ORIGINAL ARTICLE

Impacts of surface runoff and sediment on nitrogen and phosphorus loss in red soil region of southern China

X. Y. Wu · L. P. Zhang · X. X. Yu

Abstract Surface runoff plays an important role in the process of nitrogen (N) and phosphorus (P) loss. It has two common evaluation indicators, runoff and sediment, which are greatly affected by the contributing factors. To study the impacts of surface runoff and sediment on N and P loss, 36 simulated rainfalls were applied on fields with different conditions (three rainfall intensities, three coverage ratios, and two slopes) at laboratory scale with two replicates. It was found that: (1) loss modulus of both the total nitrogen and total phosphorus decreased with runoff occurrence time; (2) runoff modulus had a closer relationship with undissolved N and P than dissolved N and P; (3) N loss was more affected by runoff than P loss; (4) both N and P loss modulus followed the consistent changes with the sediment content. At last, suggestions were provided to reduce the harm of N and P loss in red soil region of southern China in different areas with different conditions.

Keywords N and P loss · Runoff · Sediment · Rainfall intensity · Coverage ratio · Slope

X. Y. Wu · L. P. Zhang (✉)
Zhejiang Provincial Key Laboratory of Subtropical Soil and Plant Nutrition, Key Laboratory of Polluted Environment Remediation and Ecological Health of Ministry of Education, College of Environmental and Resource Sciences, Zhejiang University, 866 at Yuhangtang Road, Hangzhou 310058, Zhejiang, China
e-mail: lpzhang163@163.com; lpzhang@zju.edu.cn

X. Y. Wu · X. X. Yu
Shandong Provincial Key Laboratory of Water and Soil Conservation and Environmental Protection, Linyi University, Linyi, China

Introduction

Water and soil quality degradation is mainly caused by the excessive utilization of fertilizer in fields (Falkowski et al. 2000; Conan et al. 2003; Ren et al. 2003). Nitrogen (N) and phosphorus (P) loss from fertilizer can cause both the nutrient enrichment in surface water (i.e., eutrophication) and degradation in soil (i.e., soil erosion). Eutrophication has been identified as the main source of surface water pollution (Sharpley et al. 1999). There are many methods of adding N and P into water, such as leaching, surface runoff, and dry and wet atmospheric sedimentation. Next to leaching, N and P loss by surface runoff is responsible for the majority of eutrophication.

In the past few years, numerous studies have been carried out focusing on the transfer processes of N, P from soil to surface runoff, and the forms of N, P loss in runoff (Steinheimer et al. 1998; Heathwaite and Dils 2000). The impact of precision agriculture on N loss in water has been reported in several studies and review articles (Spalding and Exner 1993; Elmi et al. 2002). Different results were reported about various N forms in surface runoff. Liu et al. (1991) reported particulate-associated N occupied the major part of N loss in runoff water and sediment compared with dissolved N. Borin et al. (2005) found the amount of TN lost in drainage is decisively affected by the amount of runoff volume. Liang et al. (2005) and Wu et al. (2007) reported that the major form of N lost in surface runoff water was the dissolved N, which included NO_3^--N and NH_4^+-N. Nitrate N accounts for the larger percentage of dissolved N.

There were also broad studies on the contributing factors to nutrient loss by surface runoff (Zeng et al. 2008). Kwong et al. (2002) reported that the heavy rainfall increases both surface runoff and loss of particulate N with the

simultaneous erosion of topsoil. Much knowledge about the influence of transport factors runoff and erosion on P movement in runoff has been achieved (Quinton et al. 2001; Hart et al. 2004). PP transport increases with increasing runoff and erosion, which is attributed to the stronger rainfall intensities (Quinton et al. 2001). Stronger intensity rainfall causes a larger percentage of PP in TP in runoff water than weaker intensity rainfall (Sporre-Money et al. 2004).

However, few studies were reported on the relationship between runoff, sediment and N, P loss. Surface runoff plays an important role in the process of N and P loss, and different contributing factors can impose effect on N and P loss through affecting the runoff and sediment. Therefore, it is a more direct way to study the impacts of runoff and sediment on N and P loss to figure out the relationship between nutrient loss and runoff.

In the present study, two indices were selected to evaluate N, P loss in surface runoff: loss modulus (the weight of N and P loss from per square field per hour during rainfalls) and loss concentration (the weight of N and P loss in per liter surface runoff during rainfalls).

Garcia Rodeja and Gil-Sotres (1997) indicated that nutrition loss caused by runoff depends on different factors: topography, land use, soil properties, and weather conditions (particularly rainfall intensity and duration), and in some cases, precipitation. In this study, considering the indoor experiments, rainfall intensity, slope, and coverage ratio were considered as the contributing factors to runoff and sediment.

The objectives of this study are thereby to investigate the relationship between runoff departure and N, P loss, the impacts of surface runoff modulus and sediment content on the characteristics of N and P loss, and the impact of the contributing factors (rainfall intensity, slope, and coverage ratio) on runoff and sediment.

Materials and methods

Materials

Simulated rainfall experiments were designed and conducted in a glasshouse. The temperature in the glasshouse was maintained at 25 °C all the time.

There were two 2-m^2 experimental wooden troughs A and B, with length, width, and height measuring 2, 1, and 0.5 m, respectively, with two replicates. The troughs were sealed at the four sides to avoid runoff leak. Troughs A and B were designed at two slopes of 11° and 21°, respectively, which were chosen based on the landforms of local vegetable land.

Troughs were filled with loam soil collected from Qingshan Lake watershed in red soil region of southern China. Same plots were selected with length and width measuring 2 and 1 m, respectively, at local fields. Five layers of soils, with 10 cm depth in each layer, were dug and stored separately. Then they were put into the troughs layer by layer in original order. The physical and chemical characteristics of the soil at five layers were measured (Table 1). Soil analysis was performed according to the description reported in "Soil and Agro-chemistry Analysis" (Bao 2000). The organic matter was measured by a modified Walkley–Black method. Total nitrogen (TN) was determined using the semi-micro Kjeldahl method. NO_3^--N was measured with the spectrophotometry method using phenol disulfonic acid. NH_4^+-N was measured with a 2 mol L^{-1} KCl extraction and indigotin spectrophotometry. Total phosphorus (TP) was determined with the molybdate blue method. Olsen-P was extracted with Bray's No. 1 method and determined by the colorimetric method with molybdate blue (Olsen and Dean 1965).

Chinese cabbage was planted in the troughs. It provided different vegetation coverage ratios with growth. Chinese cabbage in one growth period provided the coverage ratios

Table 1 The original physical and chemical characteristics of the soil in the experimental troughs

Soil depth (cm)	0–10	10–20	20–30	30–40	40–50
Soil density (g cm^{-3})	1.13	1.14	1.15	1.16	1.19
Percentage of sand (%)	46.54	47.33	48.21	49.32	50.65
Percentage of loam (%)	39.43	37.22	35.43	33.98	32.08
Percentage of clay (%)	14.03	15.45	16.36	16.70	17.27
Organic matter content (g kg^{-1})	14.86	13.85	13.28	12.96	12.76
Total nitrogen (TN) content (g kg^{-1})	1.75	1.19	1.08	0.84	0.76
Nitrate nitrogen (NO_3^--N) content (mg kg^{-1})	70.55	47.60	43.20	33.60	30.40
Ammonia nitrogen (NH_4^+-N) content (mg kg^{-1})	10.03	6.70	6.17	4.80	4.34
Total phosphorus (TP) content (g kg^{-1})	0.56	0.50	0.48	0.46	0.45
Olsen-P content (mg kg^{-1})	20.43	16.44	14.34	13.26	12.80

ranging from 13 to 98 %. Photographs were taken from the top of the trough. The orthograph of vegetation was calculated as the area of vegetation coverage.

Simulated rainfall design

Simulated rainfall equipment used in this experiment was designed and made by Chinese Academy of Sciences (CAS) (Fig. 1). The waterworks were assembled with two 6 m long stand-up steel tubes, and supported by two tripods. Two sprinklers were fixed on the top of the tubes. The sprinkler consisted of a pore in a sheet metal, a baffle, and a sprinkler body. There were 10 sizes of the pores in 10 sheet metals. Pressure gauges and valves were placed on the tubes near the water source. Rainfall intensity was controlled by pressure gauges and valves. Valves were adjusted to control water pressure at certain value, therefore, the rainfall intensity was determined only by the size of pore. Moreover, several trial and error designs were tested until a suitable water pressure and spray pattern produced the desired rainfall intensity, drop-size distribution and spatially uniform rainfall intensity based on the raindrop characteristics of the sprinkler when they were developed by CAS. The instruction of the simulated rainfall equipment supplied the standard rainfall intensity according to the pore size under certain pressure. Throughout the rainfall event, two steel tubes stood 2 m away from the troughs on either side.

There were six barrels surrounding each wooden trough to calculate the coefficient of uniform (CU) of each rainfall. Christiansen (1941) first discussed CU to describe the distributing uniform of spout quantity. It can be calculated using following equation:
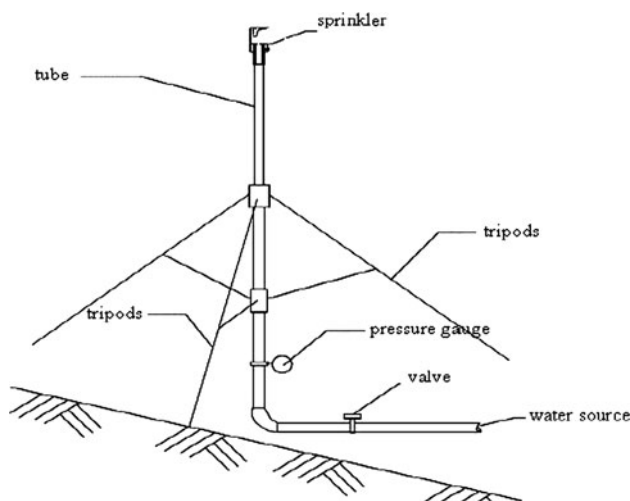

Fig. 1 Schematic diagram of simulated rainfall equipments contains a sprinkler, a pressure gauge and a valve on a tube. Sprinkler has different pore sizes in different simulated rainfalls

$$CU = 100 \times \left(1 - \frac{\sum_{i=1}^{N} x_i - \overline{x}}{N\overline{x}} \right). \tag{1}$$

where x_i is the depth of rainfall in the barrel located at i, $\overline{x}$ is the average depth of all barrels $\overline{x} = \frac{1}{N} \sum_{i=1}^{N} x_i$, and N is the number of barrels.

The coefficients of uniform in the study were all more than 85 %. CU values of the orders of 80–90 % are generally considered acceptable (Neff 1979). Water used in the simulated rainfall was distilled water.

The annual precipitation in Qingshan Lake watershed is approximately 1,426.4 mm. Under the influence of the plum rainy season, maximum precipitation occurs in June, with the annual average reaching 214.4 mm. Minimal precipitation occurs in December, with the annual average at 42.3 mm. Eighteen rainfall events were designed at three rainfall intensities 40, 80, and 120 mm h^{-1}, respectively, with two replicates (Table 2).

In each rainfall, the period from rainfall beginning to runoff occurrence was recorded as runoff occurrence time. Each rainfall lasted for approximately 20 min, including runoff occurrence time (they were different among 18 rainfall events) and runoff duration (all 15 min in 18 rainfall events).

Sample collection

To measure the gravimetric soil moisture content, soil samples from the 4 corners of the trough were collected before each rainfall and taken back to the laboratory. Another 4 soil samples were collected immediately after the rainfall in the same way.

A metal 'V'-type trough, which was connected with a metal sheet inserted in the surface soil, gathered the surface runoff into the 1,000 ml clean polyethylene bottles. In each rainfall event, 15 runoff samples were collected separately and in order per minute as soon as the runoff occurred. All of the runoff was collected. Two or more bottles were used when the runoff was more than 1,000 ml during 1 min. Then, the runoff samples were taken back to the laboratory for measurements immediately.

Sample analysis

Gravimetric soil moisture content was measured using the gravimetric method before each rainfall event (Table 2). Soil samples were placed in an oven at 105 °C for 8 h after being weighed (this weight was recorded as A). Samples were weighed again after drying (recorded as B). The difference between the two weights (A and B) yielded the weight of the water (recorded as C). Gravimetric soil moisture content could be obtained by dividing C by B.

Table 2 Eighteen rainfall events were designed in the experiment with contributing factors, including three rainfall intensities, two slopes, and three coverage ratios according to the growth of the planted Chinese cabbage

Rainfall event number	1	2	3	4	5	6	7	8	9
Slope (°)	11	11	11	11	11	11	11	11	11
Rainfall intensity (mm h^{-1})	35	35	35	70	70	70	105	105	105
Coverage ratio (%)	30	60	90	30	60	90	30	60	90
Gravimetric soil moisture content (%)	10.43	19.20	19.30	14.24	18.53	20.44	9.78	17.56	20.98
Rainfall time (h)	0.33	0.34	0.31	0.30	0.32	0.29	0.28	0.28	0.29
Rainfall event number	10	11	12	13	14	15	16	17	18
Slope (°)	21	21	21	21	21	21	21	21	21
Rainfall intensity (mm h^{-1})	35	35	35	70	70	70	105	105	105
Coverage ratio (%)	30	60	90	30	60	90	30	60	90
Gravimetric soil moisture content (%)	10.21	19.78	20.07	11.09	16.4	20.60	14.91	15.64	20.50
Rainfall time (h)	0.33	0.30	0.30	0.28	0.27	0.33	0.27	0.28	0.28

Runoff volumes, runoff occurrence times, and gravimetric soil moisture content of each rainfall event were also given

The volumes of the runoff that contained water and sediment were measured after they were kept in the bottles for 4–5 h in the laboratory at 25 °C for sedimentation.

After sedimentation, the topmost water in the first bottle of each minute sample was collected for analysis. The concentrations of TN, NH$_4^+$-N, NO$_3^-$-N, TP, and DP were measured in 24 h, respectively.

Total nitrogen was measured according to the alkaline potassium persulfate digestion—ultraviolet spectrophotometric method using unfiltered samples (National Environmental Protection Agency of China 2002). NO$_3^-$-N was measured according to the ultra-spectrophotometric method after the samples were filtered through 0.45 μm filters. NH$_4^+$-N was measured by the method of salicylate-hypochlorous acid spectrophotometric after filtration through 0.45 μm filters.

Total phosphorus was measured according to the ascorbic acid-molybdenum blue method (USEPA 1979). After being filtered using 0.45 μm filters, DP was obtained using molybdenum colorimetry after isobutanol extraction (Shimadzu Corporation 2001). Organic phosphorus (OP) is hardly soluble in water and its content is generally low, therefore, OP was neglected in the study. The difference between TP and DP concentrations yielded the particulate phosphorus (PP) concentration.

After the measurement of N and P content, the sediments were obtained by leaching water from the runoff. The weights of the sediments were measured after being dried in the oven at 105 °C for 24 h.

Calculations

In this study, the concept "modulus" was used as the indices of runoff and loss. Compared with general indications such as content and volume, the modulus considers

additional factors including time and area. The modulus is more useful when compared with the results obtained from other experimental designs with different rainfall times and plots.

Runoff modulus depicts the volume of surface runoff per hour on a per m^2 field during rainfalls. It is an index that describes runoff characteristics and can be obtained by the formula:

$$M_R = V/(S \times T), \qquad (2)$$

where M_R is the runoff modulus (L m^{-2} h^{-1}), V is the surface runoff volume (L), S is the area of experimental field (m^2), and T is the rainfall time (h).

Sediment concentration depicts the content of sediment in per liter surface runoff from the field during rainfalls. It can be obtained by the following formula:

$$C_S = C/V, \qquad (3)$$

where C_S is the sediment concentration (g L^{-1}), C is the sediment content (g), and V is the volume of the runoff (L).

The N and P loss modulus depicts the contents of N and P lost in a surface runoff from the field per m^2 per hour during rainfalls, respectively. It can describe the degree of N and P loss. The loss modulus is obtained by the following formula:

$$M_{N/P} = C_{N/P}/(S \times T), \qquad (4)$$

where $M_{N/P}$ is the N and P loss modulus (mg m^{-2} h^{-1}), C is the N and P loss content (mg), S is the area of experimental field (m^2), and T is the rainfall time (h).

Content of TN and TP in each sample was calculated by multiplying concentration with runoff volume, respectively. Total runoff volume was the sum of 15 runoff volumes in each sample in a rainfall event. Total content of TN and TP in a rainfall event was the sum of 15 contents in each sample, respectively. The average concentration of

TN and TP was calculated by dividing the total content with the total runoff volume in each rainfall event. Runoff modulus, sediment concentration, N loss modulus, and P loss modulus were calculated using formulas (2), (3), and (4), respectively.

Statistical analysis

Statistical analysis was performed using the Data Processing System (DPS). Results were obtained using DPS including the multivariable regression models and different importance of three parameters (slope, rainfall intensity, and coverage ratio).

Results

The runoff occurrence time, runoff volume, runoff modulus, sediment content, sediment concentration, TN content, TN average concentration, TN loss modulus, TP content, TP average concentration, and TP loss modulus are summarized in Table 3.

Impact of runoff departure on nitrogen and phosphorus loss

The period from rainfall beginning to runoff occurrence is recorded as a runoff occurrence time. It describes a runoff departure.

Figure 2 shows the evolutions of runoff volume, TN and TP loss modulus, and TN and TP average concentration over the runoff occurrence time.

The runoff volume showed a decreasing trend with an increase in the runoff occurrence time (Fig. 2a).

The average concentrations of TN slightly increased over runoff occurrence time, while TP average concentrations had a decreasing trend with runoff occurrence time (Fig. 2b). Total N and TP average concentrations ranged from 2.60 to 4.39 mg L^{-1}, and from 0.59 to 0.19 mg L^{-1}, respectively.

Both TN and TP loss modulus had decreasing trends with the runoff occurrence time (Fig. 2c). The TN loss modulus decreased from 692.50 to 142.65 mg m^{-2} h^{-1}, and the TP loss modulus decreased from 108.66 to 8.86 mg m^{-2} h^{-1}.

Impact of runoff modulus on nitrogen and phosphorus loss modulus

The evolutions of N (TN, NO$_3^-$-N, and NH$_4^+$-N) loss modulus are presented in Fig. 3 with increasing runoff modulus.

Figure 3 shows that all the loss modulus of TN, NO$_3^-$-N and NH$_4^+$-N had increasing trends with an increase in runoff modulus. However, the trends of curves were different from one another. This phenomenon indicates that runoff had different effect degrees on various N forms. Trend equations of loss modulus curves in Fig. 3 were as follows: y (TN) $= 1.5641x^2 - 1.7431x + 177.24$, R^2 (relativity coefficient) $= 0.8954$; y (NO$_3^-$-N) $= 0.2163x^2 + 7.8274x + 104.65$, $R^2 = 0.5787$; y (NH$_4^+$-N) $= 0.185x^2 - 1.4761x + 34.529$, $R^2 = 0.5602$.

In the trend equations of N loss modulus, the coefficients before x^2 of TN, NO$_3^-$-N, and NH$_4^+$-N were 1.5641, 0.2163, and 0.185, respectively. Based on the mathematics theory regarding parabola, when both coefficients were positive, the larger was the coefficient, and the sharper was the curve. Comparison of curve slopes showed both of them increased more quickly when runoff modulus was larger. And the order of N loss modulus in different forms was TN > NO$_3^-$-N > NH$_4^+$-N. It was to say that runoff modulus had a closer relationship with NO$_3^-$-N than NH$_4^+$-N, and a closer relationship with undissolved N than dissolved N.

The evolutions of P (TP, DP, and PP) loss modulus are presented in Fig. 4 with increasing runoff modulus.

Figure 4 shows that P loss modulus in its three forms all increased with increasing runoff modulus, and percentage of PP in TP was larger than DP in TP. PP was fixed to the soil particulates, which were loaded more easily by a larger runoff. Therefore, the loss modulus of P had a very close relationship with runoff modulus. The loss modulus of P also increased more quickly when runoff modulus was larger. The trend equations of the loss modulus in Fig. 4 are as follows: y (TP) $= 0.3106x^2 - 0.7192x + 11.046$, R^2 (relativity coefficient) $= 0.9674$; y (DP) $= 0.0783x^2 + 0.2434x + 2.5101$, $R^2 = 0.8015$; y (PP) $= 0.2323x^2 - 0.9627x + 8.5362$, $R^2 = 0.9244$. In these trend equations of P loss modulus, the coefficients before x^2 of TP, DP, and PP were 0.3106, 0.0783, and 0.2323, respectively. Based on the mathematics theory regarding parabola, the order of P loss modulus in different forms was TP > PP > DP. It was to say that runoff modulus had a closer relationship with PP than DP.

Impact of sediment content on nitrogen and phosphorus loss

The average concentration of TN and TP loss can be used to evaluate the process of the runoff delivering N and P. The relationship between sediment content and TN, TP loss concentration, and the relationship between the sediment content and TN, TP loss modulus are shown in Fig. 5a, b, respectively.

Figure 5 shows that TP concentration had a positive relationship with the sediment content, while the TN had

Table 3 The runoff volumes, sediment content, and TN and TP content in each rainfall event were measured immediately in the lab; the runoff modulus, sediment concentrations, N loss modulus, and P loss modulus were calculated by formulas (2), (3), and (4)

Rainfall number	Runoff occurrence time (min)	Runoff volume (L)	Runoff modulus (L m⁻² h⁻¹)	Sediment content (g)	Sediment concentration (g L⁻¹)	TN content (mg)	TN average concentration (mg L⁻¹)	TN loss modulus (mg m⁻² h⁻¹)	TP content (mg)	TP average concentration (mg L⁻¹)	TP loss modulus (mg m⁻² h⁻¹)
1	4.73	35.92	54.62	191.02	5.32	157.69	4.39	239.77	10.42	0.29	15.84
2	5.4	30.42	44.74	157	5.16	105.56	3.47	155.23	6.08	0.2	8.95
3	3.45	28.67	46.62	80	2.79	87.73	3.06	142.65	5.45	0.19	8.86
4	2.83	63.50	106.84	216.03	3.40	257.18	4.05	432.71	24.13	0.38	40.60
5	4.18	54.98	86.00	161.11	2.93	170.99	3.11	267.45	18.14	0.33	28.38
6	2.53	45.54	77.93	103.28	2.27	135.71	2.98	232.25	13.21	0.29	22.60
7	1.63	92.11	166.16	477.61	5.19	367.52	3.99	662.99	46.98	0.51	84.74
8	2.03	80.80	142.34	231.07	2.86	285.22	3.53	502.45	33.13	0.41	58.36
9	2.18	75.75	132.28	141.35	1.87	209.83	2.77	366.40	25.76	0.34	44.97
10	4.88	39.19	59.14	375.32	9.58	162.64	4.15	245.43	11.76	0.3	17.74
11	3.05	35.71	59.35	275.14	7.70	142.13	3.98	236.22	9.64	0.27	16.02
12	3.07	30.61	50.82	112.42	3.67	118.15	3.86	196.16	7.04	0.23	11.69
13	1.92	62.48	110.78	238.24	3.81	248.05	3.97	439.80	29.99	0.48	53.17
14	1.33	58.99	108.37	120.65	2.05	175.79	2.98	322.95	23.01	0.39	42.26
15	5	49.21	73.82	82.58	1.68	139.26	2.83	208.90	15.75	0.32	23.62
16	1.17	99.27	184.17	1677.42	16.90	373.26	3.76	692.50	58.57	0.59	108.66
17	1.92	85.86	152.23	652.79	7.60	269.60	3.14	478.01	43.79	0.51	77.64
18	1.73	79.16	141.95	299.53	3.78	205.82	2.6	369.07	37.21	0.47	66.72

Fig. 3 The relationship between N loss and runoff can be shown by the trends of the three forms of N loss modulus with the increasing runoff modulus

Fig. 4 The relationship between P loss and runoff can be shown by the trends of the loss modulus of three P forms with the increasing runoff modulus
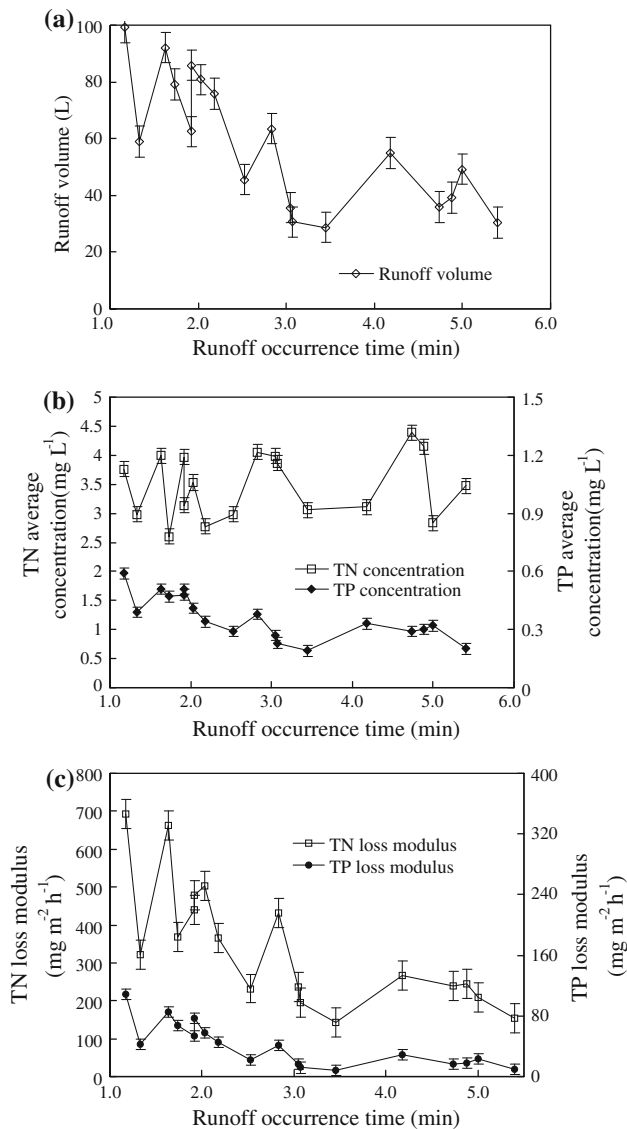

Fig. 2 Evolutions of the runoff volume (**a**), TN and TP concentration (**b**), TN and TP loss modulus (**c**) with the increasing runoff occurrence time of the rainfall events with two replicates

no appreciable relationship with the sediment content. The N and P loss modulus both had positive relationships with the sediment content. Trend equation of TP concentration curves in Fig. 5 was: y (TP concentration) $= -4E-07x^2 + 0.0007x + 0.2115$, R^2 (relativity coefficient) $= 0.4537$. Trend equation of TN and TP loss modulus curves in Fig. 5 was as follows: y (TN loss modulus) $= 160.09\ln(x) - 519.18$, $R^2 = 0.4544$; y (TP loss modulus) $= -3E-05x^2 + 0.1298x + 9.0537$, $R^2 = 0.4621$.

Impacts of contributing factors on surface runoff and sediment

Contributing factors including rainfall intensity, slope, and coverage ratio had impacts on surface runoff and sediment.
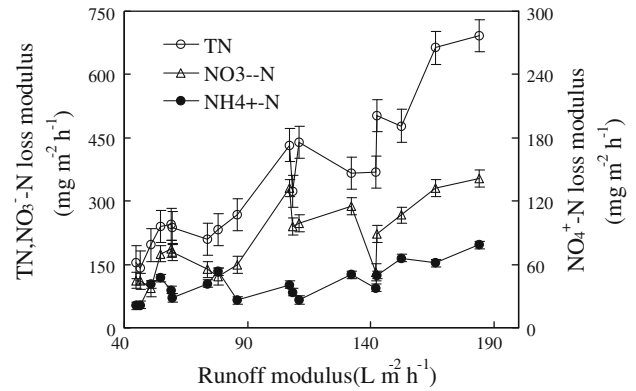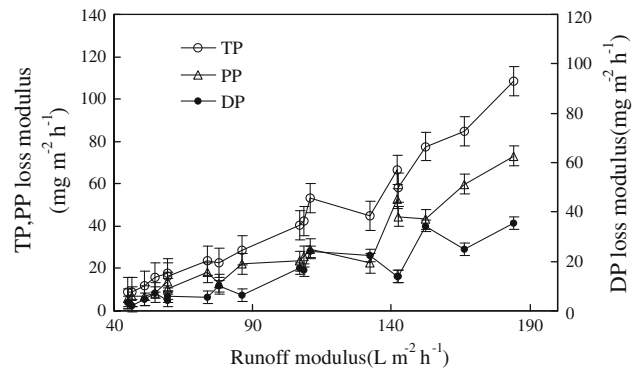
Different alternating group of contributing factors also had different impacts. DPS was used processing the experimental data comprehensively.

The multivariable regression model was developed based on three parameters (Table 4). The correlation coefficients and the significance levels of factors of the runoff modulus and sediment concentration are depicted in Table 5. In Tables 4 and 5, x_1 is slope, x_2 is rainfall intensity, x_3 is coverage ratio, and y is the runoff modulus and sediment concentration.

In Table 4, the Durbin–Watson values of the runoff modulus and sediment concentration are 2.29 and 1.75, respectively, which are closely near to 2. The accurateness of the model is higher when the difference between Durbin–Watson value and 2 is smaller. The correlation coefficients of the models of runoff modulus and sediment concentration were 0.97 and 0.88. Therefore, the models of runoff modulus and sediment concentration were accurate and convincing. Table 4 shows that runoff modulus had its maximum value when slope, rainfall intensity, and coverage ratio were 21°, 105 mm h^{-1}, and 30 %, respectively;
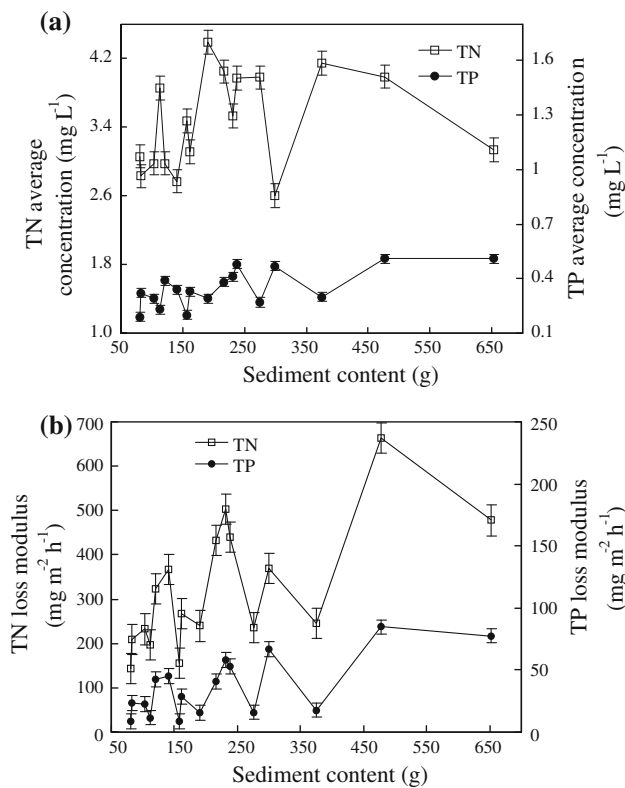
(a)

(b)

Fig. 5 The relationships between N and P loss concentration and sediment (**a**) and between N and P loss modulus and sediment (**b**) can be shown by the trends of the total N and P loss with increasing sediment content

sediment concentration had its maximum value when slope, rainfall intensity, and coverage ratio were 21°, 105 mm h^{-1}, and 30 %, respectively.

In Table 5, rainfall intensity and the alternating group of contributing factors $x_1 x_2$ both have very significant effects on runoff modulus ($P < 0.01$). Coverage ratio has a significant effect on sediment concentration ($P < 0.05$). Table 5 shows that rainfall intensity had the most important effect on runoff modulus, while coverage ratio had

more influence than slope, and coverage ratio had the most obvious effect on sediment concentration.

Discussions

According to the observation in the experiments, there were two runoff-forming situations: (1) when infiltration speed was quicker than rainfall intensity, and (2) when infiltration speed was slower than rainfall intensity. A long runoff occurrence time meant that rainwater easily infiltrated into the soil at the beginning of the rainfall. More infiltration would be produced and the soil moisture content would increase quickly if the runoff occurred with a longer occurrence time, which resulted in increasing dissolution of N and P. The main form of lost N was dissolved N and main form of lost P was PP (Liang et al. 2005; Wu et al. 2007). Based on the above previous results, it was well explained that N loss had a negative relationship with runoff departure, while P loss had a positive relationship with the runoff departure. The shorter was the runoff occurrence time, the easier the runoff occurred and the higher was the loss modulus. This indicates that the runoff departure had a direct relation to N and P contents. This result shows that rainfall event with an easier runoff departure could deliver more N and P from soils but will not generate higher N and P concentration in water.

The different runoff-forming situations can also generate different percentages of the dissolved N and DP in TN and TP, in addition to the TN and TP content in the runoff. In the first situation, there was enough time to N and P in the runoff to dissolve; in the second situation, N and P was taken away before complete dissolution. Accumulative NO_3^--N in water can lead to NO_3^--N pollution of water and vegetables, and it was very harmful to human health. Moreover, undissolved N and P will generate secondary pollution to the water body for the future. Particulate P in runoff was a supply source for DP which could be used directly by algae.

Table 4 The data were analyzed by the software Data Processing System (DPS) and multivariable regression models were obtained

Variable (y)	Durbin–Watson value	Multivariable regression model of runoff and sediment	x_1, x_2, x_3 and y when y was maximum				Correlation coefficient
			y	x_1 (°)	x_2 (mm h^{-1})	x_3 (%)	
Runoff modulus (L m^{-2} h^{-1})	2.29	$y = -20.34 + 1.01x_1 + 1.76x_2 + 0.21x_3 + 0.01x_1x_2 - 0.01x_1x_3 - 0.01x_2x_3$	178.08	21	105	30	0.98
Sediment concentration (g L^{-1})	1.75	$y = -1.36 + 0.39x_1 - 0.01x_2 + 0.11x_3 + 0.01x_1x_2 - 0.01x_1x_3 - 0.001x_2x_3$	12.06	21	105	30	0.88

In the models, the runoff modulus and sediment concentration changed with the parameters (three contributing factors) and the correlation coefficients of the models were given

x_1 is slope, x_2 is rainfall intensity, x_3 is coverage ratio, and y is the runoff modulus and sediment concentration

Table 5 The parameters and the combinations had different correlation coefficients to the runoff modulus and sediment concentration based on the multivariable regression models in Table 4

Variable (y)	Runoff modulus (L m^{-2} h^{-1})		Sediment concentration (g L^{-1})	
	Correlation coefficient	Significance level	Correlation coefficient	Significance level
Factors and their combinations				
x_1	0.1061	0.6752	0.3844	0.1153
x_2	0.9441	0.0001**	0.075	0.7674
x_3	−0.2475	0.3221	−0.5303	0.0236*
x_1x_2	0.7956	0.0001**	0.333	0.1769
x_1x_3	−0.1344	0.5948	−0.2463	0.3245
x_2x_3	0.4415	0.0666	−0.3605	0.1416
y	1	0.0001	1	0.0001

x_1 is slope, x_2 is rainfall intensity, x_3 is coverage ratio, and y is the runoff modulus and sediment concentration

** $P < 0.01$; * $P < 0.05$

As far as sediment was concerned, the major form of N loss in surface runoff water was dissolved N. Raindrop impact on the soil surface produced a thin soil zone (<10 mm), where NO_3 was released by dispersion and diffusion into the overland flow after undergoing turbulent mixing (Hooda et al. 2000). More sediment content was brought by the stronger rainfall intensity. It was disadvantageous to the dissolution of N because higher rainfall intensity brought rapid runoff and there was less time to N to dissolve. The major form of P loss was PP. The sediment content had more effect on PP because PP was always fixed on soil particulates while dissolved P in runoff water mainly originated from desorption of P in surface soil (Hooda et al. 2000). Therefore, it was obvious that PP content increased with increasing sediment content.

According to the above analysis of relationships between N and P loss and runoff and sediment, the runoff modulus had a closely positive relationship with N and P loss modulus while the N and P concentration had no significant changes with the changing runoff and sediment. The loss modulus indicated the content of N and P lost from the soil but not the N and P delivered into the water. This is because even runoff with high loss modulus will not pollute the water if there is a huge runoff volume. Furthermore, the concentration of N and P loss indicated the degree the water was polluted but not the amount of nutrients lost from the soil. This is because even less N and P loss in a short time could bring high concentration in runoff.

Moreover, phosphorus was considered to be the limiting element to the eutrophication of water (Schindler 1977; Moss et al. 2003). Comparing the trend equations of N and P loss modulus shows the coefficients before x^2 of TN and

TP were 1.5641 and 0.3106, respectively. Based on the mathematics theory regarding parabola, the curve of TN loss modulus was sharper than that of TP, which indicated the runoff influenced N loss more than P loss. Therefore, large runoff did not lead to the eutrophication of water always.

At the beginning of the rainfall, factors including rainfall intensity, slope, and vegetation coverage ratio had complicated interactions to determine the runoff-forming situations, as well as runoff occurrence time.

Based on the previous research reports about how the factors affected the runoff and sediment (Agassi et al. 1981; Norton 1987; Chen et al. 1988; Mualem et al. 1990; Sumner and Stewart 1992; Bohl and Roth 1993; Slattery and Bryan 1994; Hidalgo et al. 1997; Cerda 1998; Raya et al. 2006; Xu et al. 2006), the principles of factors contributing the runoff modulus could be summarized as follows: a stronger rainfall intensity could bring more runoff volumes and more sediment contents, and increasing rainfall intensity strengthened the runoff and then kept to a stable level; increasing slope resulted in more sediment contents and promoted the runoff when the slope was less than 28° and then reduced the runoff; increasing coverage ratio reduced the runoff and bring less sediment content.

When considering the factors synthetically, it was obvious that runoff modulus and sediment concentration both had stronger relationships with the steeper slope, stronger rainfall intensity, and less coverage ratio.

Based on the above results and discussions, suggestions on reducing harm of N and P loss in red soil region of southern China are given as follows: (1) at areas with heavier rainfalls and higher slopes, focus on the secondary pollution of N and P loss because of more undissolved nutrient loss, the security of drinking water because of higher percentages of NO_3^--N, the soil degradation because of higher N and P loss modulus, and the N/P in water more than single nutrient loss because of more impacts of runoff on N loss than P loss, and (2) at areas with weaker rainfalls and higher coverage ratios, focus on the eutrophication of water because of higher N and P loss concentration.

Conclusions

Simulated rainfalls with different conditions were designed at laboratory scale in red soil region of southern China to investigate the impacts of surface runoff and sediment on the characteristics of N and P loss, and the impact of the contributing factors on runoff and sediment.

Conclusions were obtained that the order of N loss modulus in different forms was TN > NO_3^--N > NH_4^+-N. Runoff modulus had a closer relationship with NO_3^--N

than NH_4^+-N, and a closer relationship with undissolved N than dissolved N. The order of P loss modulus in different forms was TP > PP > DP. Runoff modulus had a closer relationship with PP than DP. Total P concentration had a positive relationship with the sediment content, while the TN had no obvious relationship with the sediment content. Both N and P loss modulus had positive relationships with the sediment content.

This study also produced essential information that will help with an understanding how the characteristics of N and P loss was affected by runoff and sediment within the typical conditions of red soil region in Southern China. Suggestions on reducing harm of N and P loss in red soil region of southern China were given in different areas with different conditions. Attentions should be paid on different aspects because of different N and P loss characteristics.

References

Agassi M, Shainberg I, Morin J (1981) Effect of electrolyte concentration and soil sodicity on infiltration-rate and crust formation. Soil Sci Soc Am J 45:848–851

Bao SD (2000) Soil and agro-chemistry analysis, 3rd edn. China Agriculture Press, Beijing

Bohl H, Roth CH (1993) A simple method to assess the susceptibility of soils to form surface seals under field conditions. Catena 20(3):247–256

Borin M, Vianello M, Morari F, Zanin G (2005) Effectiveness of buffer strips in removing pollutants in runoff from a cultivated field in northeast Italy. Agric Ecosyst Environ 105(1–2):101–114

Cerda A (1998) The influence of geomorphological position and vegetation cover on the erosional and hydrological processes on a Mediterranean hillslope. Hydrol Process 12(4):661–671

Chen YZ, Jing K, Cai QG (1988) Present-day erosion and management in Loess Plateau. Scientific Publisher, Beijing

Christiansen JE (1941) The uniformity of application of water by sprinkler system. Agric Eng 22:89–92

Conan C, Bouraoui F, Turpin N, Marsily G, Bidoglio G (2003) Modeling flow and nitrate fate at catchment scale in Brittany (France). J Environ Qual 32:2026–2032

Elmi AA, Madramootoo C, Egeh M, Liu A, Hamel C (2002) Environmental and agronomic implications of water table and nitrogen fertilization management. J Environ Qual 31:1858–1867

Falkowski P, Scholes RJ, Boyle E (2000) The global carbon cycle: a test of our knowledge of earth as a system. Science 290:291–296

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

Hart MR, Quinn BF, Nguyen ML (2004) Phosphorus runoff from agricultural land and direct fertilizer effects: a review. J Environ Qual 33:1954–1972

Heathwaite AL, Dils RM (2000) Characterising phosphorus loss in surface and subsurface hydrological pathways. Sci Total Environ 251:523–538

Hidalgo GJC, Raventos J, Echevarria MT (1997) Comparison of sediment ratio curves for plants with different architectures. Catena 29:333–340

Hooda PS, Rendell AR, Edwards AC, Withers PJA, Aitken MN, Truesdale VW (2000) Relating soil phosphorus indices to potential phosphorus release to water. J Environ Qual 29:1166–1171

Kwong KFNK, Bholah A, Volcy L, Pynee K (2002) Nitrogen and phosphorus transport by surface runoff from a silty clay loam soil under sugarcane in the humid tropical environment of Mauritius. Agric Ecosyst Environ 91(1–3):147–157

Liang XQ, Tian GM, Li H (2005) Study on characteristic of nitrogen and phosphorus loss from rice field by natural rainfall runoff. J Soil Water Conserv 19(1):59–63

Liu JG, Qian ZX, Yang YS, Liang Y (1991) Studies on soil loss in slope cultivated lands with purple soil in the Yangtze Three Gorge Region. J Soil Water Conserv 3:36–44

Moss B, Stephen D, Alvarez C, Becares E, Vande, Bund W, Collings SE, Van, Donk ED, Eyto E, Feldmann T, Fernandez-Alaez C, Fernandez-Alaez M, Franken RJM, Garcia-Criado F, Gross EM, Gyllstrom M, Hansson LA, Irvine K, Jarvalt A, Jensen JP, Jeppesen E, Kairesalo T, Kornijow R, Krause T, Kunnap H, Laas A, Lille E, Lorens B, Luup H, Miracle MR, Noges P, Noges T, Nykanen M, Ott I, Peczula W, Peeters ETHM, Phillips G, Romo S, Russell V, Salujoe J, Scheffer M, Siewertsen K, Smal H, Tesch C, Timm H, Tuvikene L, Tonno I, Virro T, Vicente E, Wilson D (2003) The determination of ecological status in shallow lakes: a tested system (ECOFRAME) for implementation of the European Water Framework Directive. Aquat Conserv Mar Freshw Ecosyst. 13(6):507–549

Mualem Y, Assouline S, Rohdenburg H (1990) Rainfall induced soil seal. Part A. A critical review of observations and models. Catena 17:185–203

National environmental protection agency/Editor board of water and waste water monitoring and analyzing methods (2002) Water and waste monitoring and analyzing methods, 4th edn. China Environmental Science Press, Beijing

Neff EL (1979) Why rainfall simulation? In: Proceedings of Rainfall Simulator Workshop, Tucson, Az. USDA-SEA ARM-W-10:3-7

Norton LD (1987) Micromorphological study of surface seals developed under simulated rainfall. Geoderma 40:127–140

Olsen SR, Dean LA (1965) Phosphorus. In: Black CA (ed) Method of soil analysis. American Society of Agronomy, Madison, pp 1035–1048

Quinton JN, Catt JA, Hess TM (2001) The selective removal of phosphorus from soil: is event size important. J Environ Qual 30:538–545

Raya AM, Zuazo VHD, Martinez JRF (2006) Soil erosion and runoff response to plant-cover strips on semiarid slopes (SE Spain). Land Degrad Dev 17(1):1–11

Ren L, Ma J, Zhang R (2003) Estimating nitrate leaching with a transfer function model incorporating net mineralization and uptake of nitrogen. J Environ Qual 32:1445–1463

Schindler DW (1977) Evolution of phosphorus limitation in lakes. Science 195(4275):260–262

Sharpley AN, Daniel T, Sims T, Lemunyon J, Stevens R, Parry R (1999) Agricultural phosphorus and eutrophication. United States Department of Agriculture, Agricultural Research Service, ARS-149, Washington, DC

Shimadzu Corporation (2001) TOC-V CPH/CPN, Total Organic Carbon Analyzer, User Manual. Process and Environmental Instrumentation Division, Kyoto

Slattery MC, Bryan RB (1994) Surface seal development under simulated rainfall on an actively eroding surface. Catena 22:17–34

Spalding RF, Exner ME (1993) Effects of sludge disposal on groundwater nitrate concentrations. J Hydrol 142:213–228

Sporre-Money JL, Lanyon LE, Sharpley AN (2004) Low-intensity sprinkler for evaluating phosphorus transport from different landscape positions. Appl Eng Agric 20(5):599–604

Steinheimer TR, Scoggin KD, Krammer LA (1998) Agricultural chemical movement through a field-size watershed in Iowa: surface hydrology and nitrate losses in discharge. Environ Sci Technol 32(8):1048–1052

Sumner ME, Stewart BA (1992) Soil crusting: chemical and physical processes. Lewis Publisher, Boca Raton

USEPA (1979) Methods for the chemical analysis of water and wastes. EPA 600/R-79-020. U.S. Environmental Protection Agency, Office of Science and Technology, Washington, DC

Wu XY, Zhang LP, Zhang MX (2007) Research on characteristics of nitrogen loss in sloping land under different rainfall intensities. Acta Ecological Sinica 27(11):4576–4582

Xu XL, Zhang KL, Kong YP, Chen JD, Yu BF (2006) Effectiveness of erosion control measures along the Qinghai-Tibet highway, Tibetan plateau China. Trans Res Part D Transp Environ 11: 302–309

Zeng SC, Su ZY, Chen BG, Wu QT, Ouyang Y (2008) Nitrogen and phosphorus runoff losses from orchard soils in South China as affected by fertilization depths and rates. Pedosphere 18(1): 45–53