Surface flow–interflow-coupled nitrogen loss in gray fluvo-aquic farmland soils in the Anhui Section of the Huaihe River Basin, China

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ARTICLE

Surface flow–interflow-coupled nitrogen loss in gray fluvo-aquic farmland soils in the Anhui Section of the Huaihe River Basin, China

Hui Wang, Liangmin Gao, Zhendong Pang, Jie Yang, Xiaoqing Chen, Jinxin Zhang, Shuo Wang, Rongrong Tong, Chuang Shi, and Xudong Chen

Abstract: To reveal the characteristics of nitrogen loss and their coupling relations in the process of surface flow and interflow under various rainfall intensities in gray fluvo-aquic soil areas, the coupling loss characteristics of total nitrogen (TN), nitrate nitrogen (NO_3^--N), and ammonium nitrogen (NH_4^+-N) in the surface flow and interflow under three rainfall intensities (60, 80, and 110 $mm \cdot h^{-1}$) at a slope of 5° were studied using an artificial rainfall simulation. The results showed that (1) runoff yield and TN concentration were proportional to the rainfall intensity, with higher runoff concentrations of TN in the initial stage, and (2) surface flow yield, which was the main output mode of farmland runoff, was higher than interflow yield under a range of rainfall intensities. The average concentration of NO_3^--N in surface flow decreased with increasing rainfall intensity, whereas the opposite was true in interflow. The main loss path of NO_3^--N was interflow, whereas the main loss path of NH_4^+-N was the surface flow; NO_3^--N was the main form of TN loss. The surface flow was the main loss path of soil nitrogen loss in farmland, and the runoff yield was an important factor in controlling nitrogen loss.

Key words: rainfall intensity, surface flow, interflow, nitrogen loss, gray fluvo-aquic soils.

Résumé : Les auteurs ont étudié les pertes d'azote total (NT), de nitrates (N-NO_3^-) et d'ammonium (N-NH_4^+) attribuables à l'écoulement de surface et au ruissellement retardé sur un sol gris fluvial-aquique en pente de 5° en simulant trois intensités de précipitation (60, 80 ou 110 $mm \cdot h^{-1}$). L'objectif consistait à préciser les paramètres associés à la perte d'azote ainsi que leurs relations avec l'écoulement de surface et le ruissellement retardé lorsque les précipitations varient en intensité. Si on se fie aux résultats, (1) l'importance du ruissellement et la perte de NT sont proportionnelles à l'intensité des précipitations, la concentration de NT étant plus élevée au début du ruissellement, et (2) l'écoulement de surface, principale raison du ruissellement agricole, est plus important que le ruissellement retardé pour une fourchette d'intensités de précipitation. La concentration moyenne de N-NO_3^- dans l'écoulement de surface diminue avec l'intensité des précipitations, mais elle augmente avec l'intensité du ruissellement retardé. Ce dernier est donc à l'origine de la plus forte perte de N-NO_3^-, alors l'écoulement de surface explique les pertes plus abondantes de N-NH_4^+. La majeure partie du N total perdu l'est sous forme de N-NO_3^-. L'écoulement de surface explique la plus forte perte d'azote sur les terres agricoles et l'intensité du ruissellement est un paramètre majeur dans la lutte contre les pertes d'azote. [Traduit par la Rédaction]

Mots-clés : intensité des précipitations, écoulement de surface, ruissellement retardé, perte d'azote, sol fluvial-aquique.

Introduction

The loss of nitrogen (N) and phosphorus (P) in soil is the main cause of water eutrophication. In recent years, scholars in China and around the world have conducted many studies on N loss in farmland soil, covering the factors influencing N loss (Guo et al. 2018; Zhang et al. 2020; Chen et al. 2021), the characteristics of N loss (Jiang et al. 2017; García-Díaz et al. 2017; Gao et al.

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2019a), and the process of N migration in soil (Wang et al. 2016; Song et al. 2017; Zheng et al. 2017). Their results showed that rainfall intensity is one of the important factors affecting N loss in farmland soil, and runoff is the main pathway of N and P loss from soil and the main cause of agricultural non-point-source pollution.

Runoff includes three main forms: surface flow, interflow, and subsurface flow. Because the form of runoff affects nutrient loss, understanding runoff processes and nutrient transport pathways is of great significance for mitigating and controlling N loss (Johannes et al. 2014). Scholars in China and around the world have studied N export via surface flow and interflow, including the process of N loss under various rainfall intensities, various land-use regimes, and various slope conditions (Xing et al. 2016; Zhou et al. 2011; Gao et al. 2019b). The field test plots of these studies were designed to examine N loss characteristics under a range of vegetation coverage patterns and fertilization methods (Liu et al. 2017; Zhang et al. 2021) or to provide a comparative analysis of surface flow and interflow N losses (Kiani et al. 2018; Deng et al. 2019). Many studies on N loss in surface flow have focused on red and purple soils (Ren et al. 2013; Bouraima et al. 2016; Che et al. 2016), but relatively few studies on N loss have investigated runoff from gray fluvo-aquic soils. Moreover, the interaction between surface flow and interflow is rarely reported. Gray fluvo-aquic soil is the main soil type in the Anhui section of Huaihe River Basin, and there are few studies on the effect of rainfall intensity on N loss in this basin. Therefore, it is important to study the characteristics of N loss during surface flow and interflow in gray fluvo-aquic soils under different rainfall intensities as well as their mutual coupling relation. Hence, in the present study, a test tank was used as the platform, and the gray fluvo-aquic soil in the Anhui section of the Huaihe River Basin in China was used as the experimental soil. The runoff production and N loss characteristics of surface flow and interflow under various rainfall intensities were studied using an artificial rainfall simulation, along with the coupling relation of N loss with the surface flow and interflow. This investigation aims to provide a scientific basis for the effective control of soil N loss and regional environmental management in gray fluvo-aquic soil areas.

Materials and Methods

Test soil

The test soil was collected in November 2020 from actual farmland in Caoji Town, Funan County, Fuyang City, Anhui Province, China (32°31′06″N, 115°44′32″E); soil layers of 0–10, 10–20, and 20–30 cm were sampled. The area is located in the southern part of the North China Plain and includes the northern bank of the upper and middle reaches of the Huaihe River. The topography is divided into three types: hilly land (55%), slope land (21%), and depression land (24%). The target area has a warm temperate semi-humid monsoon climate with moderate rainfall and abundant sunshine. The mean annual temperature is 15 °C, and the typical annual rainfall is 820–950 mm, with summer as the rainiest season, accounting for >46% of the annual rainfall.

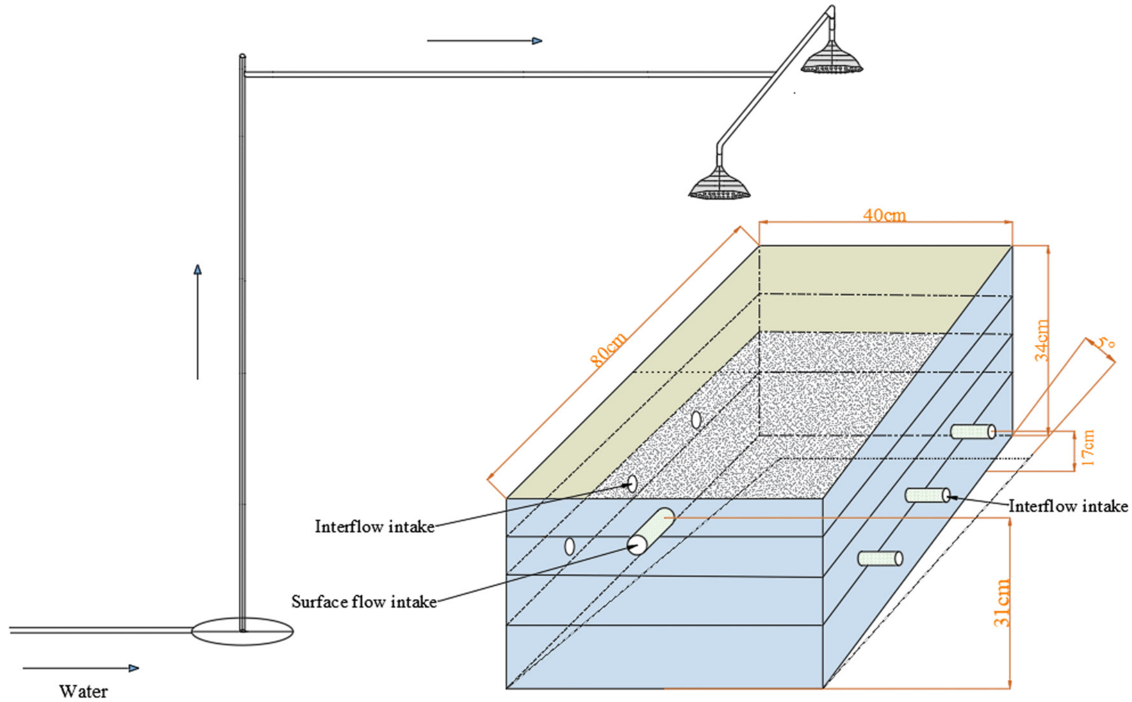
The test soil type is gray fluvo-aquic soil with a light texture. It has good tillage, poor drainage, high water table, and good drought resistance. The parent substance is modern Huaihe flood alluvial material (Lu and Wang 1986). This material, made of acidic crystalline rocks such as granite and mud rocks from the upper Funiu, Tongbai, and Dabie Mountains, is weathered, washed, carried, and deposited by water in the lake depressions on both sides of the Huaihe River and its tributaries. Due to the short timescale of physical weathering, deposition, and cultivation use, many nutrients are consumed quickly and not easily accumulated. The soil has a neutral pH, with an average porosity of 47.93%, average organic matter content of 17.45 $g\cdot kg^{-1}$, average bulk density of 1.38 $g\cdot cm^{-3}$, initial field moisture content of 8% ± 1.5%, an average total nitrogen (TN) content of 0.84 $g\cdot kg^{-1}$, and particle composition dominated by sand grains (0.05–1.00 mm) and coarse silt (0.01–0.05 mm).

Experimental design and analytical methods

The test tank is an open-top box with length, width, and height of 80, 40, and 34 cm, respectively (Fig. 1). Three round holes of 2 cm diameter were evenly distributed on each of two opposite lateral surfaces of the test tank, such that the distance between the center of the hole and the bottom surface of the test tank was 17 cm, and the distance between the two centers was 20 cm. A PVC pipe was connected to each hole to convey interflow water samples. A round hole of 2 cm diameter was made through the front side of the test tank. The distance between the center of the hole and the bottom surface of the test tank was 31 cm, and the distance between the center of the hole and the side surface of the test tank was 20 cm. A PVC pipe was connected to each hole to convey surface flow water samples.

The collected soil samples were filled into the upper, middle, and bottom layers of the tank in a corresponding order (0–10, 10–20, and 20–30 cm), with a total soil thickness of 30 cm. Based on the results of field investigation, the soil was fertilized by conventional fertilization and straw returning in the experiment, in accordance with the local fertilization method. In filling the soil, the harvested and shredded rice straw was filled to the middle layer of the soil at a density of 0.74 $kg\cdot m^{-2}$. After the straw was filled, compound fertilizer (N15, P15, K15) + urea (N46.4) was spread on the soil surface at a rate of 750 $kg\cdot ha^{-1}$ of compound fertilizer application and 150–225 $kg\cdot ha^{-1}$ of urea, using the same application method for each test box. After completing fertilization, the test tank was padded at one end with reference to the average slope of the farmland in the

Fig. 1. Simulated rainfall test device diagram. [Colour online.]



sampling area and left at an inclination of 5° for 90 d under natural conditions to allow the soil to sink naturally and restore its natural properties. After 90 d, a simulated rainfall experiment was conducted.

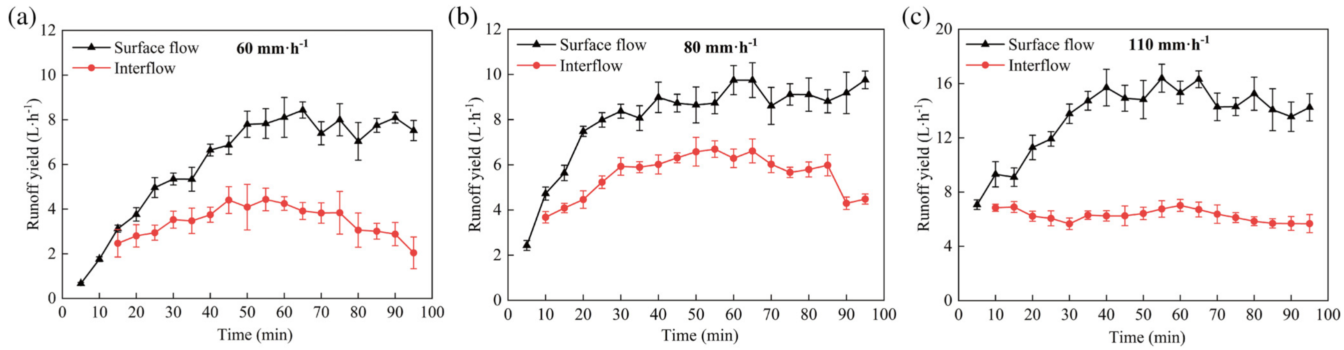
Three test tanks corresponding to three rainfall intensities were used for the experiment. After each test, the soil was removed, the test tank was cleaned with ultrapure water, and then the same soil samples as the first test were placed again to repeat the test. Further, each test was repeated three times for each rainfall intensity. Two rainfall simulation devices were erected in each test tank. A rainfall sprinkler head 80 cm above the test tank was used as the rainfall device. A submersible pump connected to the rainfall sprinkler head was used to extract the source water (tap water). The amount of water emitted from the sprinkler head was adjustable, and initial rainfall tests showed rainfall uniformity exceeding 90%, which was close to natural conditions and met the needs of the simulated rainfall tests. In accordance with the local actual rainfall level, the designed rainfall intensities were 60, 80, and 110 $mm \cdot h^{-1}$. A rain gauge was used to measure the rainfall of the rainfall device prior to the test. The generation times of surface flow and interflow were recorded. Samples were obtained every 5 min, and the runoff yield was measured using a measuring cylinder. Each simulated rainfall stopped after 95 min. After the runoff yield was measured, 400 mL water samples were retained for the determination of N concentration during each 5 min period. Samples were stored in cold storage at 4 °C until N content determination, which was completed within 48 h of sampling. Each retained water sample was divided into two parts. One part was directly tested to determine the TN content, whereas the other part was tested to determine the nitrate nitrogen (NO_3^--N) and ammonium nitrogen (NH_4^+-N) contents after filtering through a filter membrane with an aperture of 0.45 μm. Each artificial rainfall water sample was obtained as a blank sample to determine its N concentration; this blank sample N concentration was subtracted when calculating the N concentrations of runoff water samples.

Nitrogen concentrations were determined according to the standard Chinese methods. In particular, TN was determined using the alkaline potassium persulfate digestion ultraviolet spectrophotometric method (Standardization Administration of the People's Republic of China 2012), NO_3^--N was determined using ultraviolet spectrophotometry (Standardization Administration of the People's Republic of China 2007), and NH_4^+-N was determined using Nessler's reagent spectrophotometry (Standardization Administration of the People's Republic of China 2009).

Statistical analysis

The nonlinear fitting of N loss was carried out by using OriginPro 2021 software, and the model that can best describe soil N loss was determined. Before the analysis of variance (ANOVA) using SPSS software (version 20 for Windows), the data were tested for normality and homogeneity. One-way ANOVA was used to evaluate the difference of N content under different rainfall intensities. When the analysis of variance was significant

Fig. 2. Runoff yield trends under various rainfall intensities: (*a*) 60 mm·h^{-1}, (*b*) 80 mm·h^{-1}, (*c*) 110 mm·h^{-1}. Data points = mean of measurements. Error bars = standard error (n = 3). [Colour online.]



($p < 0.05$), the least significant difference (LSD) was used to compare the mean. The corrplot package in R4.0.5 was used for correlation analysis, and the significance level was $p < 0.05$. All figures are drawn by OriginPro 2021 and R4.0.5.

Results

Effect of rainfall intensity on runoff loss

Figures 2*a*–2*c* shows that surface flow yield was highest under a rainfall intensity of 110 mm·h^{-1} and lowest under a rainfall intensity of 60 mm·h^{-1}. With increasing rainfall intensity, interflow yield also increased to a certain extent, but the change was not as significant as that of surface flow. Furthermore, the start time of interflow production was later under a rainfall intensity of 60 mm·h^{-1} than under a rainfall intensity of 80 or 110 mm·h^{-1}, while the generation of interflow did not occur earlier under a rainfall intensity of 110 mm·h^{-1} than under a rainfall intensity of 80 mm·h^{-1}.

Under a given rainfall intensity, surface flow yield increased with increasing rainfall duration, whereas interflow yield fluctuated with increasing rainfall duration, with only a relatively gentle overall change trend. Surface flow yield exceeded interflow. Under a rainfall intensity of 60 mm·h^{-1}, surface flow yield increased relatively quickly in the first 50 min, from 0.67 to 4.97 L·h^{-1}, and then gradually stabilized. At rainfall intensities of 80 and 110 mm·h^{-1}, surface flow yield increased quickly in the first 40 min and then stabilized. These findings indicate earlier surface flow stabilization under higher rainfall intensities.

Effect of rainfall intensity on total nitrogen loss

The variations of TN concentration changes under different rainfall intensities are shown in Figs. 3*a*–*f*. The average TN concentrations in surface flow under the three rainfall intensities were 4.45, 6.37, and 6.90 mg·L^{-1}, respectively. The average TN concentrations in interflow were 7.40, 7.61, and 9.80 mg·L^{-1}, respectively. Thus, the average TN concentrations of both runoff forms increased with increasing rainfall intensity, with the TN concentration in interflow exceeding that in surface flow in each case.

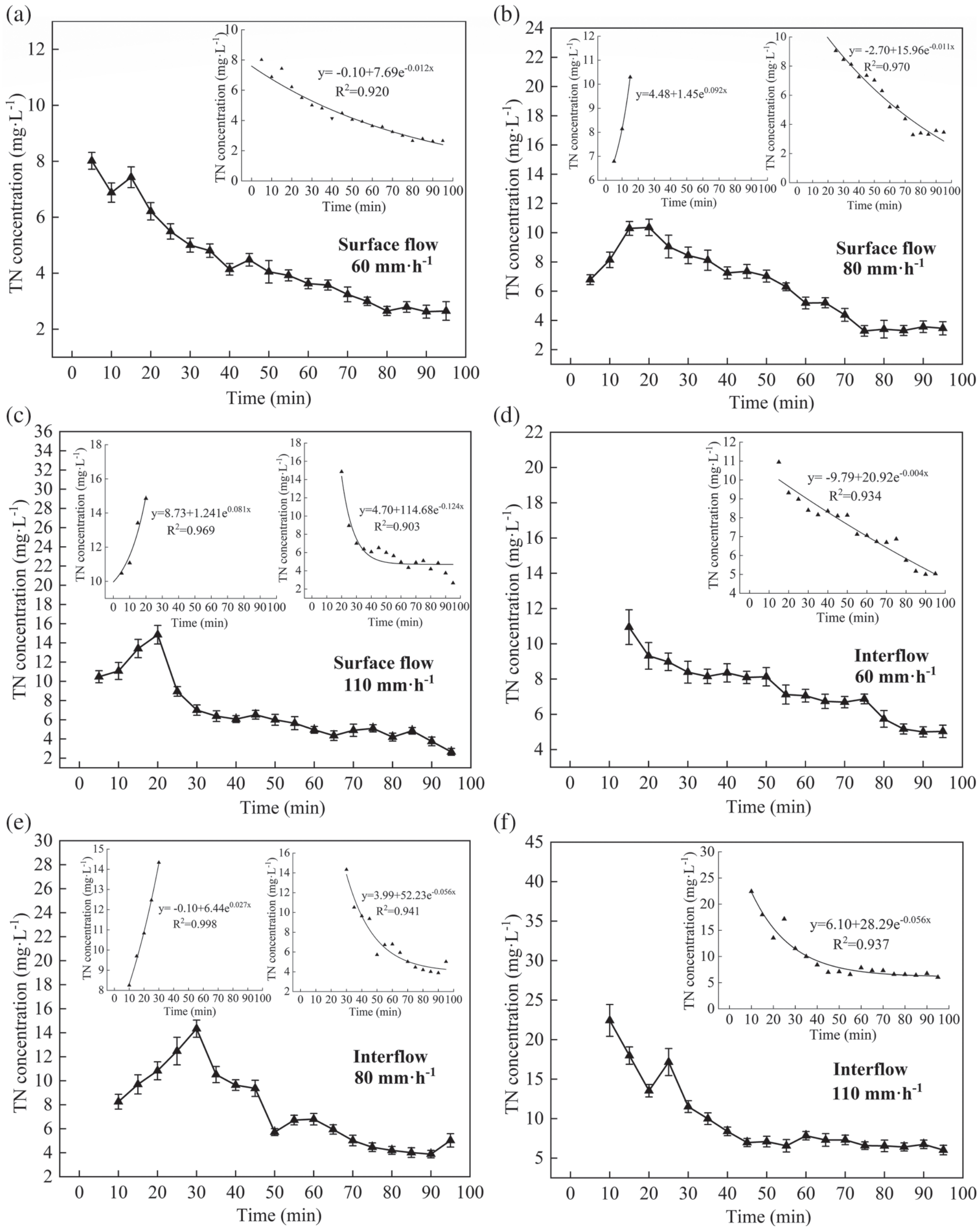
At a rainfall intensity of 60 mm·h^{-1}, the TN concentrations in surface flow and interflow gradually decreased with increasing rainfall duration from initial values of 8.02 and 10.94 mg·L^{-1}, respectively (Figs. 3*a*, 3*d*). A somewhat different pattern emerged at a rainfall intensity of 80 mm·h^{-1}; the TN concentration in surface flow tended to increase in the first 20 min to a peak value of 10.36 mg·L^{-1} and then decreased gradually until it stabilized at 75 min. Meanwhile, the TN concentration in interflow increased exponentially in the first 30 min to a peak value of 14.34 mg·L^{-1} and then decreased in a fluctuating manner (Figs. 3*b*, 3*e*). Total N concentration trends in surface flow were similar at rainfall intensity of 110 and 80 mm·h^{-1}. A maximum value of 14.85 mg·L^{-1} was reached within 20 min, followed by a rapid decrease to 7.01 mg·L^{-1} over the next 10 min; subsequently, the TN concentration tended to remain stable. Meanwhile, the maximum TN concentration in interflow was 22.43 mg·L^{-1} during the initial stage, decreasing rapidly in the first 20 min, and stabilized after 45 min (Fig. 3*c*, 3*f*).

In addition, the fitted curves in Figs. 3*a*–3*f* show that the exponential function fits the TN concentration trend well, with $R^2 \geq 0.90$. This fitting framework can provide a theoretical basis for nutrient loss control and design for gray fluvo-aquic soils.

Effect of rainfall intensity on nitrate nitrogen and ammonium nitrogen loss

The variations of NO_3^--N and NH_4^+-N under different rainfall intensities are shown in Figs. 4*a*, 4*b*. The mean concentration of NO_3^--N in surface flow was lower at higher rainfall intensities, and rainfall intensities of 60, 80, and 110 mm·h^{-1} produced NO_3^--N concentrations of 2.01, 1.60, and 1.32 mg·L^{-1}, respectively (Fig. 4*a*). The trend in NO_3^--N mean concentration in interflow was opposite that in surface flow; rainfall intensities of 60 and 110 mm·h^{-1} produced NO_3^--N concentrations of 3.52 and 5.25 mg·L^{-1}, respectively (Fig. 4*b*). In addition, the mean concentration of NO_3^--N in interflow was higher than that in surface flow.

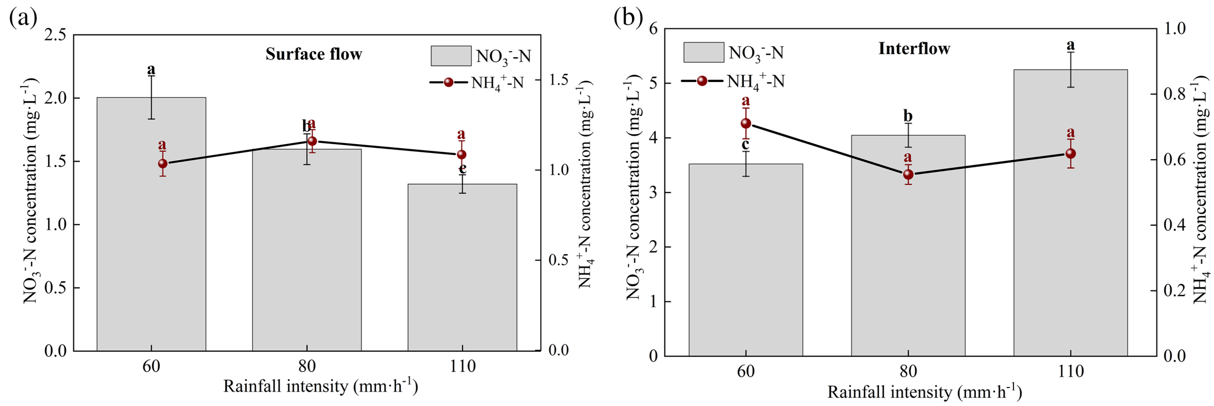
Fig. 3. Total nitrogen concentration trends under various rainfall intensities: (*a*) surface flow at 60 mm·h^{-1}, (*b*) surface flow at 80 mm·h^{-1}, (*c*) surface flow at 110 mm·h^{-1}, (*d*) interflow at 60 mm·h^{-1}, (*e*) interflow at 80 mm·h^{-1}, (*f*) interflow at 110 mm·h^{-1}. Data points = mean of measurements. Error bars = standard error ($n = 3$).



For NH_4^+-N, the mean concentrations in surface flow and interflow under various rainfall intensities showed opposite fluctuations, and the variation patterns were not as significant as for NO_3^--N. Rainfall intensities of 60, 80, and 110 mm·h^{-1} produced mean NH_4^+-N concentrations in the surface flow of 1.04, 1.16, and 1.09 mg·L^{-1}, respectively (Fig. 4*a*). These three rainfall intensities produced mean NH_4^+-N concentrations in interflow of 0.71, 0.55, and 0.62 mg·L^{-1}, respectively (Fig. 4*b*). In each case above, the concentration of NO_3^--N exceeded that of NH_4^+-N.

In addition, the two forms of N accounted for different proportions of TN loss. In surface flow, NO_3^--N accounted for 19.13%–45.02% of TN loss, averaging 29.74%, whereas NH_4^+-N accounted for 15.72%–23.26% of TN loss, averaging 19.07%. In interflow, NO_3^--N accounted for 47.62%–53.56% of TN loss, averaging 51.47%, whereas NH_4^+-N accounted for 6.32%–9.61% of TN loss, averaging 7.74%. Thus, NO_3^--N was the main form of TN loss, and the disparity between NO_3^--N and NH_4^+-N was more significant in interflow than in surface flow.

Fig. 4. Nitrate nitrogen and ammonium nitrogen mean concentration trends in (*a*) surface flow and (*b*) interflow under various rainfall intensities. Different letters represent significant differences under different rainfall intensities at $p < 0.05$. Values are the mean. Error bars = standard error ($n = 3$). [Colour online.]



Nitrogen loss load and correlation analysis of surface runoff and interflow

To further understand the effect of rainfall intensity on N loss and to lay a theoretical foundation for effective control of agricultural non-point-source pollution, the losses of different forms of N under the three rainfall intensities were compared and analyzed. As can be observed from Figs. 5*a*–5*d*, surface flow accounted for a large percentage of total runoff under each rainfall intensity, at a range of 61%–69%; interflow accounted for only approximately half as much (Fig. 5*a*). The percentages of TN and NH_4^+-N losses in the total surface flow load were 51%–60% and 71%–79%, respectively, which increased with increasing rainfall intensity (Figs. 5*b*, 5*d*). Meanwhile, NH_4^+-N loss in interflow accounted for only 21%–29% of the total load (Fig. 5*d*). The percentage of NO_3^--N loss in surface flow ranged from 35% to 47%, which decreased with increasing rainfall intensity, whereas the trend in interflow was the opposite and ranged from 53% to 65% (Fig. 5*c*).

A correlation analysis was conducted to further study the coupling between rainfall intensity, runoff yield, and TN, NH_4^+-N, and NO_3^--N concentration losses in surface flow and interflow. Figures 6*a* and 6*b* show that the runoff yields of surface flow and interflow were significantly positively correlated with rainfall intensity. Figure 6 also shows that surface flow and interflow TN concentration losses were each significantly positively correlated with both NO_3^--N and NH_4^+-N concentration losses ($p < 0.05$) but not significantly correlated with rainfall intensity. Surface flow NO_3^--N concentration loss was significantly negatively correlated with rainfall intensity ($p < 0.05$), whereas interflow NO_3^--N concentration loss was significantly positively correlated with rainfall intensity ($p < 0.05$). The correlation between NH_4^+-N concentration loss and rainfall intensity was weak for both runoff forms. In addition, the concentration losses of both species in surface flow were significantly negatively correlated with runoff yield ($p < 0.05$), whereas in interflow, both were positively correlated with runoff yield to some extent.

Discussion

Runoff loss characteristics under various rainfall intensities

The pattern of higher surface flow yield with increasing rainfall intensity may be due to the stronger erosion of surface soil under high rainfall intensity, resulting in the generation of small, narrow gullies on the slope surface. In this situation, the rainwater cannot infiltrate the slope to produce a high infiltration yield, so the surface runoff yield increases accordingly (Ma et al. 2021). The generation of interflow occurred earlier when the rainfall intensity was 80 and 110 $mm{\cdot}h^{-1}$ than when the rainfall intensity was 60 $mm{\cdot}h^{-1}$; this likely occurs because the rainfall runoff is mainly accommodated by soil infiltration in the early stages of a rainfall event. After a certain period of rainfall, the soil is saturated, allowing interflow production to begin; and the rate of rainfall infiltration tends to be stable during this early stage. Therefore, interflow yield does not change much throughout the rainfall event, although with increasing rainfall intensity, the soil may become saturated more quickly, resulting in earlier interflow; a pattern consistent with Zhou et al. (2012). However, when the rainfall intensity is higher, the diameters and limiting velocities of raindrops may be large, and their impact force on the slope soil is stronger at higher rainfall intensities. Thus, the deposition of sediment particles may block the surface pore space at higher rainfall intensities and form a soil crust. This phenomenon may increase the infiltration resistance (Lu et al. 2016), delaying the onset of interflow, which may be the reason why the interflow generation in the 110 $mm{\cdot}h^{-1}$ experiment did not occur earlier than in the 80 $mm{\cdot}h^{-1}$ experiment.

Fig. 5. Percentages of runoff and nitrogen loss load under various rainfall intensities: (*a*) runoff, (*b*) total nitrogen, (*c*) nitrate nitrogen, (*d*) ammonium nitrogen. [Colour online.]

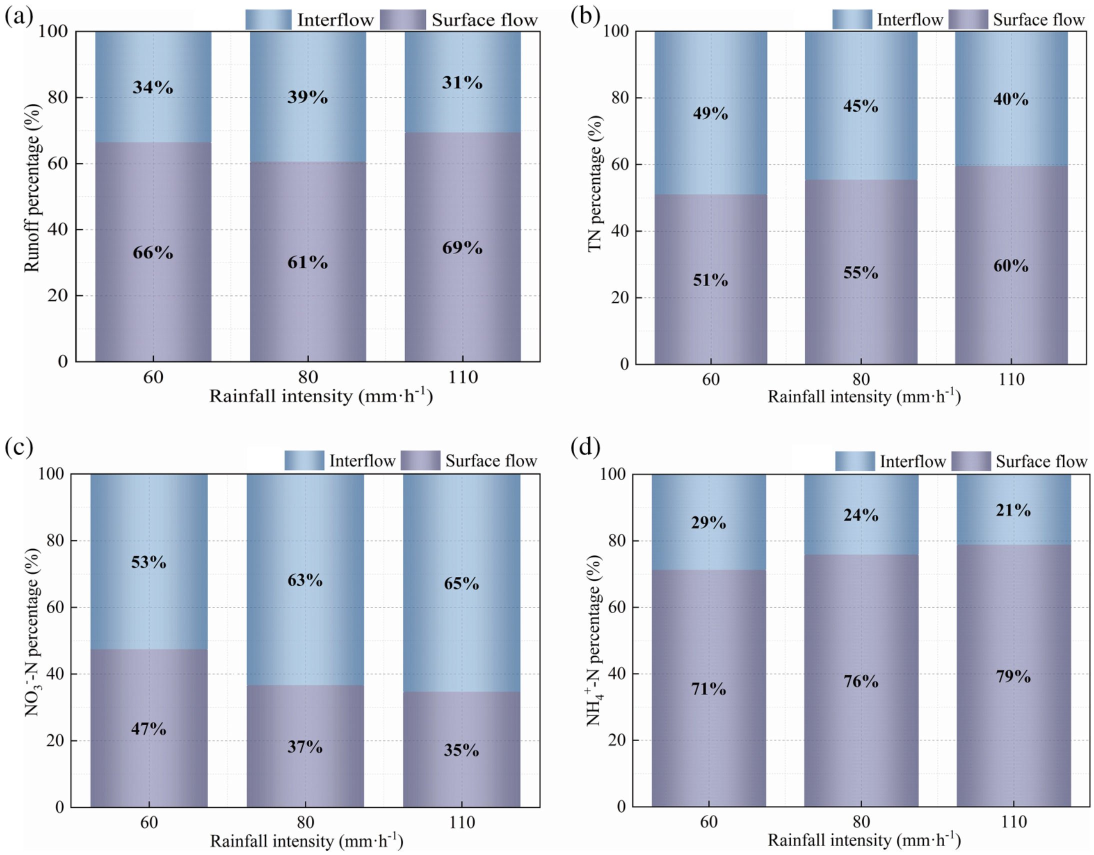
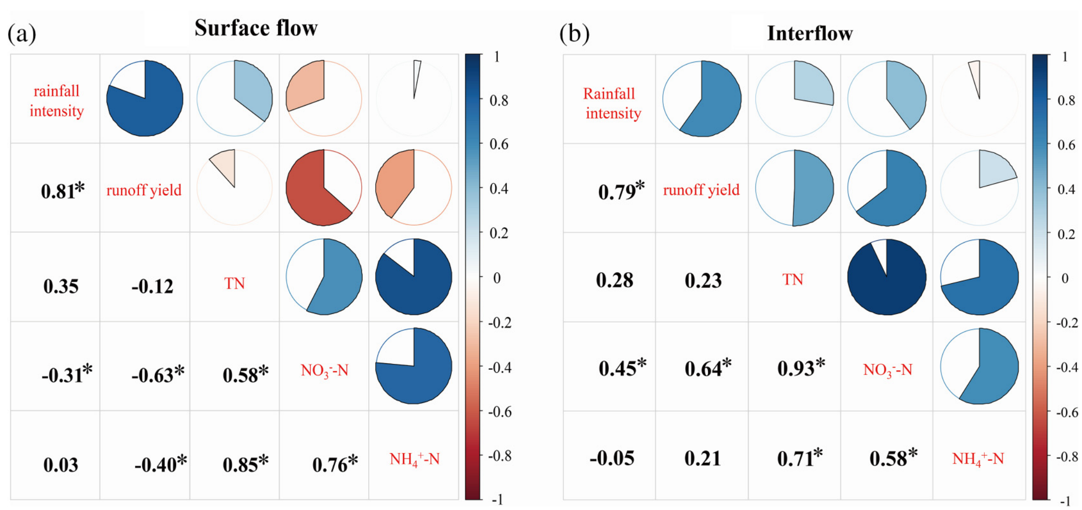


Fig. 6. Heat map of correlation coefficients for correlations between (*a*) surface flow, (*b*) interflow and each nitrogen species. An asterisk (*) indicates the correlation is significant at a level of 0.05 (two-tailed). [Colour online.]



Characteristics of total nitrogen loss under various rainfall intensities

Rainfall is the source driver of non-point-source pollution formation, and the resulting runoff is the solvent and main carrier of N and P export, whereas soil N is mainly lost in two forms: surface flow and interflow (Ao et al. 2016). In general, TN concentration is positively correlated with rainfall intensity, possibly due to the presence and interaction of various forms of N in the soil (Chen et al. 2017). The continuous rainfall runoff and the formation of soil seepage allowed a large quantity of N to enter the soil layer along with the infiltrated water. This phenomenon resulted in higher TN concentrations in interflow compared with the surface flow. Notably, the TN concentration losses under various rainfall intensities are higher than the threshold value of water body eutrophication (0.2 $mg \cdot L^{-1}$), indicating that the high N content of flowing water formed by the convergence of surface flow and interflow can pose a serious threat to the quality of surrounding natural water bodies.

Overall, TN concentrations were relatively high in each rainfall event's initial runoff and gradually stabilized after a certain period. For surface flow, this pattern occurred due to the particular looseness of the soil surface layer during the early stage of surface flow because of long-term fertilization and tillage. The soil surface layer contains a higher N nutrient load, so runoff under the effect of raindrops and runoff erosion causes preferential loss of fine soil particles with high nutrient concentration and some easily dissolved nutrients. Thus, nutrient loss is most dramatic in the initial stage. For interflow, the nutrient concentration in the surface soil gradually decreased as rainfall time increased, and N exchange between runoff and soil was gradually stabilized. Thus, runoff had a dilutive effect on nutrient concentration, so TN concentration loss in interflow tended to gradually decrease and then stabilize (Chen et al. 2013). Therefore, the implementation of relevant interventions in the early stage of runoff generation can greatly reduce the level of N migration in the soil layer. In particular, the effective control of initial runoff can be conducive to the control of non-point-source pollution. In addition, the increase in TN concentration observed in the early stages occurred due to the attachment of TN to the surface of soil particles at the early stages of runoff. Due to this attachment, the runoff N yield increases as the rainfall continues, and the interaction with the soil gradually becomes adequate, resulting in increased TN concentration losses. As the rainfall continues, the TN in the soil lessens, and the TN concentration in the runoff shows a downward trend. Finally, the TN concentration stabilizes once the runoff volume gradually stabilizes (Yu et al. 2021).

Characteristics of nitrate nitrogen and ammonium nitrogen losses under various rainfall intensities

The concentration of NO_3^--N in surface flow was negatively correlated with rainfall intensity, whereas NO_3^--N concentration in interflow was positively correlated with rainfall intensity. These patterns are logical outcomes of the processes described above; with increasing rainfall intensity, the surface flow yield increases, providing the N on the soil surface insufficient time to dissolve. The dissolution rate is lower than the surface flow yield growth rate, and NO_3^--N dissolution is limited, so the NO_3^--N concentration in surface flow decreases with increasing rainfall intensity. Meanwhile, higher rainfall intensities cause stronger soil erosion, allowing erosion effects to outpace the dilution effect of interflow. For these reasons, the NO_3^--N concentration in interflow increases with increasing rainfall intensity (Li et al. 2019).

The mean concentration of NH_4^+-N in the surface flow was higher than that in the interflow due to ammonification and other reactions converting urea to NH_4^+-N in the fertilizer applied to the surface layer of the soil. In addition, as NH_4^+-N is positively charged and soil colloids are negatively charged, so the NH_4^+-N tends to bind to the soil particles, and soil particles are probably more likely to become detached in the surface flow and not in the interflow, which is another reason why the NH_4^+-N was higher in the surface flow rather than interflow. The reason why NH_4^+-N concentrations in the runoff are lower than NO_3^--N concentrations may be due to the higher volatility of NH_4^+-N and the fact that NO_3^--N tends to be higher than NH_4^+-N in fertilized agricultural soils because the nitrification rates tend to be very high in these soils (Wang et al. 2019).

Nitrogen loss coupling relation between surface flow and interflow

The surface flow and interflow proportions of N loss load were different to some extent across the range of rainfall intensities. The main loss path of NO_3^--N was interflow. The main loss path of NH_4^+-N was surface flow, possibly due to the fertilizer applied to the soil. As the applied urea was converted to NH_4^+-N by ammonification in the soil surface layer, a higher NH_4^+-N concentration was found in surface flow, and the surface flow yield exceeded interflow yield; hence, the NH_4^+-N load loss in surface flow was much higher than that in interflow. The TN loss in surface flow was greater than that in interflow; thus, the surface flow was the main loss path of soil N loss for the farmland. Although TN concentration was higher in interflow than in surface flow, surface flow yield was much higher than interflow yield, leading to surface flow TN loss loads exceeding those of interflow. Therefore, improving soil water infiltration and reducing surface flow production are beneficial in reducing N loss in the studied area.

Overall, the effect of rainfall intensity on surface flow yield was stronger than that on interflow yield. The concentrations of each N species in surface flow were negatively correlated to some extent with yield, whereas the same correlations were positive in interflow. These results were consistent with those of Wu et al. (2018). These findings show that the dilution effect of surface flow on the concentration of each N species in the soil was stronger than that on interflow, and the runoff yield was an important factor in controlling N loss.

Conclusion

In simulated rainfall tests, the runoff yield and TN concentration increased with increasing rainfall intensity. Surface flow exceeded interflow with respect to runoff yield, whereas the mean interflow TN concentration exceeded that of surface flow. Total N concentration losses under various rainfall intensities were higher than the threshold value for water body eutrophication. Total N concentration in runoff was higher at the initial stage; therefore, effective control of initial runoff is beneficial for controlling non-point-source pollution. In addition, the mean NO_3^--N concentration in surface flow was lower at higher rainfall intensities, whereas the opposite was true for interflow. The mean NO_3^--N concentration in interflow exceeded that in surface flow, whereas the opposite pattern prevailed for NH_4^+-N. The results show that the main NO_3^--N loss path was interflow, the main loss path of NH_4^+-N was surface flow, and the main form of TN loss was NO_3^--N. The surface flow was the main path of soil N loss in the farmland, and runoff yield was an important factor for controlling N loss. Given these findings, N loss in gray fluvo-aquic soil areas can be mitigated by increasing vegetation cover, adopting cross-slope monopoly crops, and taking other measures to enhance soil water retention capacity and reduce surface flow yield.

Competing Interests

The authors declare there are no competing interests.

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References

Ao, C., Yang, P.L., Ren, S.M., Xing, W.M., Li, X., and Feng, X.W. 2016. Efficacy of granular polyacrylamide on runoff, erosion and nitrogen loss at loess slope under rainfall simulation. Environ. Earth Sci. **75**(6): 1–10. doi:10.1007/s12665-015-5110-3.

Bouraima, A.K., He, B.H., and Tian, T.Q. 2016. Runoff, nitrogen (N) and phosphorus (P) losses from purple slope cropland soil under rating fertilization in Three Gorges Region. Environ. Sci. Pollut. Res. Int. **23**(5): 4541–4550. doi:10.1007/s11356-015-5488-1. PMID:26517994.

Che, M.X., Gong, Y.B., Muhammad, N.K., Liu, L., Lv, C., and Kuang, K.L. 2016. Impacts of rainfall intensity,slope gradient on overland flow of purple soil under simulated rainfall. Bull. Soil Water Conserv. **36**(4): 164–168.

Chen, G., Elliott, J.A., Lobb, D.A., Flaten, D.N., Braul, L., and Wilson, H.F. 2017. Changes in runoff chemistry and soil fertility after multiple years of cattle winter bale feeding on annual cropland on the Canadian prairies. Agric. Ecosyst. Environ. **240**: 1–13. doi:10.1016/j.agee.2017.02.003.

Chen, L., Liu, D.F., Song, L.X., Cui, Y.J., and Zhang, G. 2013. Characteristics of nutrient loss by runoff in sloping arable land of yellow-brown under different rainfall intensities. Environ. Sci. **34**(6): 2151–2158.

Chen, Z.W., Ying, S.S., Liu, Y.X., Dong, Y.Y., and Jang, P.K. 2021. Effects of different fertilizer types on nitrogen loss in paddy field. J. Soil Water Conserv. **35**(01): 36–43.

Deng, L.Z., Fei, K., Sun, T.Y., Zhang, L.P., Fan, X.J., and Ni, L. 2019. Characteristics of runoff processes and nitrogen loss via surface flow and interflow from weathered granite slopes of Southeast China. J. Mount. Sci. **16**(5): 1048–1064. doi:10.1007/s11629-018-5253-2.

Gao, R.X., Dai, Q.H., Gan, Y.X., Peng, X.D., and Yan, Y.J. 2019a. The production processes and characteristics of nitrogen pollution in bare sloping farmland in a karst region. Environ. Sci. Pollut. Res. Int. **26**(26): 26900–26911. doi:10.1007/s11356-019-05838-z.

Gao, R.X., Dai, Q.H., Gan, Y.X., Peng, X.D., and Yan, Y.J. 2019b. Characteristics of nutrient loss from sloping farmland in Karst region as a function of rainfall intensity. Acta Pedol. Sinica. **56**(5): 1072–1084.

García-Díaz, A., Bienes, R., Sastre, B., Novara, A., Gristina, L., and Cerdà, A. 2017. Nitrogen losses in vineyards under different types of soil groundcover. A field runoff simulator approach in central Spain. Agric. Ecosyst. Environ. **236**: 256–267. doi:10.1016/j.agee.2016.12.013.

Guo, Z.L., Ma, M.J., Cai, C.F., and Wu, Y.W. 2018. Combined effects of simulated rainfall and overland flow on sediment and solute transport in hillslope erosion. J. Soils Sediments **18**(3): 1120–1132. doi:10.1007/s11368-017-1868-0.

Jiang, L.N., Hu, N.Y., Huang, P.X., Li, J.N., Yang, N.N., Yue, Y., and Li, C.X. 2017. Effect of combination of maize straw and N application on N balance and grain yield of wheat. J Triticeae Crops. **37**(08): 1087–1097.

Johannes, D., Arvo, I., Arvydas, P., Katarina, K., Inga, G., Gitte, B.M., et al. 2014. Hydrological pathways and nitrogen runoff in agricultural dominated catchments in Nordic and Baltic countries. Agric. Ecosyst. Environ. **195**: 211–219. doi:10.1016/j.agee.2014.06.007.

Kiani, F., Behtarinejad, B., Najafinejad, A., and Kaboli, R. 2018. Simulation of nitrogen and phosphorus losses in loess landforms of Northern Iran. Eurasian soil Sci. **51**(2): 176–182. doi:10.1134/S1064229318020035.

Li, QX., Ding, WF., and Xie, MX. 2019. Dynamic characteristics of nitrogen concentration in interflow of purple soil slope under simulating rainfall condition. Soil and Water Conservation in China. 9: 51–55.

Liu, Q., Li, ZB., Li, P., and Huang, W.J. 2017. Characteristics of ammonium nitrogen (NH_4^+-N) loss from slope lands with different vegetation cover/patterns under simulated rainfall. Res. Soil Water Conserv. **24**(1): 75–78.

Lu, J., Zheng, F.L., Li, G.F., Bian, F., and An, J. 2016. The effects of raindrop impact and runoff detachment on hillslope soil erosion and soil aggregate loss in the Mollisol region of Northeast China. Soil Tillage Res. **161**: 79–85. doi:10.1016/j.still.2016.04.002.

Lu, X., and Wang, C.Z. 1986. Soil of the Fuyang area. Fuyang Printing General Factory: Fuyang, China.

Ma, B.G., Guan, R.H., Liu, L., Huang, Z.X., Qi, S.W., Xi, Z.F., et al. 2021. Nitrogen Loss in Vegetable Field under the Simulated Rainfall Experiments in Hebei, China. Water. **13**(4): 552. doi:10.3390/w13040552.

Ren, X.W., Li, K.M., Liu, A.P., and Jiang, G.Q. 2013. Characteristics of nitrate nitrogen loss on red soil slope under simulated rainfall conditions. China Environ. Sci. **33** (Suppl): 119–124.

Song, X.W., Gao, Y., Green, S.M., Dungait, J.A.J., Peng, T., Quine, T.A.Q., et al. 2017. Nitrogen loss from karst area in China in recent 50 years: An in-situ simulated rainfall experiment's assessment. Ecol Evol **7**(23): 10131–10142. doi:10.1002/ece3.3502. PMID:29238543.

Standardization Administration of the People's Republic of China. 2007. Water quality-Determination of nitrate-nitrogen-Ultraviolet spectrophotometry HJ/T 346-2007. [Online]. Available from http://down.foodmate.net/standard/sort/9/11311.html. [2021 July 30].

Standardization Administration of the People's Republic of China. 2009. Water quality-Determination of ammonia nitrogen-Nessler's reagent spectrophotometry HJ 535–2009. [Online]. Available from http://down.foodmate.net/standard/sort/9/21844.html. [2021 July 30]

Standardization Administration of the People's Republic of China. 2012. Water quality-Determination of total nirtrogen-Alkline potassium persulfate digestion UV spectrophotometric method HJ 636–2012. http://down.foodmate.net/standard/sort/9/29921.html. [accessed 2021 Jul 30].

Wang, S., Feng, X.J., Wang, Y.D., Zheng, Z.C., Li, T.X., He, S.Q., et al. 2019. Characteristics of nitrogen loss in sloping farmland with purple soil in southwestern China during maize (Zea mays L.) growth stages. Catena. **182**: 104169. doi:10.1016/j.catena.2019.104169.

Wang, Y.Y., Li, H.Z., and Xu, Z.X. 2016. Rainfall-induced nutrient losses from manure-fertilized farmland in an alluvial plain. Environ. Monit. Assess. **188**(1): 1–11.

Wu, L., Qiao, S.S., Peng, M.L., and Ma, X.Y. 2018. Coupling loss characteristics of runoff-sediment-adsorbed and dissolved nitrogen and phosphorus on bare loess slope. Environ. Sci. Pollut. Res. Int. **25**(14): 14018–14031. doi:10.1007/s11356-018-1619-9. PMID:29516427.

Xing, W.M., Yang, P.L., Ren, S.M., Ao, C., Li, X., and Gao, W.H. 2016. Slope length effects on processes of total nitrogen loss under simulated rainfall. Catena. **139**: 73–81. doi:10.1016/j.catena.2015.12.008.

Yu, Y.M., Xu, J.Z., Zhang, P.C., Meng, Y., and Xiong, Y.J. 2021. Controlled Irrigation and Drainage Reduce Rainfall Runoff and Nitrogen Loss in Paddy Fields. Int J Environ. Res. Public. Health. **18**(7): 3348. doi:10.3390/ijerph18073348. PMID:33805028.

Zhang, S.H., Hou, X.N., Wu, C.S., and Zhang, C. 2020. Impacts of climate and planting structure changes on watershed runoff and nitrogen and phosphorus loss. Sci. Total Environ. **706**: 134489. doi:10.1016/j.scitotenv.2019.134489.

Zhang, S.J., Zhang, G., Wang, D.J., Liu, Q., and Xu, M. 2021. Investigation into runoff nitrogen loss variations due to different crop residue retention modes and nitrogen fertilizer rates in rice-wheat cropping systems. Agric. Water Manage. **247**: 106729. doi:10.1016/j.agwat.2020.106729.

Zheng, H.J., Liu, Z., Zuo, J.C., Wang, L.Y., and Nie, X.F. 2017. Characteristics of nitrogen loss through surface-subsurface flow on red soil slopes of southeast China. Eurasian Soil Sci. **50**(12): 1506–1514. doi:10.1134/S1064229317130063.

Zhou, L.F., Hao, L.P., and Sun, Z.H. 2011. Characteristics of nitrogen and phosphorus losses through surface flow and interflow on different types of land in Liaoning Hunhe Basin. Ecol. Environ. Sci. **20**(4): 737–742.

Zhou, L.F., Hao, L.P., and Zhang, Y.L. 2012. Characteristics of nitrogen loss through surface flow and interflow in different fertilization of farmland in Liaoning Hunhe Basin. J. Soil Water Conserv. **26**(04): 69–72.