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Research Article

Effect of Runoff Dynamic on Sediment and Nitrogen Losses in an Agricultural Watershed of the Southern Shaanxi Region, China

The southern Shaanxi region will become a water source area of the middle route of the South-to-North Water Diversion Project after 2014. However, there is little knowledge of water quality conditions in the region. Therefore, 12 rainfall events were monitored to investigate the effect of runoff dynamics on sediment and nitrogen (N) losses during the 2011 rainy season in the Hougou agricultural watershed. The results showed that at the seedling stage (SS), most of the rainfall contributed to an increase in the soil water content, both runoff and sediment yield were small, and there was a significant linear correlation between runoff and sediment yield ($r = 0.957$, $p < 0.01$). Despite an increase in vegetation coverage at the vigorous stage (VS), both runoff and sediment yield clearly increased with increasing rainfall, and there was a significant power function relationship between runoff and sediment yield ($r = 0.922$, $p < 0.01$). In addition, there was a significant linear correlation between runoff and sediment yield ($r = 0.981$, $p < 0.01$) at the harvest stage (HS). The best fit equations among N losses (N) and runoff (R), sediment yield (S) is $N = aR^bS^c$, and the method proposed was available to reduce relative error for calculation of N losses during the 2011 rainy season.

Keywords: Erosion; Sediment yield; Water quality; Water source area

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1 Introduction

The over-use of fertilizers and pesticides to increase yield has resulted in an increasingly serious agricultural non-point pollution source, with nutrient losses being the main factor causing water quality and soil degradation [1–4]. Runoff dynamics play an important role in sediment and nutrient losses [5, 6]. Several studies have shown that soil texture, infiltration, vegetation coverage, and rainfall further affect the processes of runoff dynamics and nitrogen (N) losses [7–9]. Zhang et al. [10] reported that vegetation coverage can reduce soil and water loss effectively and reduce soil total nitrogen (TN) losses accordingly. Recently, Zhu et al. [11] investigated the non-point-source N comes mainly from the storm runoff, which contributes up to 76% of the loadings in a representative small watershed in the Three Gorges Area, China. Meanwhile, Wang et al. [12] indicated N loss from sloping farmland could be reduced using contour hedgerow intercropping. Surface runoff and soil moisture are the major carriers of soil nitrate nitrogen (NO_3^--N). For soil with a high infiltration rate, infiltrating water is the main factor in soil NO_3^--N loss, especially subsurface flow [13, 14]. About 70–90% of N losses as NO_3^--N were demonstrated by Pionke et al. [15]. In addition, most past studies have been focused on N removal in surface runoff and sediment also influenced by land use, fertilizer management practices, and vegetation coverage [16–19]. However, the main causes of soil ammonium nitrogen (NH_4^+-N) loss are surface runoff and sediment adsorption [20]. Recently, many researchers have focused on the loss mechanism of N and the coupling relationship among N, runoff, and sediment yield [21–24], including Yang et al. [25] and Long et al. [26] have reported the dynamic change of N losses by short-term runoff processes. Only a few studies are related to N losses by runoff and sediment processes collectively in a single rainfall event [27, 28], and even fewer on the interaction between runoff and sediment processes throughout the rainy season in an agricultural watershed [29].

In order to evaluate the water quality of the middle route of the South-to-North Water Diversion Project and the safety of drinking water around the Danjiangkou Reservoir, the Hougou agricultural watershed was selected as a representative area for monitoring soil erosion and nutrient losses in 2011. Meanwhile, 12 rainfall events were monitored during the 2011 rainy season, which was divided into three stages; the seedling stage (SS), the vigorous stage (VS), and the harvest stage (HS), according to local agricultural practices. The objectives of this study were as follows: (i) to assess the total amount of soil erosion and N losses, (ii) to quantify the coupling relationship among N, runoff, and sediment yield at each stage, and (iii) to estimate the amount of N losses according to runoff and sediment yield at each stage.

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Abbreviations: **HS**, harvest stage; **NH_4^+-N**, ammonium nitrogen; **NO_3^--N**, nitrate nitrogen; **SS**, seedling stage; **TN**, total nitrogen; **VS**, vigorous stage

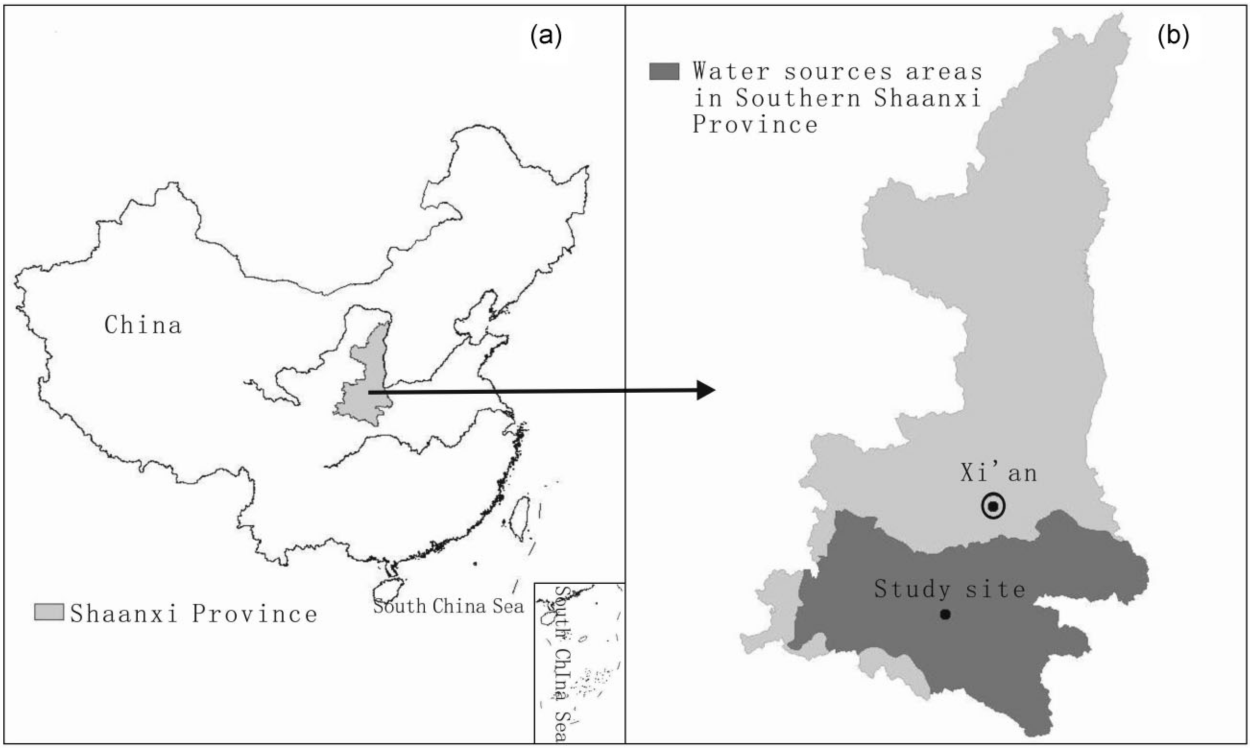

Figure 1. The location of Shaanxi Province (A), the location of study site (B) in the water sources area of the southern Shaanxi region.

2 Study site

The study was carried out in Hougou agricultural watershed, situated approximately at Lat. 33°04′N, Long. 108°13′E, which has land areas of about 8.21, about 5 km west of Hanjiang River, and 4 km south of the Shiquan County in the middle of the southern Shaanxi region (Fig. 1). In the study area, the terrain was hilly with a mean altitude of 398 m. The soil in the bottom was paddy soil, which has a loose and porous structure with high hydraulic conductivity (soil depth >70 cm), and yellow brown soil predominated on terrace and slope fields with, soil depth <40 cm. Most of the farming lands lay alongside a small grass waterway; therefore, most of the land was developed for agriculture, forest and resident area, etc. (Fig. 2 and Tab. 1). Before the study, the basic physical and chemical soil properties were analyzed [30] (Tab. 2). According to the local fertilizer applications, nitrogen fertilizer is used in the middle of July, and plant species included cypress (*Sabina squamata* Meyeri), peach tree (*Prunus persica*), mulberry tree (*Morus alba* Tortuosa), rice (*Oryza glaberrima*), maize (*Zea mays* L.), etc. The crop system, rape (*Brassica juncea* L.)–maize (*Z. mays* L.)–sweet potato (*Ipomoea batatas* L.), (late autumn) rotation by zone with animal feed or vegetables being applied between strips intervals. Therefore, the system is composed of three cycles of crop growth and two manure application cycles.

The average annual precipitation was 877 mm, with >70% of the precipitation in the study area occurring during the rainy season, from the beginning of June to October each year. Rain was unevenly distributed throughout the year, with high rainfall intensities and frequent rainstorms in summer (June–September). During 1970–2009 the minimum temperature was −10.2°C, the maximum

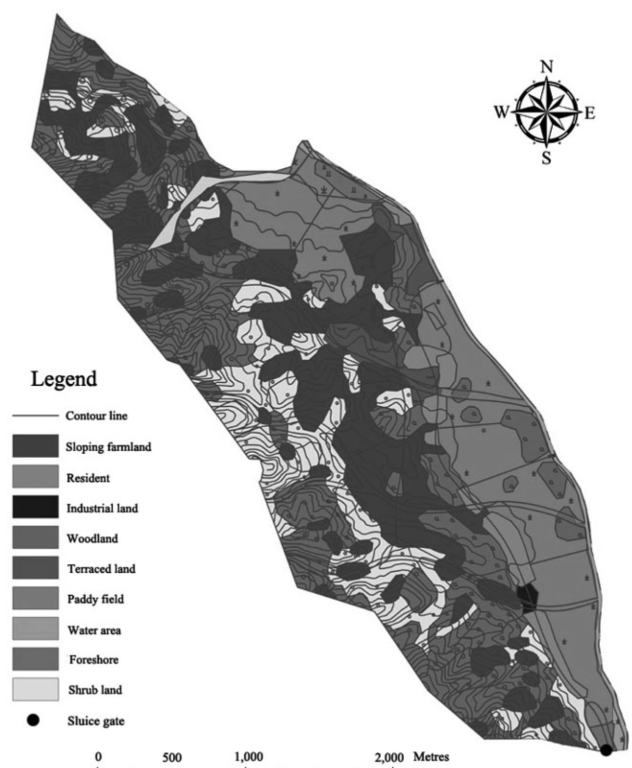

Figure 2. Land-use map in Hougou agricultural watershed in 2009.

Table 1. Land-use classification in Hougou agricultural watershed in 2009 ($\times 10^2$ hm^2).

Land type	Land use	Area ($\times 10^2$ hm^2)	Percentage (%)
Agricultural land	Sloping land	2.10	25.58
	Terraced land	0.21	2.56
	Paddy field	1.65	20.10
Forest and shrub land	Wood land	2.36	28.75
	Shrub land	1.32	16.08
Developed land	Resident	0.27	3.29
	Industrial land	0.03	0.37
Other land	Water area	0.16	1.95
	Foreshore	0.11	1.34
Total		8.21	100.00

temperature was 41.4°C, and the average annual temperature was 14.6°C.

3 Material and methods

The agricultural watershed has a sluice gate to control the amount of water and drain excess water via a grass waterway for sampling at 1-h intervals. The sluice gate was arranged at terminal position of the waterway, A WL700+® automatic water-level meter was installed over the sluice gate for measuring the water level at 5-min intervals in order to make observations simultaneously with HOBO® portable weather station. A Stalker® II SVR was used to record the velocity of flow. Samples were collected for individual storms, and all samples were weighed. After runoff events, data on the velocity of flow, the level and the sample intake were downloaded to a laptop computer using the appropriate software. Two 500-mL bottles of water samples were transferred from the runoff sampling location to the laboratory. The sediment concentration of one sample was calculated by the oven drying method, and the N concentration of the other sample was determined. All water samples were stored in a refrigerator at 4°C before analysis.

Water samples were analyzed within 24 h. The TN concentration was determined colorimetrically using a Clever chem® 200 Auto Discrete Analyzer on unfiltered samples following sulfuric acid digestion in a block digester. The NH_4^+-N and NO_3^--N concentrations were also determined with the Clever chem® 200 Auto Discrete Analyzer after filtration [31]. After being air-dried, the sediment samples were filtered through a 1-mm sieve for laboratory analysis. The TN content of the sediment samples was determined by the semi-micro Kjeldahl method, as measured by the KJELTEC SYSTEM 1026 Distilling Unit. A 5-g subsample was extracted with 50 mL of 2 M KCl. All the extracts were put on a mechanical shaker, shaken for 1 h, and then filtered. The NH_4^+-N and NO_3^--N concentrations in the soil extracts were determined by the FIAstar 5000 Analyzer FOSS TECATOR.

The total amount of runoff, sediment yield, and N losses were calculated in each rainfall event in Eqs. (1)–(3):

$$R = \sum_{i=1}^{n} R(t) \quad (1)$$

$$S = \sum_{I=1}^{N} S(t) \quad (2)$$

$$M = \sum_{i=1}^{n} (C_r(t)R(t) + C_s(t)S(t)) \quad (3)$$

In these equations, $R(t)$ is the runoff (m^3) at 1-h intervals; $S(t)$ is the sediment yield (kg), measured at 1-h intervals; $R(t)$ is the total amount of runoff, measured in m^3, in each rainfall event; $C_r(t)$ and $C_s(t)$ represent N concentrations in the runoff and the sediment (g m^{-3}, g kg^{-1}), respectively; and M is the total amount of N losses (g), in each rainfall event.

TN, NO_3^--N, and NH_4^+-N losses and runoff, sediment yield in Hougou agricultural watershed were analyzed using software SPSS16.0, the soil characteristics under different land use in Hougou agricultural watershed were analyzed in 2011 using the analysis of variance (ANOVA). Regression coefficients ($p < 0.05$) between N losses, runoff, and sediment yield were determined by testing the homogeneity of regression coefficients.

According to local agricultural practices in Hougou agricultural watershed, the SS is from June 1 to June 30, the VS is from July 1 to September 10, and the HS is from September 11 to the end of September.

4 Results and discussion

4.1 Rainfall and runoff, sediment yield analysis

Rainfall, runoff and sediment yield were all unequally distributed in 12 rainfall events monitored during the 2011 rainy season (Fig. 3). Event-averaged rain intensity ranged from 0.47 to 5.20 mm h^{-1} in 12 rainfall events, the minimum and maximum rainfall amounts were 1.57 and 134.6 mm, on July 26 and July 28, respectively. However, the extreme values of runoff and sediment yield were not synchronous with the peak rainfall. The minimum runoff and sediment yields were 149.61 m^3 and 218.98 kg, on July 26, and the maximum runoff and sediment yields were 4.17×10^5 m^3 and 1.66×10^6 kg, on September 6.

Huang et al. [32] indicated that soil water content was closer to the minimum value in a year at the SS and that tillage disturbance of the

Table 2. Soil characteristics in Hougou agricultural watershed in 2011

Land use	0–2 μm (g kg^{-1})	2–100 μm (g kg^{-1})	100–2000 μm (g kg^{-1})	Bulk density (mg m^{-3})	pH (KCl)	TN (g kg^{-1})	NH_4^+-N (mg kg^{-1})	NO_3^--N (mg kg^{-1})
Sloping land	16.5 (3.2)^a	524.0 (40.8)^a	459.4 (38.4)^a	1.47 (0.04)^a	6.6 (0.1)^a	0.49 (0.27)^a	16.34 (2.26)^a	7.70 (2.80)^a
Wood land	8.1 (3.9)^b	442.1 (64.2)^b	549.8 (76.1)^b	1.49 (0.29)^a	6.5 (0.2)^a	0.38 (0.29)^a	19.06 (1.74)^a	8.06 (4.44)^a
Vegetable field	13.0 (0.4)^{ab}	546.9 (12.1)^a	440.1 (20.2)^a	1.30 (0.03)^b	6.4 (0.1)^a	0.52 (0.04)^a	19.43 (5.67)^a	13.80 (3.50)^b
Shrub land	39.6 (14.1)^c	520.02 (31.7)^a	440.2 (22.0)^a	1.46 (0.12)^a	6.5 (0.1)^a	0.44 (0.09)^a	19.16 (9.04)^a	1.79 (0.51)^c

a, b, and c indicate the significant difference at 5% ($p < 0.05$) in the same row.

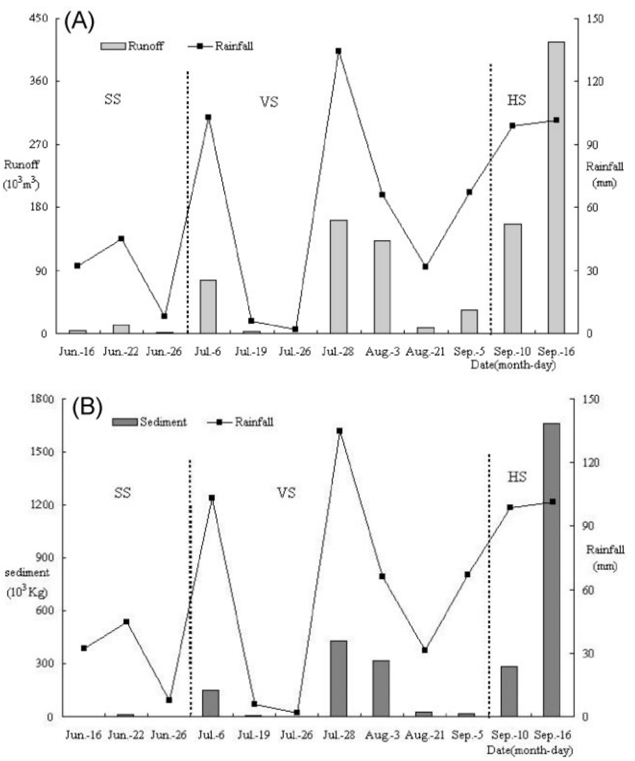

Figure 3. Rainfall and runoff (A), sediment yield (B) under each rainfall event during the 2011 rainy season in Hougou agricultural watershed. The vertical dotted line represents the border among three stages.

surface soil increased the soil porosity and increased infiltration rates. Though average rainfall intensity reached 2.91 mm h^{-1}, the rainfall during the SS was 84.60 mm, which made up about 12.2% of the total rainfall in the 2011 rainy season. After rainfall exceeded the infiltration rate, and the sheet flow dynamic was considered too weak to carry large amounts of sediment, the sediment yield was so small at the SS that it is not shown in Fig. 4. In addition, the interception effect of the vegetation in the agricultural watershed was increased because of the effect of sustained plant growth and increasing vegetation coverage [33]. Therefore, Fig. 4 shows a significant linear correlation between runoff and sediment yield ($r = 0.957$, $p < 0.01$) at the SS.

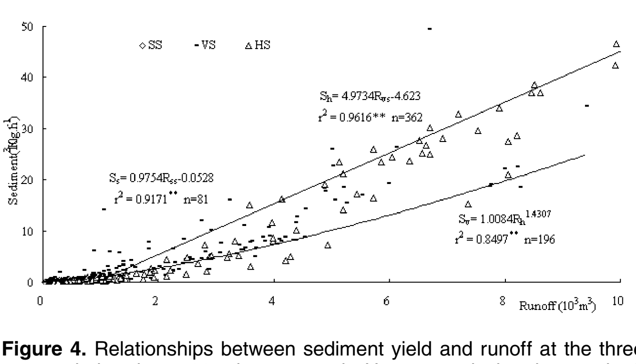

Figure 4. Relationships between sediment yield and runoff at the three stages during the 2011 rainy season in Hougou agricultural watershed. Different capital letters "S" and "R" represent sediment yield and runoff at each stage, and the lower-case letters "s", "v", and "h" represent seedling stage, vigorous stage, and harvest stage.

At the VS of vegetation growth, the vegetation coverage reached its highest, and the interception effect of vegetation and the difference of infiltration resulted in a significant power function correlation between runoff and sediment yield ($r = 0.922$, $p < 0.01$; Fig. 4) because of the high vegetation coverage at the stage. Due to the marked increase of rainfall, both in quantity and duration, the amounts of runoff and sediment yield increased by >25 and 80 times at the SS, respectively. The occurrence of rainfall events caused the emergence of stronger water flows, in which the power of the flow overtook the soil's threshold limit for withstanding the water flow and caused soil erosion. At first, topsoil was transported from the slope land by the water flow, with the delay of the rainfall duration, the difference of soil erosion under different vegetation [34], especially during rain event from July 28 to August 1. Raindrops caused the deposition of soil, which was then carried by surface water into the waterway during the later part of the VS.

At the HS, the vegetation coverage was reduced due to harvesting and the land was subsequently left unused, and the exposed soil was more vulnerable to the rain. As splashed soil caused by the impact of raindrops on the soil surface blocked infiltration, rainfall had a large impact on runoff [35].

Although the peak flow rate at the HS was approximately half of that at the VS, runoff and sediment yields were 1.38 and 2.05 times than that of the VS, respectively, the amount of those at the VS, and there was a significant linear correlation between them ($r = 0.981$, $p < 0.01$), as is described in Fig. 4. With the decrease of vegetation coverage, soil resistance ability of erosion was weak at that stage; moreover, cultivated horizon soil was destroyed in most of the farming land. Therefore, there were greater amounts of runoff and sediment yield.

4.2 N losses and runoff, sediment yield analysis

N losses displayed different characteristics at the three stages. Both runoff and sediment yield were significantly correlated with TN (runoff, $r = 0.880$, $p < 0.01$; sediment yield, $r = 0.811$, $p < 0.01$; Fig. 5A and B), which indicated the amount of TN loss in runoff and sediment yield as being less than the accumulation at the SS. The relationship between NO_3^--N loss and runoff was a significant power function correlation ($r = 0.837$, $p < 0.01$; Fig. 5C). NO_3^--N was infiltrated into the soil profiles with the soil water content [36]. At the SS, the relationship between NH_4^+-N loss and runoff was also a significant power function correlation ($r = 0.907$, $p < 0.01$; Fig. 5E), and the relationship between NH_4^+-N loss and sediment yield was a significant linear correlation ($r = 0.940$, $p < 0.01$; Fig. 5F). Wang et al. [20] indicated that soil NH_4^+-N loss occurs through surface runoff and sediment adsorption. Because NH_4^+-N in soil has not enough time to dissolve in runoff, the sediment was the major carrier of NH_4^+-N at the SS. In addition, fertilizer was absorbed by the crop to support the plant growth. Consequently, the total amount of N losses was lower at the SS.

At the VS, good vegetation cover can weaken rainfall erosion of the soil surface and increase the soil water infiltration time. In order to increase crop yields, rice (*O. glaberrima*) and maize (*Z. mays* L.) were fertilized with N at the rates of about 260 and 130 kg hm^{-2}, respectively. At this stage, the amounts of TN, NH_4^+-N, and NO_3^--N loss in runoff were 33, 23, and 57 times, respectively, as high as those at the SS. The relationship between TN loss and runoff was a significant power function correlation ($r = 0.958$, $p < 0.01$; Fig. 5A), and the relationship between TN loss and sediment yield was also a signifi-

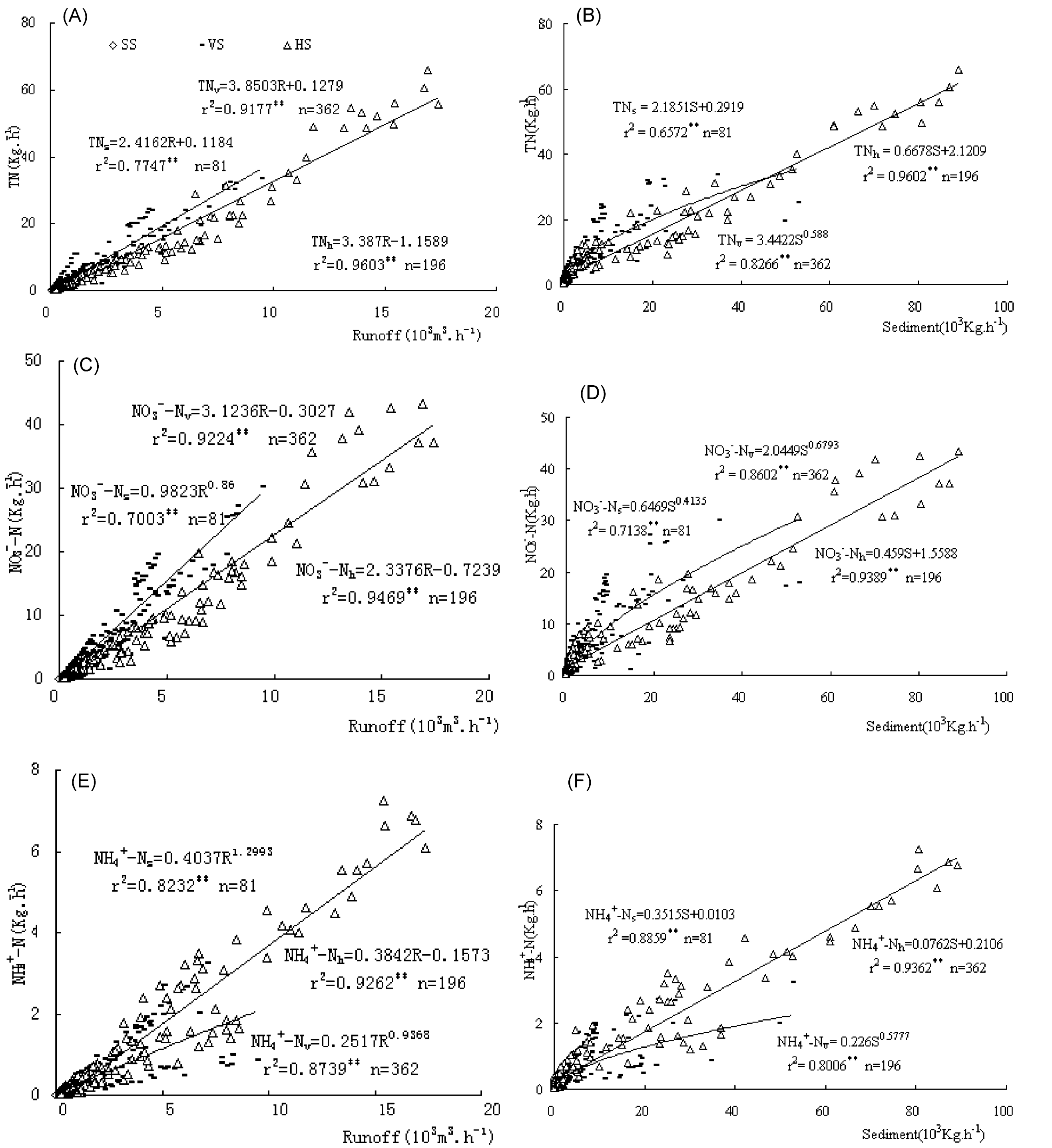

Figure 5. Relationships between TN, NH_4^+-N, and NO_3^--N loss and runoff (A), (C), (E), sediment yield (B), (D), (F) during the 2011 rainy season in Hougou agricultural watershed.

cant power function correlation ($r = 0.909$, $p < 0.01$; Fig. 5B). There were some indications that soil water content was close to saturation. In addition, N fertilization, high rainfall duration, low rainfall intensity and high vegetation coverage affected the relationships of TN loss with both runoff and sediment yield. The relationship between NO_3^--N loss and runoff was a significant linear correlation ($r = 0.960$, $p < 0.01$; Fig. 5C), and the relationship between NO_3^--N loss and sediment yield was a significant power function correlation ($r = 0.927$, $p < 0.01$; Fig. 5D). The relationship between NH_4^+-N loss and runoff was a significant power function correlation ($r = 0.935$, $p < 0.01$; Fig. 5E), and that between NH_4^+-N loss and sediment yield there was a significant linear correlation ($r = 0.968$, $p < 0.01$; Fig. 5F).

Table 3. The equations of N losses, runoff and sediment yield during the 2011 rainy season in Hougou agricultural watershed

Stages	Equations	r^2	Measured value (kg)	Prediction values (kg)	Relative error (%)
SS	$TN_s = 17.913R^{0.582}S^{0.112}$	0.800	49.49	50.34	1.72
	$NH_4^+\text{-}N_s = 0.993R^{0.08}S^{0.76}$	0.885	4.99	4.89	−2.00
	$NO_3^-\text{-}N_s = 39.564R^{0.155}S^{0.249}$	0.655	20.72	21.02	1.45
VS	$TN_v = 3.950R^{1.039}S^{-0.037}$	0.918	1642.29	1631.05	−0.68
	$NH_4^+\text{-}N_v = 5.221R^{0.193}S^{0.401}$	0.690	115.37	119.59	3.66
	$NO_3^-\text{-}N_v = 1.15\ R^{1.222}\ S^{-0.096}$	0.925	1185.20	1212.01	2.26
HS	$TN_h = 0.226R^{1.433}S^{-0.126}$	0.974	1715.50	1665.47	−2.92
	$NH_4^+\text{-}N_h = 0.347R^{0.474}S^{0.459}$	0.939	189.54	181.33	−4.33
	$NO_3^-\text{-}N_h = 0.187R^{1.454}S^{-0.161}$	0.958	1198.85	1174.55	−2.03
RS	$TN = 1.879R^{1.137}S^{-0.063}$	0.941	3407.27	3317.07	−2.65
	$NH_4^+\text{-}N = 0.315R^{0.451}S^{0.484}$	0.892	309.90	284.44	−8.22
	$NO_3^-\text{-}N = 1.607R^{1.151}S^{-0.092}$	0.917	2404.76	2454.36	2.06

TN_s, $NH_4^+\text{-}N_s$ and $NO_3^-\text{-}N_s$ represent the amount of TN, NH_4^+-N and NO_3^--N loss at the seedling stage, respectively; similarly for the other stages.

Meanwhile, the relationship of N losses with runoff and sediment yield revealed that NO_3^--N loss occurred by surface runoff and soil moisture [13, 37], whereas, NH_4^+-N loss occurred by surface runoff and sediment adsorption [20, 38].

At the HS, the inhibiting effect of vegetation for rainfall-induced erosion was weakened and the soil was exposed, thereby promoting crust formation of the soil surface. The high impact force of raindrops allows runoff to carry more sediment and N into the waterway during the process of rill erosion [16, 39, 40]. A series in Fig. 5 shows that the relationships of TN, NH_4^+-N, and NO_3^--N loss with runoff were significant linear correlations ($r > 0.962$, $p < 0.01$), and the same was true with sediment yield ($r > 0.968$, $p < 0.01$). The amount of rainfall, TN, NH_4^+-N, and NO_3^--N loss at this stage was about 28.8, 50, 61, and 49% during the 2011 rainy season, respectively. Due to vegetation coverage was very low, even the soil was exposed after harvest of crops. Therefore, the soil and runoff were run away easily and received 200.2 mm of rain, meanwhile, the 1382.17 kg of TN, 457.23 kg of NH_4^+-N were lost by soil and runoff as well, respectively. In general, the farmland was ploughed fallow when harvesting crops, leading to the subsurface flow which carried 28.16 kg of NO_3^--N from the Hougou agricultural watershed at the HS [41, 42]. These findings were indicative of the importance of vegetation coverage in regulating runoff processes and in reducing N extraction from soil surface by dissipating raindrop impact energy, and also showed that excessive fertilization and soil disturbance led to an increase in the amount of N losses at the HS.

The above analysis revealed significant correlations between N losses and runoff and N losses and sediment yield at the same stage. In order to analyze further the relationships between N losses, runoff and sediment yield, 12 rainfall events monitored during the 2011 rainy season were divided into three stages, which were compared and analyzed with all events as a whole. Subsequently, equations were fitted under different stages (Tab. 3). The results showed that a stage-by-stage method can effectively improve precision in calculating the amount of N losses because N loss processes, vegetation coverage and local agricultural practices are considered at each stage. After crop harvest, there were sharp increases in the amount of runoff, sediment yield, and N losses with the arrival of heavy rainfall; therefore a scientific and economic method was to use moderate fertilization each time at different stages. In addition, straw return for increasing of vegetation coverage was proposed in the paper, as observed for other nutrition losses by other authors in similar conditions [43, 44].

5 Conclusions

Runoff dynamics had a significant effect on sediment and N losses. Runoff volume and the presence of vegetative ground cover were the main factors that were responsible for the differences in N losses [45]. According to the above previous results, the conclusion from this study is that most of the rainfall increased the soil water content, and the runoff dynamics could not meet the demand of more sediment yield at the SS, Consequently, the sediment yield delayed the peak rainfall intensity; both runoff and sediment yield were increased and there was a significant power function correlation ($r = 0.922$, $p < 0.01$) due to the persistent rainfall at the VS. Although the rainfall during the SS was approximately half of that during the VS, runoff and sediment yield were 1.38 and 2.05 times as high, respectively, as at the VS, and there was a significant linear correlation ($r = 0.981$, $p < 0.01$) at the HS. Hence, plantation and exclusion were regarded as effective control soil and runoff losses measures and reduce soil erosion by runoff in Hougou agricultural watershed. However, plantation and exclusion implementation in the watershed could cause loss of grazing land and reduce surface flows to the reservoirs [46]. Meanwhile, the local should build more receiving pools to collect runoff and sediment, which should be returned to the field as a method of drought control and as fertilizer for crop growth. Hence, as the above concerns would have some socio-economic consequences, careful evaluation should be made before implementation.

N losses predictions done stage-by-stage can have improved accuracy. Although the fitted equations between the amount of N losses and runoff and sediment yield were $N = aR^bS^c$ assessed stage-by-stage, the method was supported by the study for predicting the amount of N losses during the 2011 rainy season in the Hougou agricultural watershed. The above results were representative of an agricultural watershed during a rainy season, therefore, under conventional cultivation systems, soil-test-fertilization and stage-by-stage fertilization may control N loss in runoff and sediment, and there is great need for further research for long-term monitoring of other agricultural watersheds of the Southern Shaanxi Province in order to predict the amount of N losses and to take measures for preventing the pollution of drinking water.

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