water bodies from eutrophication and groundwater from pollution. Extensive researches have examined the effects of various factors on N and P losses including rainfall intensity, soil properties, land topography, crop cover, and soil conservation practices (Delcampillo et al. 1999; Havis et al. 1992; Mcdowell and Sharpley 2002; Sims et al. 1998; Walton et al. 2000; Zhang et al. 2000). Soil surface water regime is one of the most important factors governing the amounts and forms of nutrient loss, while less literature are available to show how it affects nutrient transport to runoff and eroded sediment.

At a hillslope scale, conditions at the soil surface varying with the topographic position can cause different hydrologic regimes. Free drainage condition generally occurs at the upper backslope, and seepage condition represents the hydraulic regime at the middle/lower backslope. The generation of seepage flow depends on soil conditions, water conductivity, and rainfall properties (Ticehurst et al. 2003; Jia et al. 2007), while one necessary condition for seepage occurrence is that soil water reaches saturated. Therefore, soil surface water regimes include free drainage, saturation, and seepage conditions. Zhang and Zheng (2007) studied the effects of near-surface soil water conditions on soil erosion process, and found that soil loss from saturation condition, 75 % of soil moisture, and 50 % of soil moisture were 50, 25, and 1.3 times greater than that from 25 % of soil moisture, respectively. In respect of seepage flow, it not only greatly enhanced soil loss (Huang and Laflen 1996; Gabbard et al. 1998; Huang et al. 2001), but also changed erosion regime. Zheng et al. (2000) reported the dominant erosion process shifted from detachment-limited to transport-limited regime when soil surface water regimes shifted from free drainage condition to seepage condition. Further, seepage-induced rills and gullies were observed in fields with an impeding layer especially during the wet season. Along with the increase in soil loss induced by saturated and seepage flow, nutrient loss would sharply increase.

Although the effects of soil surface water regimes on soil erosion were well documented, a few data were available for the effects on nutrient loss, especially under seepage condition. When artesian seepage flowed from the impervious layer to soil surface, the accumulation of nutrients in the topsoil layer would increase the potential for seepage flow to transport chemicals. According to long-term field data, researchers found that seepage flow was an important pathway for chemical loss. Baker and Laflen (1983) stated that dissolved nutrient from seepage flow was the maximum source of nonpoint pollution. Also, sorbed chemical loss was closely associated with seepage flow, although it was strongly absorbed by soil particles (Gburek et al. 2000; Heathwaite and Dils 2000). Nutrient concentration from seepage flow was several folds greater than that from surface flow (Peterson et al. 2002; Silva et al. 2005; Jia et al. 2007), and nutrient loss from seepage flow was more than that from runoff (Pionke et al. 2000). Although known the importance of nutrient loss by seepage flow, less attention was given to the transport mechanism. This induced consideration for soil surface water regimes contributions to nutrient loss was largely been neglected in assessments, due to the lack of experimental observations and insufficient understanding of lost processes.

To our knowledge, there have been only two studies that specifically investigated nutrient loss and transport mechanism under different soil surface water regimes in the laboratory. Zheng et al. (2004) found that NO_3–N and PO_4–P concentrations in runoff from seepage condition were 1,000 and 7 times greater than those from free drainage condition, and saturation and seepage conditions caused greater chemical transport than drainage condition. Tian et al. (2009) studied chemical transport mechanism from soil to surface runoff under the case without rainfall and reported that the Bernoulli effect and diffusion were the dominant mechanisms under free drainage and saturation conditions, while convection played a dominant role under seepage condition. An important shortage to Zheng's study was that they neglected nutrient loss by eroded sediment. Tang et al. (2008) identified nutrient loss by a multi-scale monitoring in an agricultural catchment and found about 50 % of nitrogen and more than 97 % of phosphorus lost in particulate forms. The weakness for Tian's study was that the functions of raindrop impact on nutrient loss were not considered. Therefore, it is necessary to quantify how raindrop impact affects nutrient loss under different soil surface water regimes, especially for saturation and seepage conditions.

It is widely recognized that soil erosion is initiated by raindrop impact, and raindrop impact enhances soil detachment and runoff disturbance (Schultz et al. 1985; Guy et al. 1987; Gabet and Dunne 2003; Kinnell 2005). Process-based erosion models have been developed to predict raindrop-induced soil detachment rate, such as water erosion prediction project (WEPP) model (Nearing et al. 1989) and Rose model (Hairsine and Rose 1991). Nevertheless, none of which explicitly accounted for the effects of raindrop impact on soil erosion under seepage condition. For the effects on nutrient transport to surface runoff, the literatures reflected two opposite interpretations. Some researches reported that the increase in runoff disturbance caused by raindrop impact enhanced nutrient desorption from soil particles (Dunne and Zhang 1991; Thompson et al. 2001), while others pointed that nutrient concentration in surface runoff was reduced (Soileau et al. 1994; Zhang et al. 2004). Although process-based chemical transport model that incorporated the solute transport rate of raindrop-controlled processes was developed, the model was only applied to chemicals under saturated condition (Gao et al. 2005). To improve the reliability and accuracy of chemical transport model, additional efforts are needed to study raindrop impact effects on nutrient transport mechanisms under different soil surface water regimes.

In this study, we hypothesized that soil surface water regimes showed different influences on nutrient losses and raindrop impact greatly affected nutrient losses but with different influence degrees under different soil surface water regimes. An experimental study by using simulation rainfall was designed to quantify the interaction between soil surface water regimes and raindrop impact on soil erosion as well as nutrient loss.

2 Materials and methods

2.1 Experimental equipment

The rainfall simulation experiment was conducted in the rainfall simulation laboratory of the state key laboratory of soil erosion and dryland farming on the Loess Plateau, Yangling city, China. A rainfall simulator system with side-sprinkle was used to apply rainfall. This rainfall simulator can be set to any selected rainfall intensity ranging from 20 to

300 mm h^{-1} by nozzle sizes and water pressure, and these nozzles are approximately 16 m high above the soil surface. Simulated storm with uniformity of above 90 % has the similar raindrop size and distribution to natural rainfall. The experimental soil pan is 1 m long, 0.5 m wide, and 0.45 m deep with 16 drainage holes (2 cm aperture) at the bottom. A constant head tank was designed to supply water to soil pan from the bottom through these drainage holes. Details of the experimental setup are shown in Fig. 1.

The used soil was collected from the upper 20 cm of plow layer in maize field near Liujia town (44°43′N,126°11′E), Jilin Province, where is the center of black soil area in the northeast China. The soil water content at collection time was 13.8 %. The collected soil was air-dried and then broken into subangular-blocky clods less than 4 cm in size before packing into the soil pan, but was not sieved or ground in order to keep the in situ soil aggregation fabric. The tested soil was a silt loam soil, consisting of 3.32 % sand (2–0.05 mm), 76.38 % silt (0.05–0.002 mm), and 20.30 % clay (<0.002 mm). Aggregate stability analysis showed that the experiment soil included 23.82 % of <0.25 mm soil aggregate and 30.06 % of >5 mm soil aggregate, and the mean weight diameter (MWD) was 2.16 mm by the dry sieving method (Institute of Soil Science, Chinese Academy of Sciences 1978). The pH in water was 5.92, measured with a 1:2.5 solid-to-water ratio on a weight basis. For chemical properties, the soil contained 23.81 g kg^{-1} soil organic matter, 18.08 mg kg^{-1} NO_3–N, 16.01 mg kg^{-1} NH_4–N, and 1.48 mg kg^{-1} PO_4–P.

2.2 Experimental design

Experimental treatments in this study included four soil surface water regimes: free drainage with rain (FD+R), a saturated soil water profile with rain (Sa+R), artesian

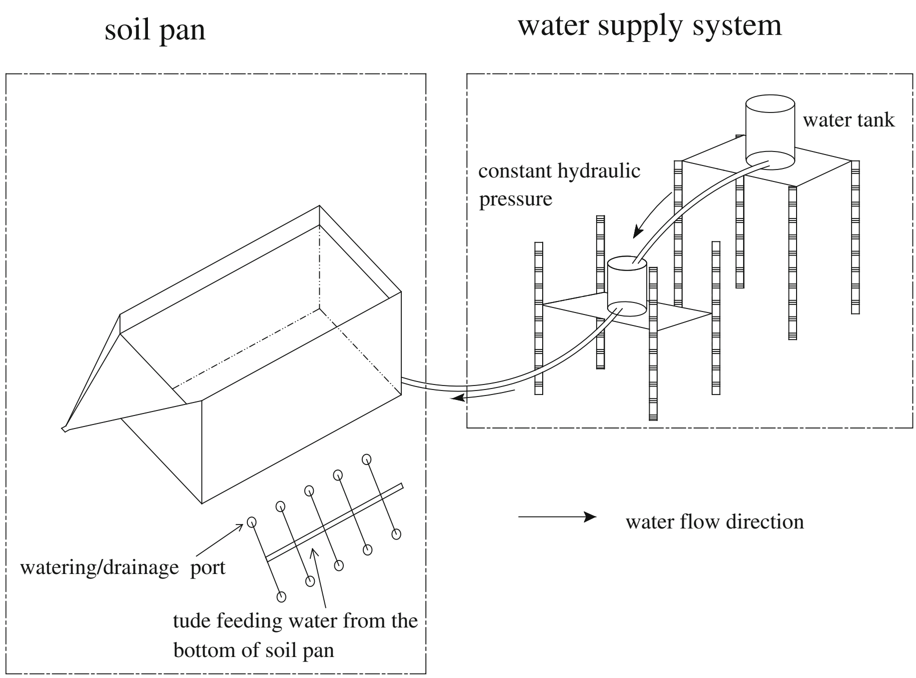

Fig. 1 Schematic diagram of equipment setup

seepage under 20 cm of water pressure without rain (SP20), and artesian seepage under 20 cm hydrologic pressure with rain (SP20+R). These soil surface water regimes were subjected to two treatments: raindrop impact present and absent. For the treatment raindrop impact present, the soil surface of soil pan was bare and fallow; for the treatment raindrop impact absent, nylon net with 1 mm aperture was placed 10 cm over the test soil pan, which reduced the raindrop kinetic energy by 99.6 % (Zheng et al. 1995). The occurrence frequency of 60–70 mm h^{-1} intensity was 36 % according to the observed data from institute of soil and water conservation in Hei Longjiang, which could cause moderate intensity of soil erosion in the black soil region (Zhan et al. 1998). Therefore, the typical 60 mm h^{-1} of rainfall intensity was chosen in this study. For each treatment, three replicates were made. In this study, fertilizer ($CO(NH_2)_2$ and $Ca_2(PO_4)_2H_2O$) were applied to soil pan before simulated rainfall and the input rate was 200 kg N $ha^{-1}$and 90 kg P ha^{-1}.

2.3 Preparation of soil pans

Before packing the soil pan, soil water content was measured to determine the amount of soil needed to obtain a bulk density of 1.20 g cm^{-3}. A 10-cm sand layer was packed at the bottom of soil pan that allowed free drainage of excessive water. Then, a 20-cm layer of black soil was packed in 5-cm increments on top of sand layer. Each soil layer was raked lightly before packing the next layer to ensure uniformity. A top 2-cm layer of soil was thoroughly mixed with 21.4 g CO $(NH_2)_2$ and 64.7 g Ca_2 $(PO_4)_2{\cdot}H_2O$ before packing. For each rain storm event, four soil pans were prepared: two were used for collecting pre-run soil profile samples and the other two for performing the simulated rainfall experiments.

A saturated condition was created when the water level of the supply tank was set at soil surface of soil pan. Identifying soil saturation was that water droplets occurred on soil surface and distributed the most area of soil pan. A seepage condition was created when the water level of supply tank was set 20 cm above soil surface of the tested soil pan. Identifying seepage occurrence was that seepage flowed out from the outlet of soil pan and remained steady state. The supply water system maintained constant water levels during the entire rainfall for Sa+R, SP 20, and SP 20+R treatments. For free drainage condition, soil pan drained freely under gravity.

2.4 Experimental procedures and analytical methods

A pre-rain with 20 mm h^{-1} intensity was applied to soil pan until runoff occurred, which lasted about 40 min. To eliminate raindrop-induced surface sealing and splash, the nylon net was placed over soil pan during this phase. The pre-rain allowed the mixed-in fertilizer to leach into the deeper layer of the soil profile. Additionally, this rain created uniform surface soil moisture condition and reduced surface variability in the micro-relief and smoothness that was created during the packing process.

One day after the pre-wetting phase, soil pans were adjusted to 5° slope and subjected to the designed soil surface water regimes. A rainfall intensity of 60 mm h^{-1} was applied to FD+R, Sa+R, and SP20+R treatments for 60 min. For Sa+R and SP20+R treatments, the rainfall was supplied after soil reached saturated or when seepage occurred. During simulated rainfall, runoff samples were continuously collected at 2-min intervals during the early stages by 5-L buckets. When runoff rate was relatively stabilized, the sampling interval was increased to 5 min. For SP20 treatment, runoff samples were continuously collected for durations of 5 min due to the low seepage flow. During each rain storm, a 100-mL rain sample was collected to obtain reference of N and P contents. The rainfall amount was measured by four rain gauges around soil pans for each rainfall.

After each storm event, runoff samples were immediately weighed and then settled about 5 h to precipitate suspended sediments. A 100-mL supernatant liquid was taken from the settled runoff sample and filtered through 0.45-μm filter paper. The filtered solution was stored in refrigerator at 4 °C and analyzed within 24 h. Decanting the left clear supernatant, the remaining wet sediment was oven-dried at 50 °C for 24 h. The dried sediment was gravimetrically determined. Sediment concentration was defined as the ratio of dry sediment mass to runoff volume.

Soil samples, collected from soil pans before and after rainfall, were analyzed for soil water and nutrient content. The "before-run" soil samples were taken one day after the pre-wetting phase and the "after-run" samples were taken one day after the experiments. To ensure representation of the profile distribution, samples were taken at three different locations (25, 50, and 75 cm) along the length of soil pan. At each location, samples were collected at six depth intervals including 0–1, 1–2, 2–5, 5–10, 10–15, and 15–20 cm. Soil samples from a given depth increment were combined together. A small part of these soil samples was dried at 105 °C to determine soil water content, and the left was dried at 50 °C for nutrient analysis.

The dried sediment and soil samples were ground and then sieved through 1-mm screen. About 5 g of sieved sample was mixed with 50 g of deionized water in plastic bottles. The mixed samples were shaken for 30 min, centrifuged at 8,000 rpm for 10 min, and then filtered through 0.45-μm filter paper. Concentrations of NO_3–N and NH_4–N in runoff, eroded sediment, and soil samples were determined by the continuous flow analyzer and PO_4–P concentration by the molybdenum blue spectro-photometry method.

2.5 Statistical analysis

Comparisons of runoff, soil loss, sediment concentration, nutrient concentrations, and losses among soil surface water regimes were conducted using LSD test, and the values were statistically significant at the 95 % confidence. Mann–Whitney *U* test was used to identify the differences in nutrient concentrations and losses between the treatment raindrop impact present and absent. The Mann–Whitney *U* test is one of the most well-known nonparametric statistical hypothesis tests, assessing whether two independent samples of observations are drawn from the same or identical distributions. All analyses were performed using SPSS version 16.0 (SPSS company, Chicago, IL, USA).

3 Results and discussions

3.1 Runoff and soil loss

Rainfall ranged from 28.5 to 60.3 mm (Table 1). From Table 1, it can be seen that a wide range of differences in runoff and soil loss as soil surface water regimes were reversed from exfiltration to infiltration conditions. Seepage flow was 4.4 mm and induced little soil loss, which could be negligible. When soil surface was subjected to saturation and seepage conditions, an increased runoff and a higher soil loss was observed. Nevertheless, the increment was related to raindrop impact. Runoff from SP20+R and Sa+R treatments was statistically higher than that from FD+R treatment, with an average magnitude of

1.53–1.81 and 1.79–1.99 times greater, respectively. The increased runoff was the direct result of the added supply flow. However, the difference between SP20+R and Sa+R treatment depended on raindrop impact. The difference in runoff among soil surface water regimes may influence nutrient transport to runoff and eroded sediment.

For soil loss, it increased gradually with the variation of soil surface water regimes from infiltration to exfiltration condition. This differed from Stolte et al. (1990). They studied the effects of seepage on soil erosion from a loam and sand, and found seepage effects on sand but not on the loamy soil. In the presence of raindrop impact, compared with FD+R treatment, soil loss from Sa+R and SP20+R treatments increased by 11.4 and 68.1 %, respectively, but no significant difference was found between FD+R and Sa+R treatment; compared with Sa+R treatment, soil loss from SP20+R treatment significantly increased by 50.8 %. This is because soil strength and soil's resistance to detachment were greatly reduced under saturation and seepage conditions, namely soil stress became lower, while the reduction of the effective soil stress was in proportion to the hydraulic potential gradient (Howard and McLane 1988). However, no significant difference in sediment concentration was observed among soil surface water regimes, although runoff increased greatly when soil surface water regimes changed from infiltration to exfiltration condition. This indicated soil detachment was limited under saturation and seepage condition. In the absence of raindrop impact, soil loss from Sa+R and SP20+R treatments was statistically greater than that from FD+R treatment, increasing by 67.1 % and 74.5 %, respectively. However, when soil surface water regimes shifted from Sa+R to SP20+R treatment, it was more difficult to detach soil particle as the flow depth increased because overland flow may not have the capacity to detach material from within the underlying surface (Kinnell 2005), so soil loss only increased by 4.3 %. The comparison of sediment concentration between them firmly confirmed soil detachment rather than transport was limited for seepage condition. The average sediment concentration from Sa+R treatment was only 1.04 times greater than that from SP20+R treatments.

As noted above, saturation and seepage conditions promoted soil loss. The increased soil loss implied that sediment regime would change when soil surface was subjected to

Table 1 Runoff, soil loss, and sediment concentration under different soil surface water regimes

Treatment[a]	Soil surface water regimes[b]	Runoff (mm)	Soil loss ($g\ m^{-2}$)	Sediment concentration ($g\ L^{-1}$)
Raindrop impact present	FD+R	33.66 (3.99[c]) c[d]	53.68 (6.60) b	1.59 (0.25) a
	Sa+R	51.39 (2.94) b	59.75 (7.02) b	1.29 (0.21) a
	SP 20	4.38 (0.01) d	_	_
	SP 20+R	60.30 (0.00) a	90.21(1.34) a	1.54 (0.29) a
Raindrop impact absent	FD+R	28.49 (1.60) c	15.20 (0.82) b	0.43 (0.16) b
	Sa+R	51.56 (6.74) a	25.41(1.16) a	0.55 (0.13) a
	SP 20+R	56.82 (0.41) a	26.53 (0.79) a	0.53 (0.19) a

[a] Raindrop impact present: the soil surface of soil pan was bare and fallow; raindrop impact absent: a nylon net with 1 mm aperture was placed 10 cm over the test soil pan

[b] FD+R, free drainage with rain; Sa+R, a saturated soil water profile with rain; SP20, artesian seepage under 20 cm hydrologic pressure without rain; SP 20+R, artesian seepage under 20 cm hydrologic pressure with rain

[c] The data in parentheses are standard deviations

[d] Mean values for a treatment followed by identical letters are not significantly different at the 95 % confidence level according to LSD tests

exfiltration condition. However, in current soil erosion models, such as WEPP and universal soil loss equation (USLE), little consideration is given to sediment regime under saturation and seepage conditions. Additionally, the comparison of runoff and soil loss showed that the influence degree of soil surface water regimes on soil erosion was connected with raindrop impact. Therefore, the interaction between soil surface water regimes and raindrop impact on soil erosion should be addressed.

For a given soil surface water regime, runoff was not markedly different between the case with and without raindrop impact, but soil loss for the condition without raindrop impact was significantly lower than that with raindrop impact for all soil surface water regimes. This indicated the effect of raindrop impact on soil loss was more sensitive than that on runoff. When soil surface water regimes shifted from FD+R to Sa+R then to SP20+R treatment, soil loss was reduced by 71.6, 59.4, and 70.6 % as the elimination of raindrop impact, respectively. If the difference in soil loss between raindrop impact presence and absence was regard as the raindrop erosion, raindrop erosion accounted for 59.4–71.6 % of the total soil loss, indicating raindrop impact still made a great contribution to soil loss when soil water reached saturated.

3.2 Concentrations and losses of NO_3–N, NH_4–N, and PO_4–P in runoff

The effects of difference in soil surface water regimes were also observed on the measured nutrient concentrations and losses in runoff. Although seepage flow was relatively low, it made a great contribution to nutrient losses (Table 2). About 82.32 mg L^{-1} of NO_3–N concentration from SP20 treatment substantially exceeded the permissible drinking water standard of 10 mg L^{-1} and the measured PO_4–P concentration of 1.02 mg L^{-1} was higher than the accepted standard of 0.1 mg L^{-1} (USEPA 1996). Therefore, surface runoff from SP20 treatment tested in this study could potentially lead to serious pollution of groundwater. NO_3–N, NH_4–N, and PO_4–P concentrations from SP20 treatment were 228.7, 38.4, and 7.3 times greater than those from FD+R treatment, respectively. Regardless of raindrop impact present or absent, if one compares concentrations and losses of NO_3–N, NH_4–N, and PO_4–P from FD+R and Sa+R treatments with those from SP20+R treatment, then one notices an increase in the measured values. These results indicated that saturation and seepage conditions promoted N and P transport to runoff.

In the presence of raindrop impact, only NO_3–N concentrations from FD+R, Sa+R, and SP20+R treatments were statistically different, although nutrient concentrations gradually increased as soil surface water regimes shifted from infiltration to exfiltration condition. NO_3–N concentrations from Sa+R and SP20+R treatments were 4.06 and 14.81 times greater than those from FD+R treatment, respectively. However, nutrient loss was significantly different among FD+R, Sa+R, and SP20+R treatments. Nutrient losses from Sa+R and SP20+R treatments were statistically higher than those from FD+R treatment, with magnitudes of 5.25 and 26.83 times greater for NO_3–N, 2.07 and 3.15 times greater for NH_4–N, 2.18 and 2.81 times greater for PO_4–P, respectively. In the absence of raindrop impact, only NO_3–N concentrations from Sa+R and SP20+R treatments were statistically higher than those from FD+R treatment, with a magnitude of 5.75 and 20.96 times greater, respectively. Nevertheless, nutrient losses from Sa+R and SP20+R treatments were statistically greater than those from FD+R treatment. Compared with FD+R treatment, NO_3–N, NH_4–N, and PO_4–P losses from Sa+R treatment were 9.38, 1.30, and 2.63 times greater, respectively, and the corresponding nutrient losses from SP20+R increased by factors of 40.11, 3.20, and 3.48 times, respectively.

Table 2 Concentrations and losses of NO_3–N, NH_4–N, and PO_4–P in runoff under different soil surface water regimes

Treatment[a]	Soil surface water regimes[b]	Concentrations			Losses		
		NO_3–N ($mg\ L^{-1}$)	NH_4–N ($mg\ L^{-1}$)	PO_4–P ($mg\ L^{-1}$)	NO_3–N ($g\ ha^{-1}$)	NH_4–N ($g\ ha^{-1}$)	PO_4–P ($g\ ha^{-1}$)
Raindrop impact present	FD+R	0.36 (0.05[c]) d[d]	0.39 (0.09) c	0.14 (0.01) b	121.14 (0.00) c	131.93 (20) d	46.70 (3.03) c
	Sa+R	1.46 (0.64) c	0.53 (0.11) bc	0.18 (0.07) b	752.73 (300) b	269.84 (70) c	102.00 (30.03) b
	SP 20	82.32 (0.13) a	15.00 (0.07) a	1.02 (0.01) a	3,612.20 (0.00) a	0.66 (0.00) a	40.00 (0.01) c
	SP 20+R	5.33 (0.02) b	0.68 (0.00) b	0.22 (0.01) b	3,211.11 (120) a	407.42 (140) b	131.31 (0.94) a
Raindrop impact absent	FD+R	0.28 (0.06) c	0.35 (0.03) b	0.10 (0.04) a	80.18 (10) c	99.20 (0.00) c	27.70 (9.55) b
	Sa+R	1.61(0.56) b	0.44 (0.06) b	0.19 (0.06) a	828.36 (300) b	227.90 (30) b	100.50 (33.16) a
	SP20+R	5.87 (2.21) a	0.73 (0.03) a	0.22 (0.01) a	3,333.67 (1,280) a	416.36 (100) a	124.21 (3.76) a

[a] Raindrop impact present: the soil surface of soil pan was bare and fallow; raindrop impact absent: a nylon net with 1 mm aperture was placed 10 cm over the test soil pan

[b] FD+R, free drainage with rain; Sa+R, a saturated soil water profile with rain; SP20, artesian seepage under 20 cm hydrologic pressure without rain; SP 20+R, artesian seepage under 20 cm hydrologic pressure with rain

[c] The data in parentheses are standard deviations

[d] Mean values for a treatment followed by any identical letters are not significantly different at the 95 % confidence level according to LSD tests

The differences of nutrient transport pathway in soil profile between infiltration and exfiltration could explain why saturation and seepage conditions enhanced nutrient transport to runoff. For free drainage condition, nutrients leached into the deeper layer of soil profile or sublayer as rainfall processed. After rainfall, NO_3–N concentration from FD+R treatment at 15–20 cm soil depth increased by 103.20 % relative to that before rainfall (Table 3). For seepage condition, nutrient moved with seepage flow to soil surface. After rainfall, NO_3–N concentration from SP20 treatment in the 0–10 cm topsoil increased by 61.65 %, and the corresponding NH_4–N and PO_4–P concentrations in the 2–5 cm topsoil increased by 10.64 % and 32.83 %, respectively, compared with those before rainfall. Moreover, after rainfall, NO_3–N and NH_4–N concentrations in the 0–2 cm topsoil from SP20 treatment were higher than those from FD+R treatment; NO_3–N, NH_4–N, and PO_4–P concentrations in the 0–5 cm topsoil from SP20+R treatment increased by 106.47 %, 27.98 %, and 10.72 % relative to those from FD+R treatment, respectively, although nutrient losses from seepage condition were statistically greater than those from free drainage condition. This further demonstrated that nutrient transferred from subsurface of soil profile to soil surface as the movement of seepage flow.

The comparison of nutrient losses suggested that the effect of soil surface water regimes on nutrient transport to runoff for the case with raindrop impact differed from that without raindrop impact. Maybe, raindrop impact showed different influence degrees on nutrient losses under different soil surface water regimes. Statistical analysis (Mann–Whitney *U* test) showed that difference in nutrient concentration between raindrop impact present and absent became insignificant for all soil surface water regimes, although raindrop impact could enhance nutrient concentration by increasing nutrient diffusion and mixing (Ahuja 1990). This is because the lower soil loss in the absence of raindrop impact increased friction factors of sheet flow (Pan and Shang guan 2006) and the increase in surface roughness induced more mobile nutrients transport to surface runoff (Ahuja et al. 1983). For nutrient losses, significant difference between with and without raindrop impact only was observed for FD+R treatment. Mineral N and P losses from FD+R treatment were reduced by 40.7 % and 28.0 % as the elimination of raindrop impact, respectively, indicating a portion of nutrients entered the flow through turbulent mixing of pore water and surface water caused by raindrop impact. This result was consistent with previous studies which reported nutrient loss by runoff was markedly reduced as the decrease in effective raindrop kinetic energy under free drainage condition (Dunne and Zhang 1991; Wang et al. 2002). For saturation and seepage conditions, raindrop impact showed slight influence on nutrient transport to runoff. This may be due to: when water was applied from the bottom of soil pan to either saturate the soil or induce seepage flow, the upward water movement brought nutrients to soil surface, causing higher concentrations at the top of soil layer, which masked the role of raindrop impact on nutrient losses to some extent.

3.3 Concentrations and losses of NO_3–N, NH_4–N, and PO_4–P in eroded sediment

Previous studies reported N and P concentrations in eroded sediment are enriched relative to those in the original soil (Flanagan and Foster 1989; Mcisaac et al. 1991). In many typical models of nonpoint pollution, enrichment ratio was taken as the distinctly important parameter to predict nutrient loss, such as agricultural nonpoint source pollution (AGNPS) (Young et al. 1989), soil and water assessment tool (SWAT) (Arnold et al. 1998), and erosion–productivity impact calculator (EPIC) (Sharpley and Williams 1990). In this study, NO_3–N, NH_4–N, and PO_4–P concentrations in eroded sediment were 48.61–149.21, 13.81–53.26, and 0.40–3.03 mg kg^{-1}, and the corresponding enrichment ratios were

Table 3 The vertical distribution of NO_3–N, NH_4–N, and PO_4–P concentrations in soil profile before and after rainfall

Soil depth (cm)	NO_3–N (mg kg^{-1})			NH_4–N (mg kg^{-1})			PO_4–P (mg kg^{-1})		
	Before rainfall	After rainfall		Before rainfall	After rainfall		Before rainfall	After rainfall	
		FD+R[a]	SP 20[b]		FD+R	SP 20		FD+R	SP 20
0–1	5.02 (1.07[c])	4.87 (0.11)	16.27 (0.63)	9.59(0.64)	8.35 (0.55)	8.00 (0.80)	6.33 (0.09)	3.04 (0.42)	2.64 (0.01)
1–2	4.67 (0.19)	8.14 (0.10)	13.04 (0.62)	10.65(1.54)	8.17 (0.74)	8.97 (0.82)	9.96 (1.18)	9.68 (0.26)	9.55 (1.04)
2–5	5.99 (0.79)	6.13 (0.97)	17.70 (0.42)	13.02 (1.33)	11.29 (0.52)	14.57 (1.29)	4.81 (0.45)	8.26 (0.93)	7.16 (1.69)
5–10	16.30 (1.75)	12.17 (0.02)	30.82 (0.59)	23.35 (1.06)	20.87 (1.52)	24.68 (3.92)	0.80 (0.18)	1.36 (0.25)	0.83 (0.14)
10–15	40.49 (4.99)	20.66 (1.55)	28.21 (0.18)	18.86 (0.86)	21.38 (1.33)	20.41 (0.76)	1.05 (0.06)	1.10 (0.32)	0.69 (0.16)
15–20	18.71 (1.24)	38.00 (0.99)	13.89 (0.02)	16.50 (0.93)	17.46 (2.73)	15.03 (1.48)	1.45 (0.13)	1.38 (0.06)	0.79 (0.09)

[a] FD+R, free drainage with rain

[b] SP20, artesian seepage under 20 cm hydrologic pressure without rain

[c] The data in parentheses are standard deviation

Table 4 Concentrations and losses of NO_3–N, NH_4–N, and PO_4–P in eroded sediment under different soil surface water regimes

Treatment[a]	Soil surface water regimes[b]	Concentrations			Loss		
		NO_3–N (mg kg^{-1})	NH_4–N (mg kg^{-1})	PO_4–P (mg kg^{-1})	NO_3–N (g ha^{-1})	NH_4–N (g ha^{-1})	PO_4–P (g ha^{-1})
Raindrop impact present	FD+R	48.61 (19.05[c]) a[d]	13.81 (0.51) a	1.87 (0.63) a	26.09 (7.60) b	7.41 (0.63) b	1.00 (0.43) b
	Sa+R	58.59 (16.38) a	21.37 (10.36) a	3.03 (1.28) a	35.00 (1.27) b	12.76 (0.25) a	1.81 (0.03) a
	SP 20+R	55.40 (0.07) a	14.54 (0.38) a	2.47 (0.02) a	49.38 (0.07) a	12.96 (0.03) a	2.21 (0.01) a
Raindrop impact absent	FD+R	76.54 (14.82) a	18.24 (3.57) b	0.40 (0.07) b	11.77 (1.63) c	2.79 (0.69) c	0.06 (0.01) b
	Sa+R	80.62 (34.61) a	24.41 (0.47) b	1.81 (0.62) a	20.40 (0.78) b	6.17 (1.11) b	0.46 (0.18) a
	SP 20+R	149.21 (39.32) a	53.26 (22.52) a	2.06 (0.55) a	39.06 (9.10) a	9.72 (0.03) a	0.54 (0.30) a

[a] Raindrop impact present: the soil surface of soil pan was bare and fallow; raindrop impact absent: a nylon net with 1 mm aperture was placed 10 cm over the test soil pan

[b] FD+R: free drainage with rain; Sa+R: a saturated soil water profile with rain; SP20: artesian seepage under 20 cm hydrologic pressure without rain; SP 20+R: artesian seepage under 20 cm hydrologic pressure with rain

[c] The data in parentheses are standard deviations

[d] Mean values for a treatment followed by any identical letters are not significantly different at the 95 % confidence level according to LSD tests

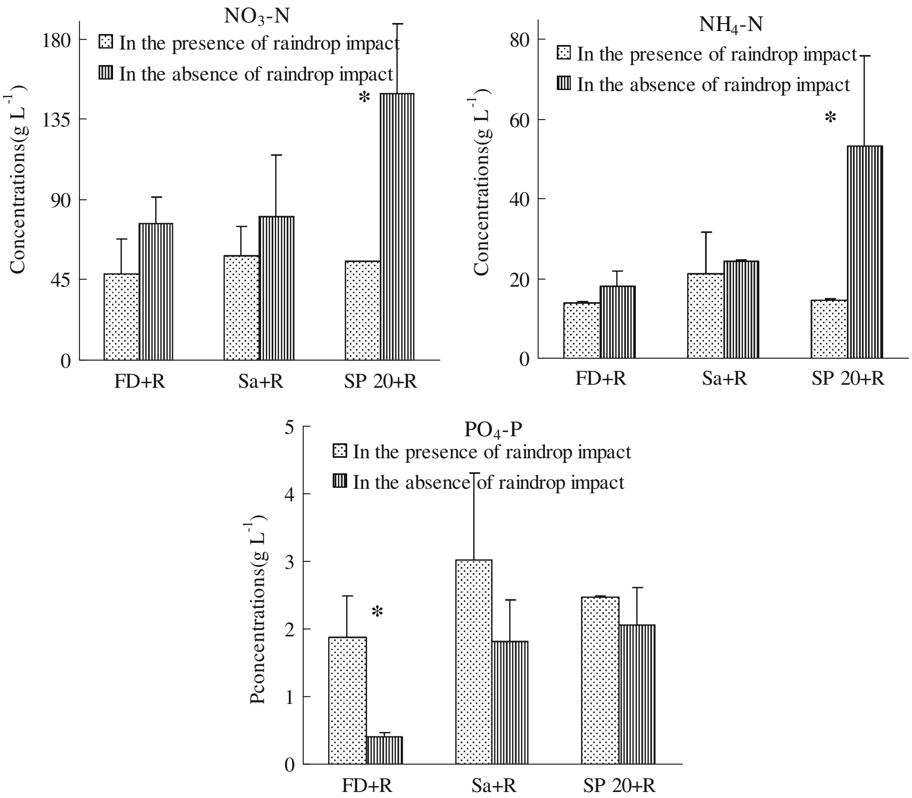

Fig. 2 Comparison of NO_3–N, NH_4–N, and PO_4–P concentrations in eroded sediment between in the presence and absence of raindrop impact under different soil surface water regimes. FD+R, free drainage with rain; Sa+R, a saturated soil water profile with rain; SP20+R, artesian seepage under 20 cm of hydrologic pressure with rain. In the presence of raindrop impact: the soil surface of soil pan was bare and fallow; in the absence of raindrop impact: a nylon net with 1 mm aperture was placed 10 cm over the test soil pan. Error *bars* indicate standard derivations. * = statistically significant difference between raindrop impact present and absent

2.69–8.25, 0.79–3.33, and 1.22–2.05, respectively (Table 4). The high enrichment ratio may induce more nutrient loss.

From Table 4, it can be seen that nutrient losses with eroded sediment were determined not only by soil surface water regimes but also raindrop impact. In the presence of raindrop impact, there was no significant difference in nutrient concentrations among soil surface water regimes. NO_3–N, NH_4–N, and PO_4–P losses from Sa+R and SP20+R treatments were significantly higher than those from FD+R treatment, with magnitudes of 1.37 and 1.84 times, 1.72 and 1.75 times, 1.81 and 2.21 times greater, respectively. In the absence of raindrop impact, when soil surface water regimes changed from FD+R to Sa+R, then to SP20+R treatment, both nutrient concentrations and losses gradually increased; nutrient losses from Sa+R and SP20+R treatment were statistically greater than those from FD+R treatment, with magnitudes of 1.73 and 3.32 times for NO_3–N, 2.21, and 3.48 times for NH_4–N, 7.67, and 9 times for PO_4–P greater, respectively. These findings further confirmed saturation and seepage conditions promoted nutrient loss.

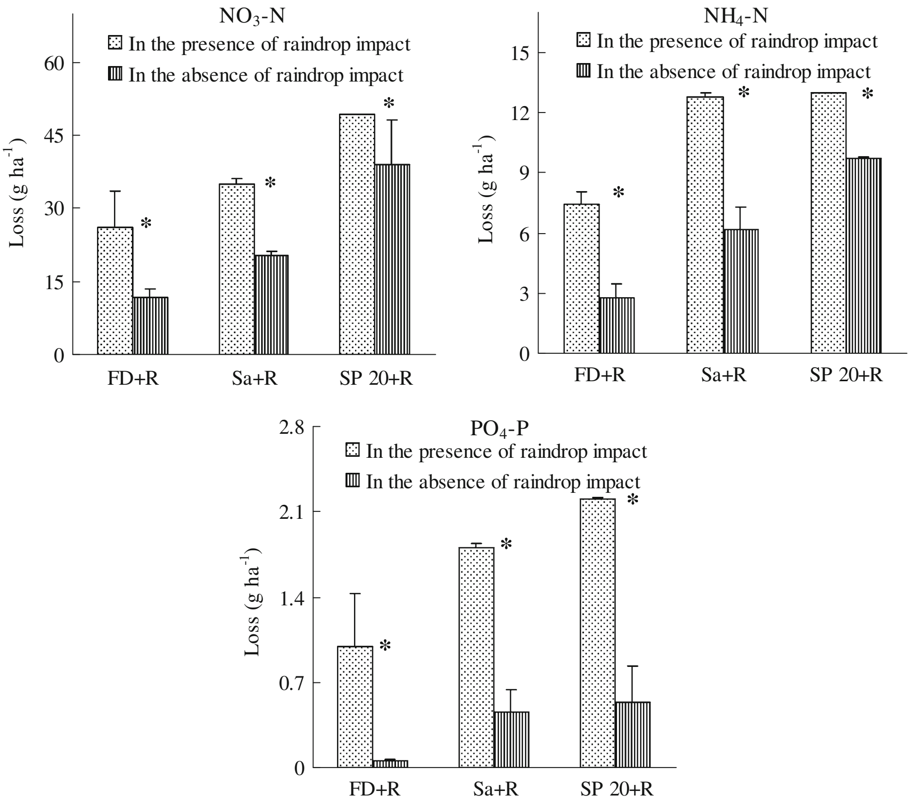

Fig. 3 Comparison of NO_3–N, NH_4–N, and PO_4–P losses in eroded sediment between the presence and absence of raindrop impact under different soil surface water regimes. FD+R, free drainage with rain; Sa+R, a saturated soil water profile with rain; SP20+R, artesian seepage under 20 cm of hydrologic pressure with rain. In the presence of raindrop impact: the soil surface of soil pan was bare and fallow; in the absence of raindrop impact: a nylon net with 1 mm aperture was placed 10 cm over the test soil pan. Error *bars* indicate standard derivations. * = statistically significant difference between raindrop impact present and absent

The MWD of soil aggregate became 0.52 mm by the Yoder method (Institute of Soil Science, Chinese Academy of Sciences 1978) and decreased by 75.93 % relative to that by the dry sieving method. Wang (2009) studied the soil aggregate breakdown mechanism of the black soil by the Le Bissonnais method and found MWD values from slow wetting treatment, wet-stirring treatment, and fast-wetting treatment were 0.19–1.33 mm, 0.20–0.67 mm, and 0.53–1.66 mm, respectively, which decreased by 23.14–91.20 % compared with that by the dry sieving method. This meant soil aggregate stability of the tested soil became much weakened under the action of water power and raindrop impact. Soil almost lost cohesion under saturation and seepage conditions, which would result in lower soil aggregate stability. Soil aggregate breakdown mechanisms largely determined erosion rates (Yan et al. 2008), and soil aggregate stability index was positive to interrill erosion rate (Shi et al. 2010). The difference in soil aggregate breakdown mechanisms among soil surface water regimes may also induce different sizes of sediment particles, while sediment particles have different enrichment ratios for nutrient. Therefore, the difference in nutrient losses with eroded sediment among soil surface water regimes may be

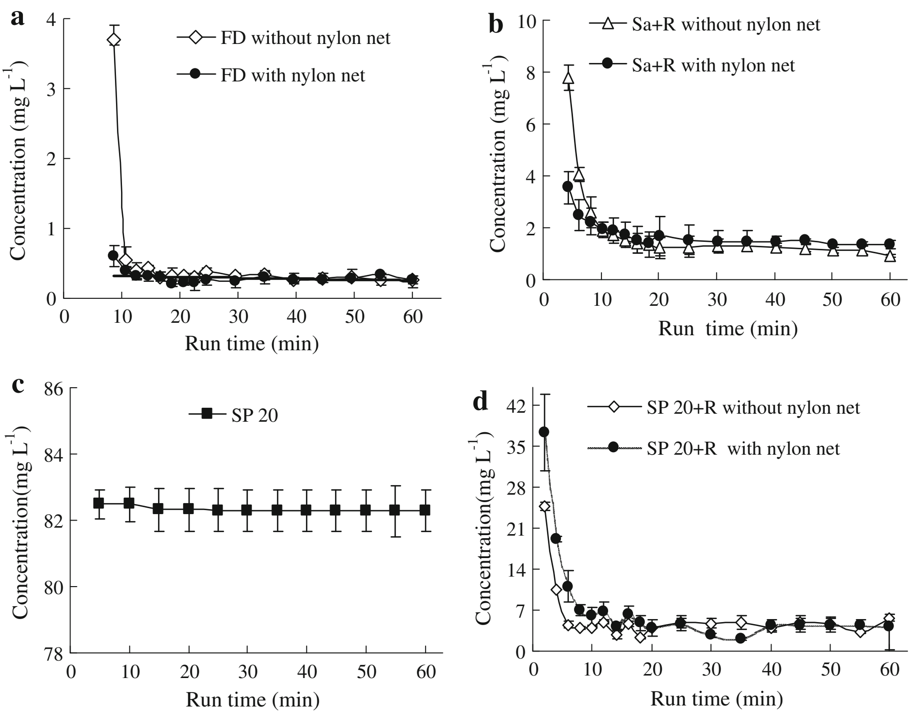

Fig. 4 NO_3–N concentrations in runoff versus run time for different soil surface water regimes. FD+R, free drainage with rain; Sa+R, a saturated soil water profile with rain; SP 20, artesian seepage under 20 cm hydrologic pressure without rain; SP 20+R, artesian seepage under 20 cm hydrologic pressure with rain. Without nylon net: the soil surface of soil pan was bare and fallow; with nylon net: a nylon net with 1 mm aperture was placed 10 cm over the test soil pan. Error *bars* indicate standard derivations

induced by the difference in soil aggregate breakdown mechanisms, while that needs further study.

The comparison of soil loss and nutrient losses at various soil surface water regimes allows us to identify the critical soil surface water condition that causes serious water quality problems at field scale. During a gentle rainstorm or a short rainstorm, a hillslope may only generate subsurface flow (Dunne 1983), and a prolonged low intensity rainfall is much more likely to cause subsurface flow and in greater volume than a short high intensity rainfall (Naef et al. 2002). In this study, seepage made significant contribution to nutrient losses with runoff and eroded sediment. Therefore, more attention should be paid to the gentle rainstorm than the high intensity storm to control NPS pollution. However, managers are more concerned with NPS pollution induced by severe intensity rainfall. Additionally, seepage is the common phenomenon in the middle or lower portion of the hillslope during the wet season. So, special management practices should be taken where seepage occurs.

As might be expected, the elimination of raindrop impact would induce less nutrient losses with eroded sediment. In this study, raindrop impact showed different influence degrees on nutrient transport to eroded sediment under different soil surface water regimes (Figs. 2, 3), and the effect was also related to nutrient forms. NO_3–N and NH_4–N concentrations without raindrop impact were higher than those with raindrop impact for all soil surface water regimes, while only for SP20+R treatment the difference became significant, with

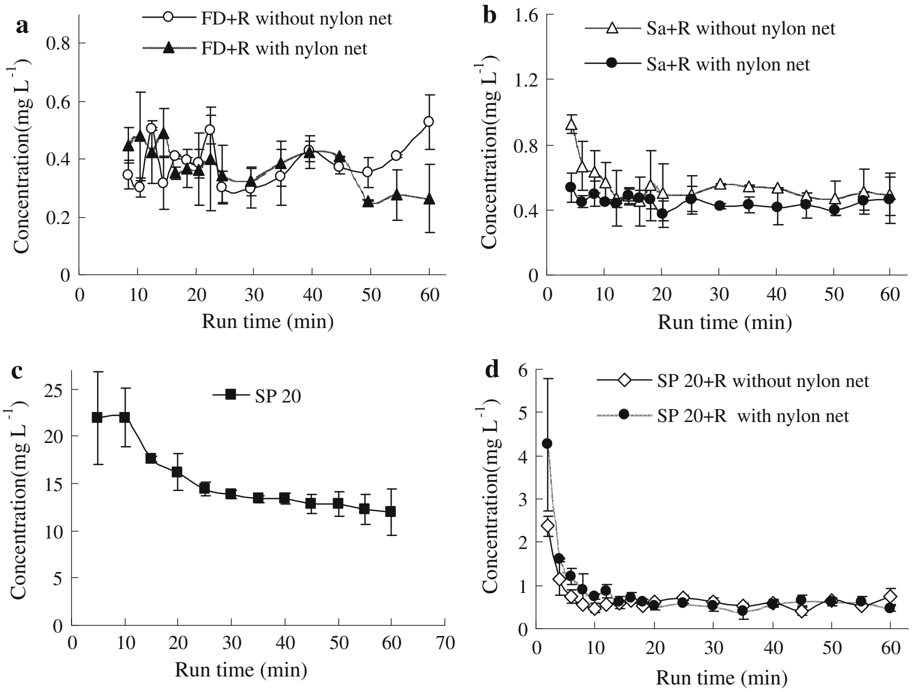

Fig. 5 NH_4–N concentrations in runoff versus run time for different soil surface water regimes. FD+R, free drainage with rain; Sa+R, a saturated soil water profile with rain; SP 20, artesian seepage under 20 cm hydrologic pressure without rain; SP 20+R, artesian seepage under 20 cm hydrologic pressure with rain. Without nylon net: the soil surface of soil pan was bare and fallow; with nylon net: a nylon net with 1 mm aperture was placed 10 cm over the test soil pan. Error *bars* indicate standard derivations

magnitudes of 2.69 times for NO_3–N and 3.66 times for NH_4–N greater, respectively. On the contrary, PO_4–P concentrations for the case without raindrop impact became lower relative to those with raindrop impact, while only for FD+R treatment significant difference was found. This indicated that the elimination of raindrop impact enhanced mineral N concentration but reduced PO_4–P concentration. However, regardless of different soil surface water regimes, nutrient losses were significantly reduced with the decrease in soil loss (59.4–70.6 %) when raindrop impact was eliminated (Fig. 3). When soil surface water regimes changed from FD+R to Sa+R, and then to SP20+R treatment, NO_3–N loss for the case of raindrop impact absent reduced by 54.89 %, 41.71 %, and 20.90 %, respectively, compared with raindrop impact present. Likewise, NH_4–N loss significantly decreased by 62.34 %, 51.65 %, and 25.0 %, and PO_4–P loss by 94.0 %, 74.59 %, and 75.57 %, respectively, as the elimination of raindrop impact. This indicated raindrop impact greatly enhanced nutrient loss with eroded sediment for all soil surface water regimes and the effect was the most pronounced for free drainage condition based on the reduction percentage of nutrient loss, thereby enhancing soil surface mulching effectively controlled NPS pollution.

3.4 The temporal variation of NO_3–N, NH_4–N, and PO_4–P concentrations in runoff

NO_3–N, NH_4–N, and PO_4–P concentrations in runoff during rain storms are shown in Figs. 4, 5, and 6, respectively. As can be seen from these Figures, nutrient concentration

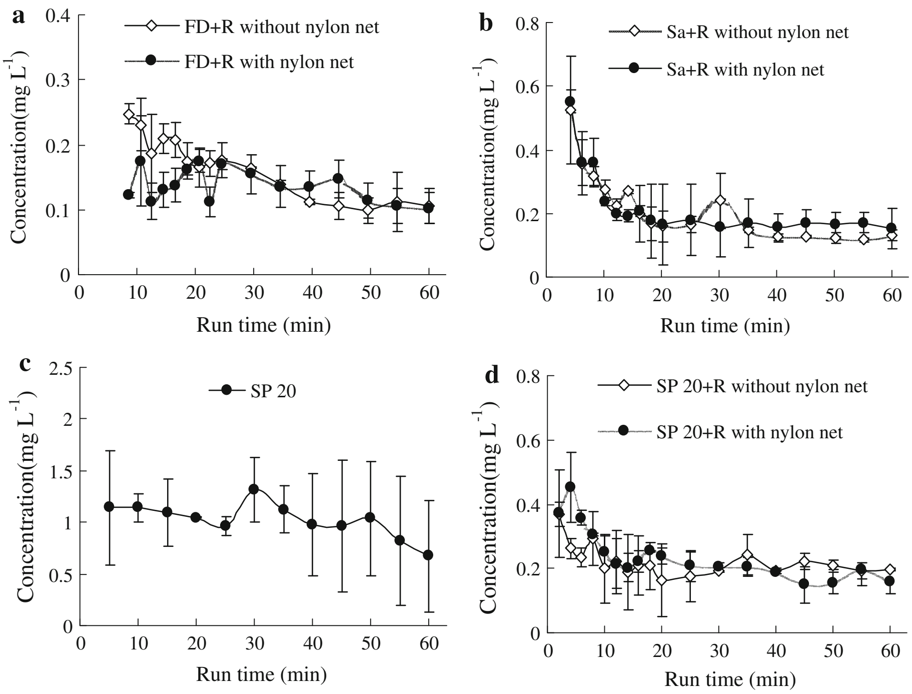

Fig. 6 PO_4–P concentrations in runoff versus run time for different soil surface water regimes. FD+R, free drainage with rain; Sa+R, a saturated soil water profile with rain; SP 20, artesian seepage under 20 cm hydrologic pressure without rain; SP 20+R, artesian seepage under 20 cm hydrologic pressure with rain. Without nylon net: the soil surface of soil pan was bare and fallow; with nylon net: a nylon net with 1 mm aperture was placed 10 cm over the test soil pan. Error *bars* indicate standard derivations

presented the same trend as rainfall progressed for a given soil surface water regime, regardless of raindrop impact present or absent. For SP20 treatment, concentrations of NO_3–N, NH_4–N, and PO_4–P all varied slightly due to the low flow rate. This result differed from Zheng et al. (2004) who found that nutrient concentration under seepage condition presented a gradual increasing trend as rainfall proceeded, indicating that the effect of seepage on nutrient loss was closely associated with soil characteristics. For FD+R, Sa+R, and SP20+R treatments, the greatest NO_3–N concentration was observed at the beginning of rainstorm which then sharply decreased with an increase in runoff volume and nutrient loss until reaching relatively low level after 20 min of rain (Fig. 4 a, b, d), and lastly kept a steady state. Further, NO_3–N concentration was reduced more sharply at the beginning of rainfall and the time to reach a steady state became shortened when soil surface water regimes shifted from infiltration to exfiltration. Because NH_4–N and PO_4–P were less mobile than NO_3–N, the temporal variations of them became less pronounced and PO_4–P concentration just fluctuated in a narrow range during rainfall (Figs. 5, 6). These results implied that the temporal trends of NO_3–N, NH_4–N, and PO_4–P concentrations during the 60-min rainfall not only depended on soil surface water regimes but also nutrient mobility in the soil profile.

The temporal variation of nutrient concentration suggested that soil surface water regimes and nutrient mobility must be considered when we predict nutrient loss by models. However, previous models based on variation trend of nutrient concentration to predict nutrient loss were developed under free drainage or saturation condition and ignored nutrient form, such as "Uniform, Complete Mixing" model, and "Non-uniform and Incomplete Mixing" models (Ahuja 1982; Ahuja and Lehman 1983; Snyder and Woolhiser 1985), and the effective transport model (Wang et al. 1999) models.

4 Conclusions

A laboratory study was conducted to evaluate the interaction between soil surface water regimes and raindrop impact on soil erosion and nutrient losses (NO_3–N, NH_4–N, and PO_4–P). Results showed saturation and seepage conditions caused greater soil loss and nutrient transport than free drainage condition. Soil loss from Sa+R and SP20+R treatments increased by 11.4–67.1 % and 68.1–74.5 % relative to that from FD+R treatment, respectively. Nutrient concentrations in runoff from SP20 treatment were 7.3–228.7 times greater than those from FD+R treatment. Compared with FD+R treatment, nutrient losses with runoff from Sa+R and SP20+R treatments increased by factors of 1.30–9.38 and 2.81–40.11 times, and the corresponding nutrient losses with eroded sediment by 1.37–7.67 and 1.75–9.0 times, respectively. The comparison of soil loss and nutrient losses at various soil surface water regimes allows us to identify seepage flow is the critical condition that induces serious water pollution in the field. However, the differences in soil loss and nutrient concentrations among soil surface water regimes were related to raindrop impact. Regardless of different soil surface water regimes, raindrop impact induced 59.4–71.6 % of the total soil loss which significantly promoted nutrient losses by eroded sediment, but it only significantly affected nutrient losses in runoff for FD+R treatment. The understanding of interaction effect on nutrient loss may contribute to more effective measures to control soil loss and nonpoint source pollution.

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