Effects of rainfall intensities and slope gradients on nitrogen loss at the seedling stage of maize (*Zea mays* L.) in the purple soil regions of China

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Abstract: Loss of soil nitrogen has been reported to reduce soil productivity and result in eutrophication. The objective of this work was to understand the mechanisms of nitrogen loss at the maize seedling stage from purple soil in the sloping farmlands of southwest China. The characteristics of nitrogen loss were explored in experiments simulating rainfall conditions during the maize seedling stage at different rainfall intensities (60 mm/h, 90 mm/h, and 120 mm/h) and slope gradients (10°, 15°, and 20°). The results showed that the runoff and sediment yield increased with time. The surface runoff and sediment yield increased with the rainfall intensity and slope gradient. Nitrogen losses increased in the surface runoff and sediment but decreased in the interflow as the rainfall intensity and slope gradient increased. Dissolved total nitrogen (DTN) was the main form of nitrogen in the surface runoff and interflow, and nitrate nitrogen (NO_3-N) was the main form of DTN. The surface runoff and sediment accounted for less than half of the TN losses. Thus, interflow was the main pathway for nitrogen loss. The regression lines between the surface runoff and forms of nitrogen losses in the runoff and interflow were linear. The results indicated that an increasing rainfall intensity and slope gradient generally increased the surface runoff, sediment, and nitrogen losses. However, the opposite trend was observed for the interflow and its nitrogen losses.

Keywords: forms of nitrogen, surface runoff, interflow, sediment yield, slope gradient, rainfall intensity
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1 Introduction

Soil erosion removes nutrients from onsite soil and reduces soil productivity, and it is becoming an increasingly serious environmental problem[1-3]. In the last 50 years, rapid growth in the input of nitrogen fertilizer has increased crop yields, but 37%-82% of the nitrogen in agricultural fields is lost to water, which is a major cause of eutrophication[4-6]. Understanding the dynamic characteristics is important to controlling the amounts and forms of nitrogen loss from agricultural fields into water.

Studies on soil erosion and nitrogen loss have identified contributing factors such as the slope gradient and rainfall intensity[7-10]. The surface runoff and sediment yield increased with the rainfall intensity and slope gradient increased[11,12], but some have found evidence of a critical rainfall intensity or slope gradient[13]. Nitrogen loss from agricultural fields through soil erosion by water is classified into three pathways: surface runoff, interflow, and sediment. Previous studies mainly focused on nutrient enrichment due to surface runoff and sediment[14], but most have ignored interflow. Wang et al.[15] proposed that the nitrogen loss from interflow can be a major contributor compared with surface runoff. Nitrogen loss from interflow has the same environment effects as losses from surface runoff and sediment yield[16]. Nitrate nitrogen (NO_3-N) and ammonium nitrogen (NH_4-N) are the main forms of nitrogen loss in runoff and are representative indicators of soil fertility[17-19]. Thus, studying the forms of nitrogen loss from the three pathways at different rainfall intensities and slope gradients is important.

Purple soil formed from the purple rock series of the Trias-Cretaceous system and is mainly found in the Sichuan Basin, which is one of the most important agricultural areas of southwest China. Intensive cultivation and socioeconomic pressure had accelerated soil erosion and nitrogen loss on sloping farmland[20]. Maize is an important food and cash crop that is grown in the Sichuan Basin. The growth periods of maize coincide with the timing of rainstorms. Soil erosion and nitrogen loss decrease with an increasing ratio of vegetation coverage[21]. It has been shown that the vegetation coverage of maize reaches a minimum at the maize seedling stage, at which time soil erosion reaches a significant maximum[22]. However, there are no detailed data for nitrogen loss at the maize seedling stage, which is not helpful for maize growth and nutrient management in the purple soil region.

In this study, the aims were to (1) investigate the characteristics of surface runoff, interflow, and sediment yield at different rainfall intensities and slope gradients; (2) investigate the characteristics of total nitrogen (TN), dissolved total nitrogen (DTN), NO_3-N, and NH_4-N losses from surface runoff, interflow, and sediment yield; (3) quantify the effects of runoff and sediment yield on TN, DTN, NO_3-N, and NH_4-N losses.

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2 Materials and methods

2.1 Study site

The study site is located at Songtao, Yanjiang District, Ziyang City (104°34'12"-104°35'19"E, 30°05'12"-30°06'44"N), Sichuan Province, China, this site has a subtropical humid monsoon climate, moderate weather and an annual average temperature of 16.8℃. The average annual precipitation is 965.8 mm occurs from May to September, with an average of 965.8 mm. The area is dominated by purple soil formed from purple sandy shale, which is classified as an Entisol according to the soil taxonomy of the United States Department of Agriculture (USDA)[23]. It is usually 50-80 cm in depth with a relatively light texture and poor soil fertility. The original soil properties are listed in Table 1.

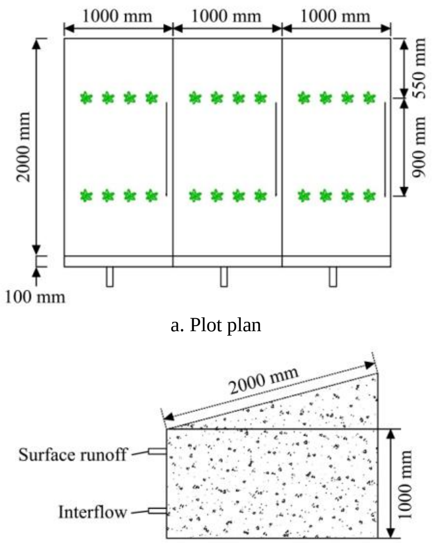
Table 1 Physical and chemical properties of soil from the study site

Soil bulk density/g cm^{-3}	pH	Soil particle distribution/%			SOM/ g kg^{-1}	TN/ g kg^{-1}	AN/ mg kg^{-1}	AP/ mg kg^{-1}	AK/ mg kg^{-1}
		Sand (2-0.02 mm)	Silt (0.02-0.002 mm)	Clay (<0.002 mm)					
1.21	7.5	49	29	22	11.62	0.73	40.13	14.08	86.64

Note: SOM: Soil organic matter; TN: total nitrogen; AN: available nitrogen; AP: available phosphorus; AK: available potassium.

2.2 Configuration of soil plots

The experimental runoff plots were 2.0 m×1.0 m. The slope gradients of the runoff plots were 10°, 15°, and 20°, and three connected plots constituted one slope gradient group. In total nine plots were set up. The bottom of each plot was reinforced with concrete to form a relatively impermeable layer that coincided with the slope gradient of the soil surface. A 10 cm thick quartz was spread on the relatively impermeable layer, which was then covered with a 60 cm thick soil layer. A V-shaped collection groove was placed underneath the slope surface of each concrete-reinforced plot, and polyvinyl chloride (PVC) pipe was used to connect each groove to the runoff collection barrel. Upon the start of the rainfall simulation, the time to runoff initiation (i.e., when runoff started to flow at the outlets of the plot) was recorded. Surface runoff and sediment samples were continuously collected with plastic buckets. At 40 cm, the soil had an impervious layer to collect interflow, PVC pipe was used to connect the impervious layer and runoff collection barrel, and interflow was continuously collected with plastic buckets (as shown in Figure 1).



a. Plot plan

b. Plot section

Figure 1 Design of the experimental plot

2.3 Experimental design

The simulated rainfall experiments were conducted at a field observation station at the Sichuan Academy of Agricultural Sciences. The Simulator was programmed and equipped with two spray nozzles (SR; V-80100 series) installed by the Institute of Soil and Water Conservation, Chinese Academy of Sciences. The rainfall simulator height was 6.5 m, and the effective rainfall area was approximately 48 m^2. The rainfall uniformity of the simulator was approximately 85%[24]. The simulated rainfall intensities were 60 mm/h, 90 mm/h, and 120 mm/h. These were maintained with a pressure gage (ranging from 0 to 1.0 bar) to match the characteristics of local storms, which are concentrated in the summer and autumn of the study area. The runoff durations was 60 min, 40 min, and 30 min, respectively, to ensure a consistent amount of rainfall from the beginning of runoff for each rainfall event, and the soil moisture content was 9.25% before the simulated rainfall. Using the same external environment minimized the differences between the antecedent soil water conditions among the treatments.

The maize (*Zea mays* L.) used in this study was Zhenghong 6, which was initially seeded on April 7, 2016. Planting was managed according to local conditions, Two thousand seven hundred plants were cultivated in an area of 666.7 m^2, and the row and plant spaces were 80 cm and 30 cm, respectively. The fertilizers application rates were 70 kg N/hm^2, 15 kg P/hm^2, and 90 kg K/hm^2 before sowing. Weeds in the plots were removed periodically by hand. Contour tillage and topdressing were performed according to local farming methods. Fertilizers use of N and K were mixed with water to irrigate the nest, while P was applied dry in the nest. Each treatment was repeated three times. The experiments were conducted at the maize seedling stage.

2.4 Runoff and sediment collection system and chemical analyses

For each treatment, the surface runoff, interflow, and sediment samples were continually collected in buckets at a regular interval of 6 min, during the rainfall duration. The runoff and sediment yield generation times and the duration of the rainfall were used to examine the rainfall-runoff process. The volumes of surface runoff and interflow in the bucket were measured with a measuring cylinder. After approximately 3 h of settling, 250 mL of the supernatant was placed into a clean polyethylene bottle, to which 1 mL 98% H_2SO_4 was added to suppress microbial activity. The treated samples were stored at 4℃ for subsequent chemical analysis. The sediment on the surface of the runoff buckets was dried in an oven at 105℃ for weighing.

The TN of each collected surface runoff and interflow sample was measured before the sample was filtered through 0.45 μm filter paper. The concentrations of TN, DTN, NO_3-N, and NH_4-N in the surface runoff and interflow were measured with an auto discrete analyzer (Cleverchem 380). The TN in the sediment was measured by the semi-micro Kjeldahl method. All chemical elements were analyzed according to standard procedures and instrument instruction manuals[25].

2.5 Data processing and statistical analyses

Statistical analyses were conducted in DPS11.0. An analysis of variance (ANOVA) test was performed to determine the relationships between different treatments. Regression analysis was used to evaluate the influence of the runoff and sediment yield on the forms of nitrogen losses. For all analyses, results were considered statistically significant at $p<0.05$.

3 Results

3.1 Runoff and sediment yield

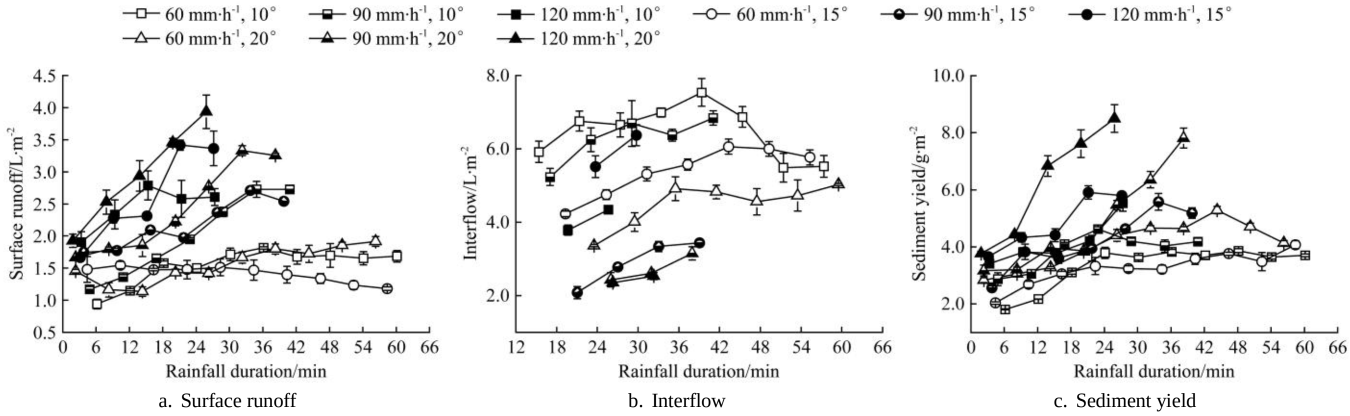
The surface runoff increased over time with different treatments. Generally, the surface runoff increased with the slope gradient and rainfall intensity increased (Figure 2a). The surface runoff was greater at a rainfall intensity of 120 mm/h than at 90 mm/h and 60 mm/h, regardless of the different slope gradients. Compared with the rainfall intensity of 60 mm/h, the average surface runoffs at rainfall intensity of 90 and 120 mm/h increased 1.55 and 1.90 times, respectively, at a slope gradient of 20°. Similar increasing trends were observed for the slope gradients of 10° and 15°.

The interflow appeared at runoff duration of 18 and 24 min. It gently increased over time with different treatments except at a slope gradient of 10° and the rainfall intensity of 60 mm/h. The interflow reached a maximum at a runoff duration of 42 min. The interflow decreased as the slope gradient and rainfall intensity increased (Figure 2b). The interflow time was shortest at a rainfall intensity of 120 mm/h, the interflow time was shorter than that of other rainfall intensities. Compared with a slope gradient of 10°, the average interflow decreased by 15.12% and 28.67% at slope gradients of 15° and 20°, respectively, at a rainfall intensity of 60 mm/h. The decreasing trend for the interflow was also observed at rainfall intensities of 90 and 120 mm/h.

The trends for the sediment yield over time were similar to those for the surface runoff with different treatments. The average sediment yield increased with the slope gradient and rainfall intensity (Figure 2c). The sediment yield reached a steady value towards the end of the experiment at a rainfall intensity of 60 mm/h, in contrast to the other two rainfall intensities of 90 mm/h and 120 mm/h. The average sediment yield under the rainfall intensities of 120 mm/h and 90 mm/h were respectively 1.27 times and 1.16 times higher than the sediment yield at a rainfall intensity of 60 mm/h with a slope gradient of 10°. A similar increasing trend for the sediment yield was also observed at slope gradients of 15° and 20°.

3.2 Nitrogen losses in runoff

The nitrogen loss in the surface runoff increased to a maximum at a runoff duration of 30 min and then gradually reached a steady state over time (Figure 3).



Note: Data are means ±SE of three individual replicates. The same as below.

Figure 2 Dynamic variation characteristics of surface runoff, interflow and sediment yield under different slope gradients and rainfall intensities

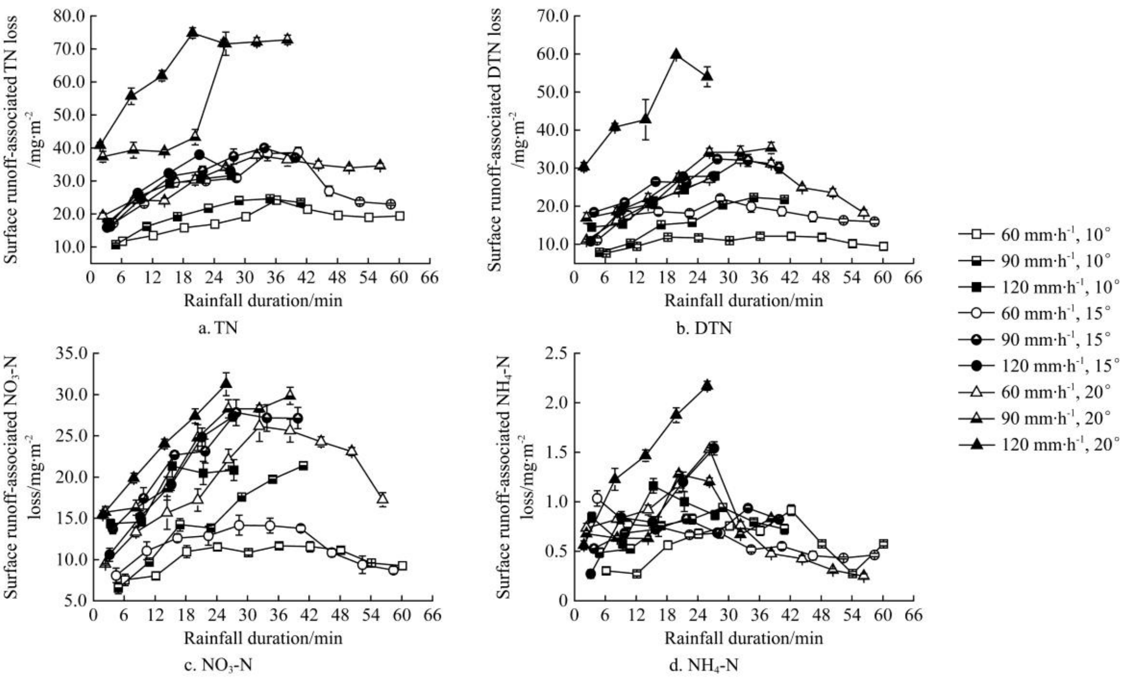


Figure 3 Dynamic variation characteristics of surface runoff-associated nitrogen losses under different slope gradients and rainfall intensities

However, the DTN and NO_3-N losses in the surface runoff decreased towards the end of the experiment at a rainfall intensity of 60 mm/h. The NH_4-N loss in the surface runoff was volatile over time. The nitrogen losses (TN, DTN, NO_3-N, and NH_4-N) in the surface runoff increased with the rainfall intensity and slope gradient. The average concentrations of the TN, DTN, NO_3-N, and NH_4-N losses in the surface runoff were 31.69 mg/m^2, 21.82 mg/m^2, 17.30 mg/m^2, and 0.79 mg/m^2, respectively. The main form of nitrogen loss in the surface runoff was DTN, and NO_3-N was the main form of DTN. The nitrogen losses in the interflow increased to a maximum at a rainfall duration of 42 min, and then decreased towards the end of the experiment (Figure 4).

The nitrogen losses in the interflow reached a minimum at a slope gradient of 20°. However, the NH_4-N loss in the interflow reached a maximum at a slope gradient of 20°. The average nitrogen losses reached their maximum and minimum at rainfall intensities of 60 mm/h and 120 mm/h respectively. The TN loss in the interflow was 77.11-326.58 mg/m^2. The average DTN, NO_3-N, and NH_4-N losses in the interflow were 133.69 mg/m^2, 104.28 mg/m^2, and 2.00 mg/m^2, respectively. DTN was the main form of nitrogen loss in the interflow, and NO_3-N was the main form of DTN.

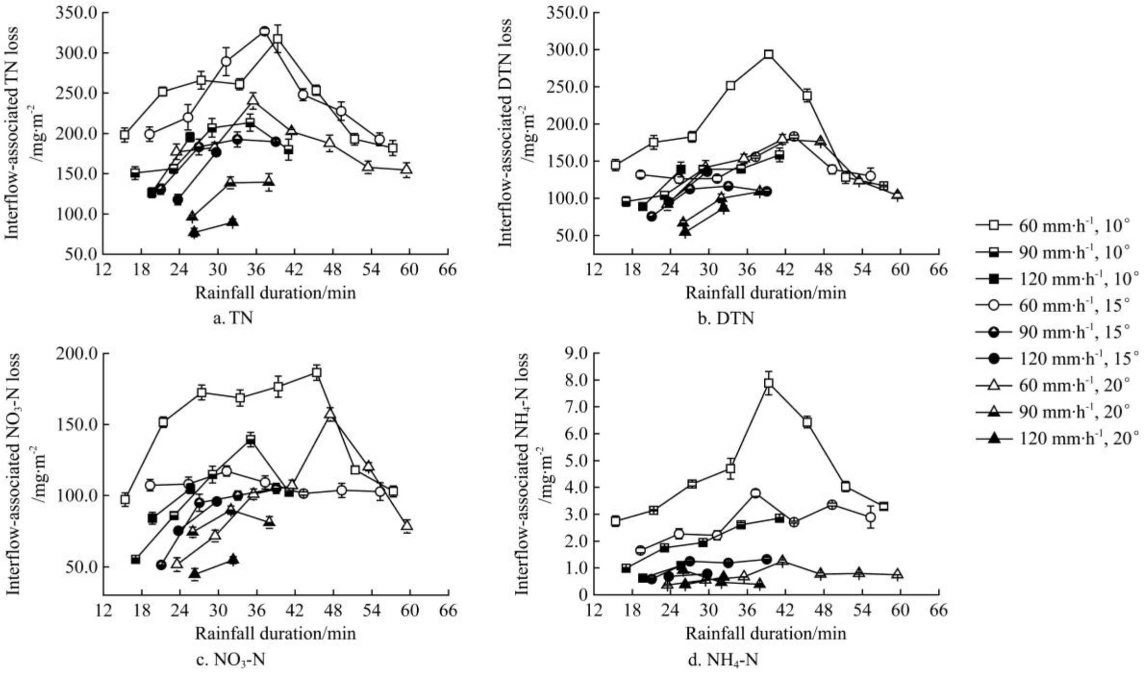


Figure 4 Dynamic variation characteristics of Interflow-associated nitrogen losses under different slope gradients and rainfall intensities

3.3 Nitrogen losses in sediment yield

The nitrogen losses in sediment increased with time, but reached a steady state at rainfall intensities of 60 and 90 mm/h towards the end of the experiment. The trends were similar to those of sediment with different treatments. The average concentration of nitrogen losses in sediment increased with the slope gradient and rainfall intensity (Figure 5). The nitrogen loss in the sediment reached 5.08 mg/m^2 at a slope gradient of 20° and rainfall intensity of 120 mm/h.

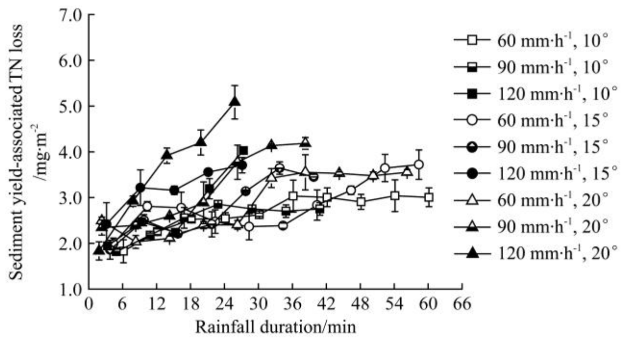


Figure 5 Dynamic variation characteristics of sediment-associated nitrogen losses under different slope gradients and rainfall intensities

4 Discussions

4.1 Surface runoff, interflow, and sediment yield

The characteristics of the surface runoff, interflow, and sediment yield in the soil were mainly depended on the rainfall intensity and slope gradient[8,9]. In the present study, the surface runoff increased with the rainfall intensity and slope gradient (Figure 2a), which agrees with the results of Liu et al[10]. However, they found that a critical rainfall intensity or slope gradient existed depending on the soil physical properties[10]. In contrast, the interflow decreased as the rainfall intensity and slope gradient increased in this study (Figure 2b). Though the ridge could effectively increase soil water infiltration and reduce runoff volume by intercepting the runoff and reducing the flow velocity[26], soil crust is easy to form in furrows in present study. This may be because the infiltration rate decreased as the slope increased which formed a soil crust[27,28]. The interflow reached a maximum at a runoff duration of 42 min (Figure 2b), which was mainly because it took the form of a macropore flow in the initial stage of rainfall[4]. Increasing the rainfall intensity and slope gradient resulted in a greater sediment yield (Figure 2c) because of the increased raindrop energy and surface runoff velocity. The sediment yield showed the same trend as the surface runoff. The results also showed that the sediment yield is closely related to the surface runoff [29,30].

4.2 Nitrogen losses in surface runoff, interflow, and sediment yield

Nitrogen can move from soil to water as it dissolves in surface runoff and interflow, and may be adsorbed on the surface of soil particles. The amount of nitrogen loss depends on the surface runoff, interflow and sediment yield[14]. In this study, the nitrogen loss reached a maximum in the surface runoff and interflow at runoff durations of 30 and 42 min, respectively, except at a rainfall intensity of 2.0 mm/min. The reason was twofold: nitrogen from different soil depths was taken away by complete dissolution, and nitrogen was released from soil particles destroyed by runoff[21]. The nitrogen concentrations in the surface runoff, interflow, and sediment showed no significant differences with the different treatments, which indicates that the rainfall intensity and slope gradient had only small impacts[9]. This result may be related to growing maize. However, the average TN concentration in the surface runoff, interflow, and sediment were 15.95 mg/kg, 39.80 mg/kg and 1.42 mg/kg, respectively, which are easily above the level to cause eutrophication (0.2 mg/L). These results also showed that the nitrogen concentration in the sediment yield was enriched (1.42 mg/kg) compared with the original concentration in the purple soil (0.73 mg/kg). The nitrogen loss in the surface runoff, interflow, and sediment accounted for 9.27%-45.95%, 50.79%-89.35%, and 1.37%-4.89%, respectively, of the TN loss with different treatments (Table 2), which indicates that interflow dominated the TN loss. Mo et al.[31] also found that the interflow is the main pathway of nitrogen loss. This is because purple soil has a high infiltration rate, which increases the interflow and the nitrogen concentration in the interflow. This increases the nitrogen loss[15,32]. In the purple soil region, the NH_4-N concentrations in the surface runoff and interflow were always low during rainfall and were volatile as the rainfall duration increased (Figures 3 and 4). This is because NH_4^+ was easily absorbed by the negatively charged soil particles[33,34]. DTN was the main form of nitrogen loss in the surface runoff and interflow. NO_3-N was the main form of DTN[10].

Table 2 Nitrogen loss in the runoff, interflow and sediment under different slope gradients and rainfall intensities

Rainfall intensity /mm h^{-1}	Slope gradients /(°)	Nitrogen loss/mg m^{-2}					
		Surface runoff		Interflow		Sediment	
		Nitrogen loss	Percentage	Nitrogen loss	Percentage	Nitrogen loss	Percentage
60	10	180.56	9.27	1740.13	89.35	26.77	1.37
	15	281.43	17.47	1301.62	80.79	28.16	1.75
	20	309.47	15.16	1702.92	83.42	28.97	1.42
90	10	139.98	13.15	906.62	85.19	17.62	1.66
	15	219.86	23.57	693.85	74.37	19.23	2.06
	20	375.28	29.27	884.69	68.99	22.31	1.74
120	10	134.20	28.57	321.57	68.47	13.88	2.96
	15	145.53	44.32	166.75	50.79	16.06	4.89
	20	304.89	45.95	340.63	51.34	17.96	2.71

4.3 Influences of surface runoff on sediment yield, runoff, and nitrogen losses, and sediment yield on nitrogen losses

The sediment yield increased with the rainfall intensity and slope gradient because of the increased raindrop energy and surface runoff velocity[9]. Regression analyses determine the relationship between the sediment yield and surface runoff. The results showed that a linear regression best described the runoff and sediment yield (Figure 6), this has been widely accepted to describe the relationship between the surface runoff and sediment yield at different rainfall intensities and slope gradients[35]. The sediment yield increased linearly with increasing runoff for different treatments, which is consistent with other experiments results[36,37]. Rainfall power results in soil detachment, and runoff energy causes the transport of eroded sediment[38]. The results may be explained by the increased transport capacity to carry the detached sediment as the surface runoff rate increase. These results differ from those of Xing et al.[32], who found a nonlinear relationship between the sediment and runoff. This difference may be because the relationship between the surface runoff and sediment loss was generated by five rainfall simulations with different slope lengths, this differs from the relationship between the surface runoff and sediment yield rate based only on one rainfall event. Under these conditions, the detachment potential was sufficiently large because of the greater rainfall intensity and slope gradient[9].

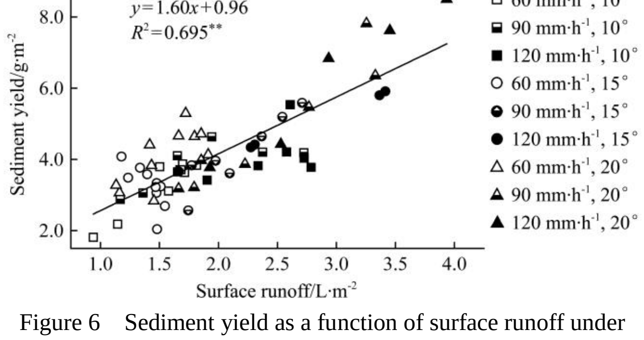


Figure 6 Sediment yield as a function of surface runoff under different slope gradients and rainfall intensities

The nitrogen loss was influenced by runoff in two main ways: nitrogen loss in runoff and nitrogen loss in sediment yield[32]. The influence of the surface runoff on its nitrogen loss was analyzed. Regression analysis showed that the surface runoff had a significant influence on its nitrogen loss (Figure 7). The forms of nitrogen loss in the surface runoff increased linearly with the runoff in experiments (p<0.01). The results confirmed the finding of the previous study[39]. These experimental results showed that the forms of nitrogen loss in the surface runoff were controlled by the surface runoff load capacity.

The interflow is an important pathway for nitrogen loss, and it was found to have a similar influence on the nitrogen loss (Figure 8) to that of the surface runoff (p<0.01). The results showed that the forms of nitrogen loss in the interflow are linearly correlated with the interflow. The nitrogen desorption and nitrogen load capacity are the two most important variables that influence the nitrogen loss rates in the surface runoff[16]. The experimental results of the present study also showed that the nitrogen load capacity controls the forms of nitrogen losses in the interflow. The other experimental results indicate that the forms of nitrogen loss in the surface runoff and interflow are significantly influenced by the surface runoff and interflow rather than the forms of nitrogen concentration[9].

In this study, the sediment yield had a significant influence on nitrogen loss from the sediment (Figure 9). Regression analysis confirmed that the best fit was linear and significant (Y=0.46X+0.99, R^2=0.732, p<0.01). This has also been found to be the case for different crop types and vegetation coverages[6]. The TN loss exhibited a significant linear relationship with the sediment yield, which indicates that it was the main influencing factor that controlled the nitrogen loss. Guo et al.[39] found significantly positive correlations between sediment yield and N losses on contour tillage slope.

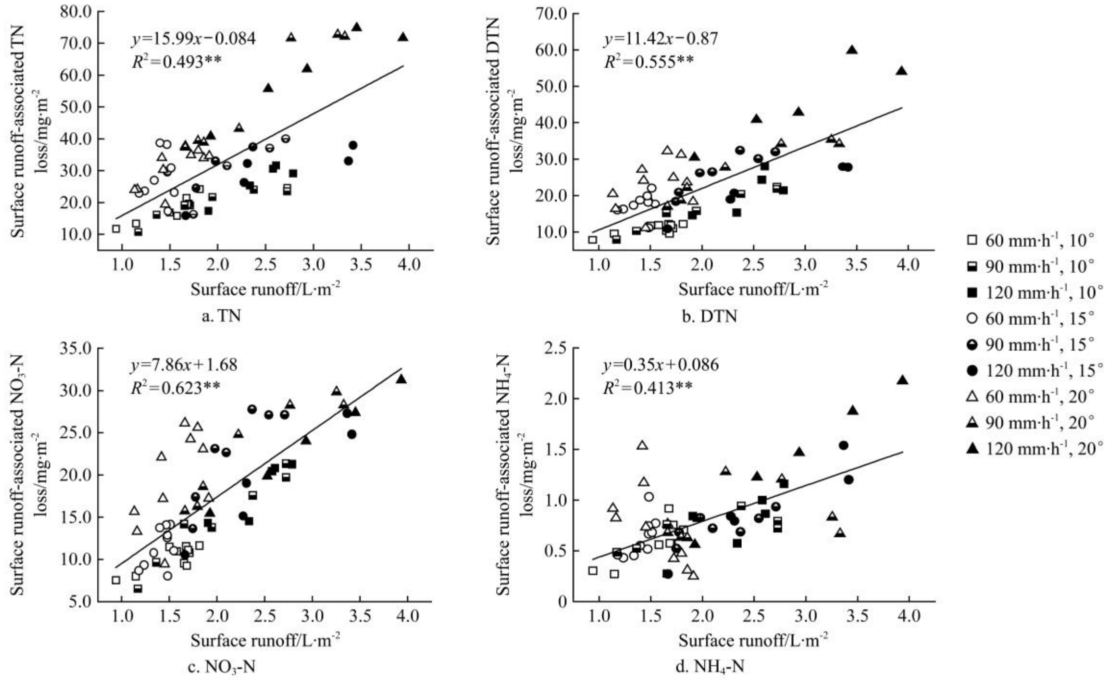


Figure 7 Surface runoff-associated nitrogen loss as a function of runoff under different slope gradients and rainfall intensities

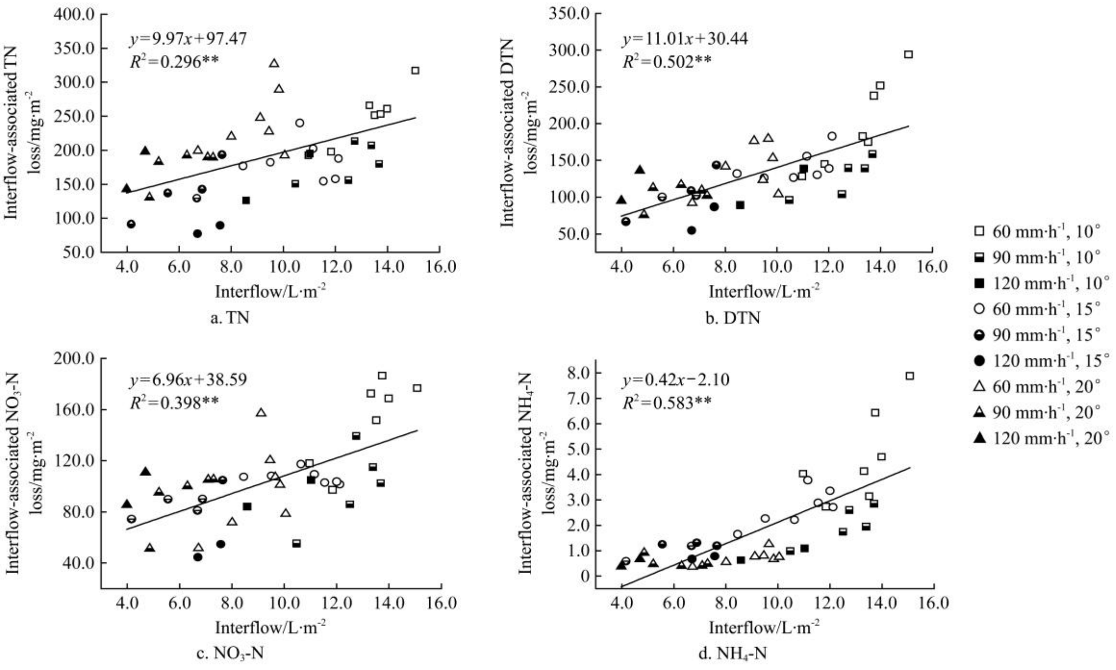


Figure 8 Interflow-associated nitrogen loss as a function of interflow under different slope gradients and rainfall intensities

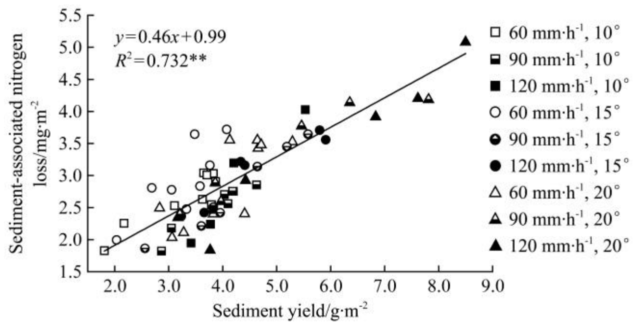


Figure 9 Sediment-nitrogen loss as a function of sediment under different slope gradients and rainfall intensities

5 Conclusions

This study demonstrated that the runoff and sediment increased with time at different rainfall intensities and slope gradients for maize in the seeding stage. The surface runoff and sediment increased but the interflow decreased as the rainfall intensity and slope gradient increased. The nitrogen losses in the surface runoff and interflow accounted for 9.27%-45.95% and 50.79%-89.35%, respectively, of the TN losses for all the treatments. DTN was the main form of nitrogen loss in the surface runoff and interflow, and NO_3-N was the main form of DTN. The relationship between the sediment and surface runoff at different rainfall intensities and slope gradients was found to be linear. Regression analysis determined a linear relationship between the runoff and forms of nitrogen loss in the runoff. The nitrogen losses in the surface runoff and interflow were found to be mainly controlled by the surface runoff and interflow, thus, they behaved similarly to the nitrogen loss in sediment. The rainfall intensity and slope gradient were the main influencing factors for soil erosion and nitrogen loss. The results indicated that increasing the rainfall intensity and slope gradient generally increased the surface runoff, sediment, and nitrogen losses. However, the opposite trend was observed for the interflow and their nitrogen loss. The results suggest that it should be noticed to the effective prevention and control of runoff and sediment yield at maize seedling stage for the implementation of contour tillage measures in the purple soil region.

Acknowledgements

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