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Different Impacts of Rainfall Intensity on Surface Runoff and Sediment Loss between Huang-mian Soil and Brown Soil

ABSTRACT

Huang-mian soil and brown soil are typical soils in Loess Plateau and Yimeng mountainous area, respectively. The differences of surface runoff and sediment loss between the two soils are important to special environmental protection management in two areas. In order to study the impacts of rainfall intensity on surface runoff and sediment from Huang-mian soil and brown soil, four simulated rainfalls were applied on fields with different soils on a laboratory scale. Huang-mian soil under 60×10^{-3} m hr^{-1} had the shortest runoff occurrence time, while brown soil under 30×10^{-3} m hr^{-1} had the longest time; Huang-mian soil under 30×10^{-3} m hr^{-1} had the most sediments; Huang-mian soil has less loss of phosphorus (P) in concentration than brown soil, which explains why Loess Plateau has more soil and water loss but less eutrophication than the Yimeng mountainous area. Under the same rainfall intensity, Huang-mian soil had more runoff volume than brown soil; however, higher rainfall intensity decreased the difference. Increasing rainfall intensity had more impact on sediment content in brown soil than Huang-mian soil. It also had more impact on nitrate nitrogen (NO_3^--N) content in brown soil than ammonia nitrogen (NH_4^+-N) loss content in Huang-mian soil. Finally, suggestions were provided to reduce the harm of N and P loss in Huang-mian soil and brown soil regions.

Key words: *N and P loss, runoff, sediment, rainfall intensity, Huang-mian soil, brown soil*

Xiyuan Wu[1,2*]
Xingxiu Yu[1]
Yujiao Gao[3]
Guirong Wang[4]

[1] Shandong Provincial Key Laboratory of Water and Soil Conservation and Environmental Protection, College of Resources and Environment, Linyi University, Linyi, 276000, P.R. China
[2] State Key Laboratory of Soil Erosion and Dryland Farming in the Loess Plateau, Institute of Water and Soil Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi, 712100, P.R. China
[3] School of Civil Engineering and Architecture, Linyi University
[4] Hangzhou Raw Seed Growing Farm, Hangzhou, P.R. China

*Corresponding author: wuxiyuan616@yahoo.com

INTRODUCTION

Huang-mian soil possesses an abundant loam and sand with unconsolidated soil, which makes it easy to be rushed and eroded heavily, especially on the steep sloping fields. More than 40% of the rainfall events during storm periods take away the sediments and nutrients in surface runoff from sloping farmlands every year. It is calculated that an average of 1cm depth soil has been eroded annually, leading to heavier soil degradation (*Shen 1998*). Brown soil has deeper layers with high organic matter content in surface soil. Generally, brown soil located at foothills and hilly areas which are farmlands have worse soil and water loss. The ones located at the high hills and mountain areas with fewer forests also have serious soil and water loss (*Shen 2009*).

Nitrogen (N) and phosphorus (P) loss from fertilizer can cause both the nutrient enrichment in surface water (i.e., eutrophication) and degradation in soil (i.e., soil erosion). Therefore, excessive utilization of fertilizer in fields causesincrease water and soil quality degradation, especially for eutrophication (*Falkowski et al. 2000; Conan et al. 2003; Ren et al. 2003*). There are many methods of adding N and P into water, such as leaching, surface runoff, and dry or wet atmospheric deposition. Next to leaching, N and P loss by surface runoff is responsible for the majority of eutrophication. Eutrophication has been identified as the main source of surface water pollution (*Sharpley et al. 1999*). In the past few years, numerous studies have been carried out focusing on the transfer processes of N, P from soil to surface runoff, and the forms of N, P loss in runoff (*Steinheimer et al. 1998; Heathwaite and Dils 2000*).

The impact of precision agriculture on N and P loss in water from Huang-mian soil and brown soil has been reported in several studies and review articles (*Spalding and Exner 1993; Elmi et al. 2002*). Different results were reported about various N forms in surface runoff. *Liu et al.* (*1991*) reported particulate-associated N occupied the major part of N loss in runoff water and sediment compared with dissolved N. *Liang et al*. (*2005*) reported that the major form of N lost in surface runoff water was the dissolved N, which included nitrate nitrogen (NO_3^--N) and ammonia nitrogen (NH_4^+-N). Nitrate N accounts for the larger percentage of dissolved N. Much knowledge about the influence of transport factors on runoff and erosion, and P movement in runoff has been attained (*Quinton et al. 2001; Hart et al. 2004*). Particulate phosphorus (PP) transport increases with increasing runoff and erosion, which is attributed to the stronger rainfall intensities (*Quinton et al. 2001*). There are two types of runoff formations: surface runoff and interflow, which have different characteristics. Surface runoff has 68.4 percentages in all while interflow has 31.6 (*Chen et al. 2013*).

There were also broad studies on the contributing factors to nutrient loss by surface runoff (*Zeng et al. 2008; Zhang et al. 2011; Napoli et al. 2017*). *Garcia Rodeja and Gil-Sotres* (*1997*) indicated that nutrition loss caused by runoff depends on different factors: topography, land use, soil properties, and weather conditions (particularly rainfall intensity and duration); *Kwong et al.* (*2002*) reported that the heavy rainfall increases both surface runoff and loss of particulate N with the simultaneous erosion of topsoil; Stronger intensity rainfall causes a larger percentage of PP in Total P in runoff water than weaker intensity rainfall (*Sporre-Money et al. 2004*). Rainfalls with higher intensity (46.8×10^{-3} m hr^{-1}) and a short period (about 1 hr) had a percentage of 40-70 in all of the rainfalls during June to August at Loess Plateau. This kind of rainfall is the major factor leading to soil and nutrient loss (*Zhu 1983*). As the rainfall intensity increased, soil and nutrient loss had increasing trends (*Fraser et al. 1985; Quinton et al. 2001; Sharpley 1985*). However, few studies were reported on the difference of runoff and sediment loss between Huang-mian soil and brown soil. The objectives of this study are to investigate the different characteristics of runoff, sediment, N and P loss between Huang-mian soil and brown soil; and the different impacts of rainfall intensity on runoff and sediment loss between Huang-mian soil and brown soil.

MATERIALS AND METHODS

Materials

The Huang-mian soil was taken from a test station of Chinese Academy of Sciences in Ansai County, Shanxi province. Ansai County is located at the Loess Plateau and is a classic hilly and gully region. The brown soil was taken from Wanggou town, which is located at the Yimeng mountainous area in Shandong province. The physical and chemical characteristics of the Huang-mian soil and brown soil were measured (**Table 1**).

There were two experimental troughs, A and B, with length, width, and height measuring 1.6, 1.6, and 0.4m, respectively. A dam-board was kept in a trough to divide it into two identical troughs. Both of the troughs, A and B, were designed at slopes of 12°, which is the typical slope in Yimeng mountainous area. Soils were placed in the troughs as the original soil density after they were sifted to 5 mm. The depth of the soil in the troughs was 20 cm and the soil surface was 2 cm higher than the collective hole of surface runoff on the troughs.

Simulated rainfall design

Simulated rainfall experiments were conducted at Linyi University. The simulated rainfalls were conducted by using the equipment designed and produced by Beijing Normal University. Six barrels surrounded each trough to calculate the coefficient of uniform (CU) of each rainfall. *Christiansen* (*1941*) first discussed CU to describe the distributing of uniform spout quantity. It can be calculated using the following equation:

$$CU = 100\times\left(1-\frac{\sum_{i=1}^{N}\left|x_i-\bar{x}\right|}{N\bar{x}}\right) \quad (1)$$

Where xi is the depth of rainfall in the barrel

Table 1. The original physical and chemical characteristics of brown soil and Huang-mian soil.

Soil Characteristics	NH_4^+-N (10^{-6} kg kg^{-1})	NO_3^--N (10^{-6} kg kg^{-1})	TN (10^{-6} kg kg^{-1})	TP (10^{-6} kg kg^{-1})	pH	Sand (%)	Silt (%)	Clay (%)
Brown soil	128.20	11.30	1.40	1.00	5.10	71.30	28.00	0.70
Huang-miansoil	5.20	28.36	0.88	0.86	8.20	24.10	66.80	9.10

Note: Soil classification is based on GB/T 17296-2009.

located at I, is the average depth of all barrels

$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$, and N is the number of barrels.

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

The annual precipitation in the Yimeng mountainous area is approximately $680\text{-}860\times10^{-3}$ m.

According to the highest frequency of the rainfall events in the area, two rainfall events were designed at rainfall intensities 30 and 60×10^{-3} m hr^{-1}, respectively, with two replicates. In each rainfall, the period from rainfall beginning to runoff occurrence was recorded as runoff occurrence time. Each rainfall lasted for approximately 30 min.

Sample collection and analysis

To measure the gravimetric soil moisture content, soil samples at three points in the troughs were collected before and after each rainfall event, respectively. Soil samples were placed in an oven at 105° C for 8 hrs after being weighed (this weight was recorded as A). Samples were weighed again after drying (recorded as B). The difference between the two weights (A and B) yielded the weight of the water (recorded as C). Gravimetric soil moisture content could be obtained by dividing C by B.

Surface runoff was collected via the holes and kept in 1×10^{-3} m^3 clean polyethylene bottles. In each rainfall event, 15 runoff samples were collected separately and in order per minute as soon as the runoff occurred. All the runoff was collected. Two or more bottles were used when the runoff was more than 1×10^{-3} m^3 during 1 min. Then, the runoff samples were measured immediately. The volumes of the runoff that contained the water and the sediment were measured after they were kept in the bottles for 4-5 hrs in the laboratory at 25°C for sedimentation.

After sedimentation, the surface water was collected in the first bottle each minute for chemical analysis. The concentrations of NH_4^+-N, NO_3^--N and dissolved P (DP) were measured in 24 hrs, respectively. NO_3^--N was measured according to the ultra-spectrophotometric method after the samples were filtered through 0.45×10^{-6} m filters. NH_4^+-N was measured by the method of salicylate-hypochlorous acid spectrophotometric after filtration. After being filtered, DP was obtained using molybdenum colorimetry after isobutanol extraction (*Shimadzu Corporation 2001*). Organic phosphorus (OP) is hardly soluble in water and its content is generally low, therefore, OP was neglected in the study.

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

Calculations

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

$$CS=C/V \quad (2)$$

Where CS is the sediment concentration (kg m^{-3}), C is the sediment content (kg), and V is the volume of the runoff (m^3).

Content of N and P in each sample was calculated by multiplying concentration with runoff volume, respectively. Total runoff volume was the sum of 15 runoff volumes in each sample in a rainfall event. Total content of N and P in a rainfall event was the sum of 15 contents in each sample, respectively. The average concentration of N and P were calculated by dividing the total content with the total runoff volume in each rainfall event. The runoff occurrence time, total runoff volume, total sediment content, average sediment concentration, total NO_3^--N content, NO_3^--N average concentration, total NH_4^+-N content, NH_4^+-N average concentration, total DP content and DP average concentration were also summarized (**Table 2**).

Statistical analysis

Statistical analysis was performed using the Data Processing System (DPS).

RESULTS AND DISCUSSION

Different runoff departures between brown soil and Huang-mian soil

The runoff volumes in each trial showed an increasing trend over the rainfall time (**Figure 1a**). All of the trends had a sharper increase at the very beginning of rainfall, and then, kept stable as time increased. Huang-mian soil under 60×10-3 m hr^{-1} had the most absolute

Table 7: Calculated values and determined DCC of Socio- economic indicators in Shemiran's districts.

Rainfall event	Gravimetric soil moisture 2 cm (%)	Gravimetric soil moisture 7 cm (%)	Runoff occurrence time (min)	Runoff volume (10^{-3} m^3)	Sediment content (10^{-3} kg)	Sediment concentration (kg m^{-3})	NH_4^+-N content (10^{-6} kg)	NH_4^+-N concentration (10^{-3} kg m^{-3})	NO_3^--N content (10^{-6} kg)	NO_3^--N concentration (10^{-3} kg m^{-3})	DP content (10^{-3} kg m^{-3})	DP average concentration (10^{-3} kg m^{-3})
B-30	4.95	8.41	6.57	8.07	45.25	5.60	5.48	0.68	22.96	2.84	5.80	0.72
H-30	18.50	4.32	2.75	13.47	667.81	49.60	7.31	0.54	38.96	2.89	7.02	0.52
B-60	10.77	7.47	3.92	16.18	255.05	15.76	8.26	0.51	52.92	3.27	9.40	0.58
H-60	13.03	12.78	2.00	23.54	417.66	17.74	16.17	0.69	71.70	3.05	9.97	0.42
B-60/B-30	2.17	0.89	-	2.00	5.64	2.81	1.51	0.75	2.30	1.15	1.62	0.81
H-60/H-30	1.72	0.58	-	1.75	0.63	0.36	2.21	1.27	1.84	1.05	1.42	0.81
H-30/B-30	3.74	0.51	-	1.67	14.76	8.85	1.33	0.80	1.70	1.02	1.21	0.73
H-60/B-60	1.21	1.71	-	1.45	1.64	1.13	1.96	1.35	1.35	0.93	1.06	0.73

Notes: B-30 and B-60 means brown soil with rainfall intensity 30 mm h^{-1} and 60 mm h^{-1}; H-30 and H-60 means Huang-mian soil with rainfall intensity 30 mm h^{-1} and 60 mm h^{-1}, respectively.

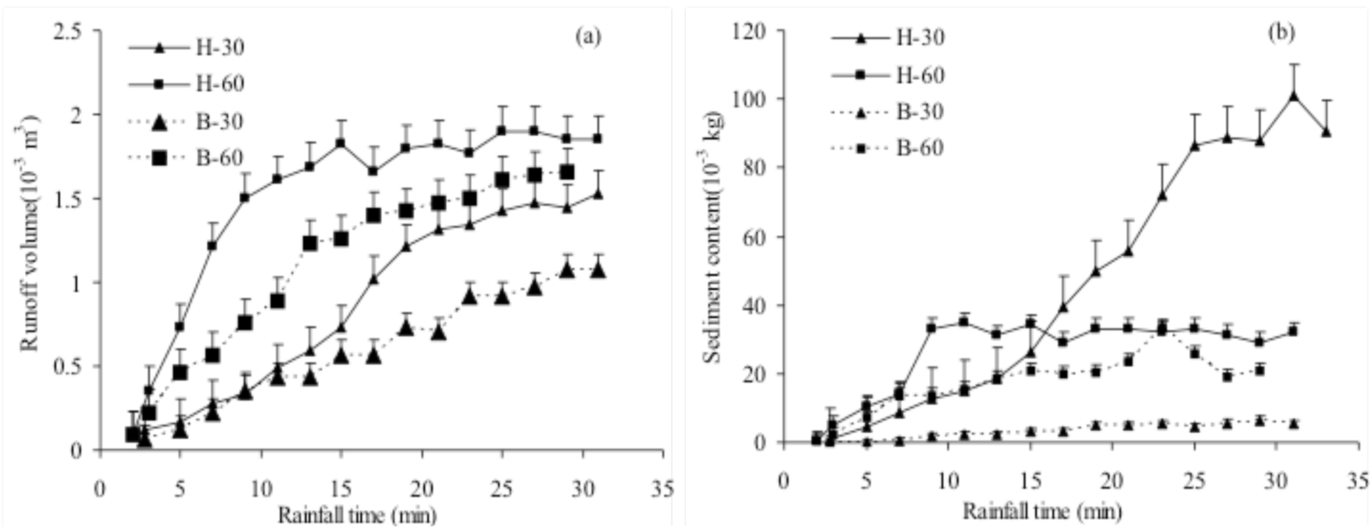

Figure 1. Evolutions of the runoff volume (a) and sediment concentration (b) with the increasing rainfall time in the rainfall events with two replicates.

number. That was because stronger rainfall intensity was advantageous to increase the precipitation and accelerate the runoff speed which leads to shorter time for rainfall infiltration. Brown soil under 30×10^{-3} m hr^{-1} had the least volume with the weak rainfall intensity; the mostimportant reason for this result should be the different particle size distribution of brown soil and Huang-mian soil (**Table 1**). The brown soil had more sand content than Huang-mian soil, which could lead to a faster infiltration with more macropores in it (**Table 1**).

The period from rainfall beginning to runoff occurrence is recorded as a runoff occurrence time, which can describe the departure of runoff. Generally, shorter runoff occurrence time meant more runoff volume and nutrient loss. According to the observation in the experiments, there were two runoff-forming situations: when infiltration speed was quicker than rainfall intensity, and when infiltration speed was slower than rainfall intensity. A long runoff occurrence time meant that rainwater easily infiltrated into the soil at the beginning of the rainfall. More infiltration would be produced and the soil moisture content would increase quickly if the runoff occurred with a longer occurrence time (**Table 2**). The Huang-mian soil under 60 mm hr^{-1} had the shortest ones, while brown soil under 30×10^{-3} m hr^{-1} had the longest time. It could be explained as higher percentages of clays in Huang-mian soil stopped the water to filter into soil.

The most significant result was Huang-mian soil under rainfall intensity 30×10^{-3} m hr^{-1} had the most sediment and the differences between this trial and other trials were obvious (**Figure 1b**). It was because of the physical characteristics of Huang-mian soil. Lower rainfall intensity is advantageous to rainfall infiltration but not heavy enough to produce the crust. Besides, the loose construction also played an important role to release clays into the water.

Characteristics of nitrogen and phosphorus loss in brown soil and Huang-mian soil

The evolutions of NH_4^+-N and NO_3^--N concentration and contents in surface runoff with increasing rainfall time (**Figures 2** and **3**).

The concentration of NO_3^--N has a sharp descending trend (**Figure 3**) while NH_4^+-N does not have obvious changes (**Figure 2**). Both have increasing contents with increasing rainfall time. Increasing runoff volumes play an important role on increasing contents. Another important reason is the processes of nitrification-denitrification and ammonia volatilization.

There are complicated translations among different N forms in surface runoff, mainly including these two processes. The process of nitrification-denitrification is very important to translation between NH_4^+-N and NO_3^--N, in which NH_4^+-N is oxidized into nitrite nitrogen (NO_2^--N) and then translates into NO_3^--N through nitrification. Nitrate nitrogen translates into nitrogen (N_2) through denitrification to release from the water environment eventually. The process of ammonia volatilization could be described as follows: NH_4^+-N→NH_4^+-N (liquid state) →NH_3 (liquid state) → NH_3 (gas state) → NH_3.

According to the above theory, the researchers found out that the runoff had a closer relationship with NO_3^--N concentration than NH_4^+-N. *Wu et al.* (*2012*) found in red soil region that the runoff modulus had a closer relationship with NO_3^--N than NH_4^+-N. It could be concluded that both Huang-mian soil and brown soil had similar results with red soil concerning the relationship between runoff and nitrogen forms.

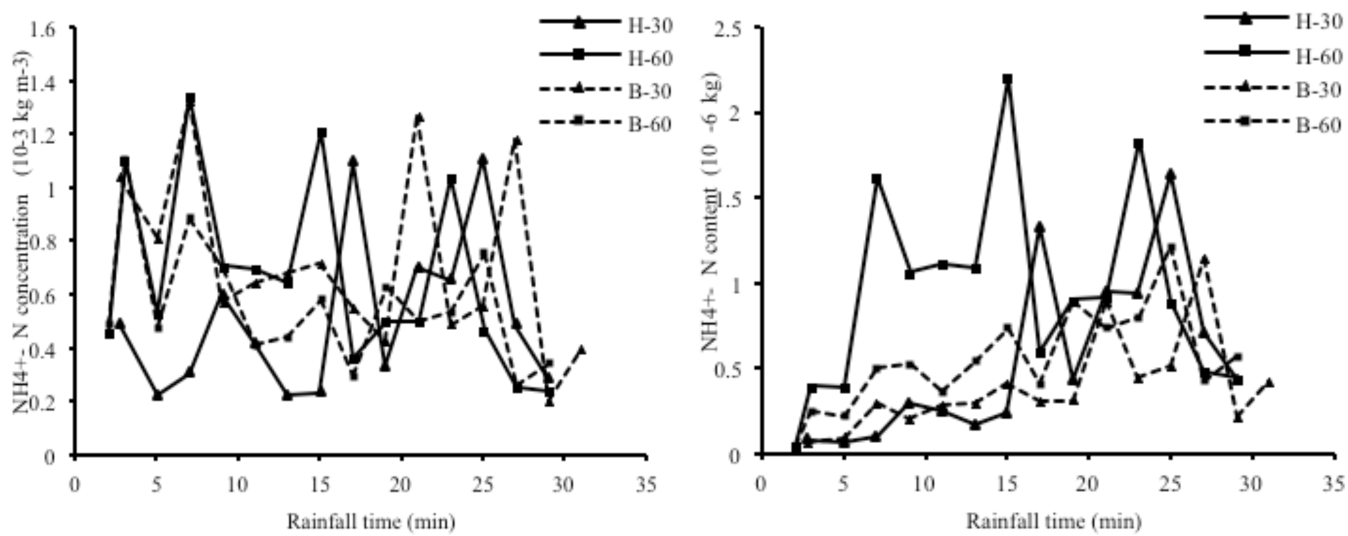

Figure 2. The trends of NH_4^+-N concentration and content with the increasing rainfall time under different rainfall intensities on brown soil and Huang-mian soil.

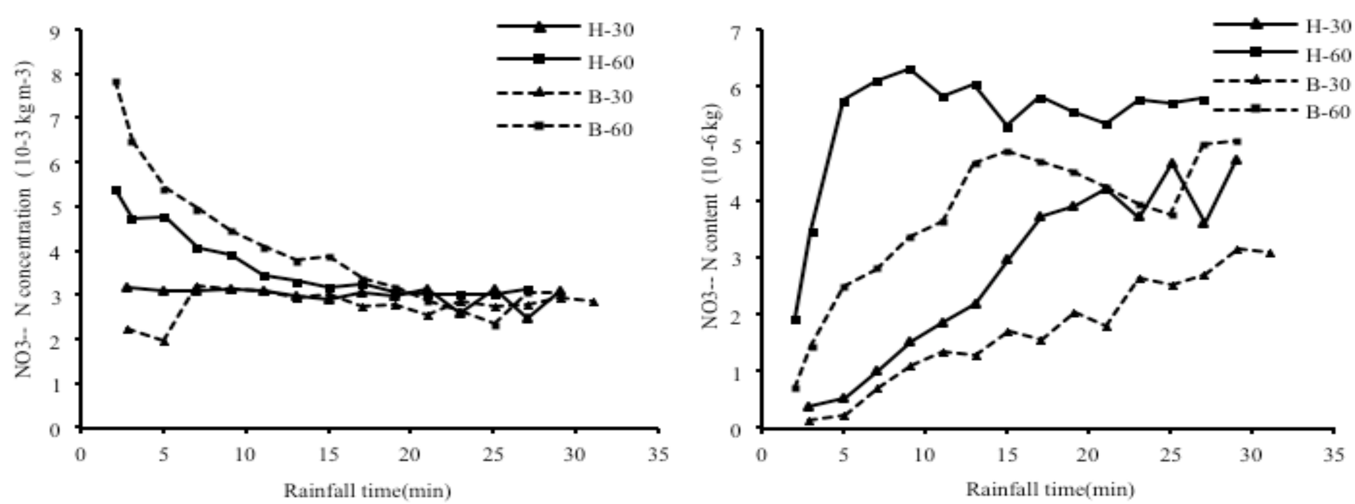

Figure 3. The trends of NO_3^--N concentration and content with the increasing rainfall time under different rainfall intensities on brown soil and Huang-mian soil.

The DP concentration in brown soil under two rainfall intensities both have higher values than Huang-mian soil, which means Huang-mian soil has less loss of P in concentration than brown soil (**Figure 4**). That could explain why Loess Plateau has huge soil and water loss but less eutrophication than the Yimeng mountainous area. The contents of DP had an increasing trend over rainfall time (**Figure 4**). Huang-mian soil and brown soil both have the higher values under 60 mm hr^{-1}, which means that the impacts of rainfall intensity are stronger than the impacts of soil types. Therefore, eutrophication control should be paid special attention at places with high intensity rainfall.

Impacts of rainfall intensity on surface runoff and sediment between brown soil and Huang-mian soil

Based on the previous research reports about how the factors affected runoff and sediment (*Slattery and Bryan 1994; Hidalgo et al. 1997; Raya et al. 2006; Wu et al. 2012*), the principles of rainfall intensity contributing to the runoff and sediments could be summarized as follows: a stronger rainfall intensity could bring more runoff volume and more sediment content, and increasing rainfall intensity strengthened the runoff and then kept to a stable level. Rainfall events with an easier runoff departure could deliver more N and P from soils but will not generate higher N and P concentration in water.

The average concentration of N and P loss can be used to evaluate the process of the runoff delivering N and P. The total contents and average concentration of each rainfall event were calculated (**Table 2**). The ratios between four trials were also given.

From the differences between gravimetric soil moisture content before and after each rainfall event, Huang-mian soil changed 3.74 times at the top 2×10^{-2} m more than brown soil under the same rainfall intensity of 30×10^{-3} m hr^{-1}; while at the 7th cm, it changed only 0.51 times than brown soil. It can be explained that Huang-mian soil has higher hygroscopicity than brown soil, but only at surface soil. Increased rainfall intensity will decrease the differences of hygroscopicity in surface Huang-mian soil and brown soil, as well as increase the differences of hygroscopicity at the deep layers. Brown soil under rainfall intensity 60×10^{-3} m hr^{-1} changed 2.17 times more than under 30×10^{-3} m hr^{-1} at surface layer, while less than 30×10^{-3} m hr^{-1} at the deep layers.

Higher rainfall intensity had more impact on runoff volume in brown soil than in Huang-mian soil. Under the same rainfall intensity, Huang-mian soil had more runoff volume than brown soil, but higher rainfall intensity will decrease the difference.

Sediment concentration in Huang-mian soil was 8.85 times more than in brown soil; Huang-mian soil had 0.255 kg sediment content under 60×10^{-3} m hr^{-1} and 0.045 kg sediment content under 30×10^{-3} m hr^{-1}, meanwhile, Huang-mian soil had 0.418 kg sediment content under 60×10^{-3} m hr^{-1} and 0.668 kg sediment content under 30 m hr^{-1}. It shows that increasing rainfall intensity had more impact on sediment content in brown soil than Huang-mian soil. It can be concluded that under higher rainfall intensity, more attention should be given to soil erosion in brown soil, and also, lower rainfall intensity will lead to more sediment loss in Huang-mian soil.

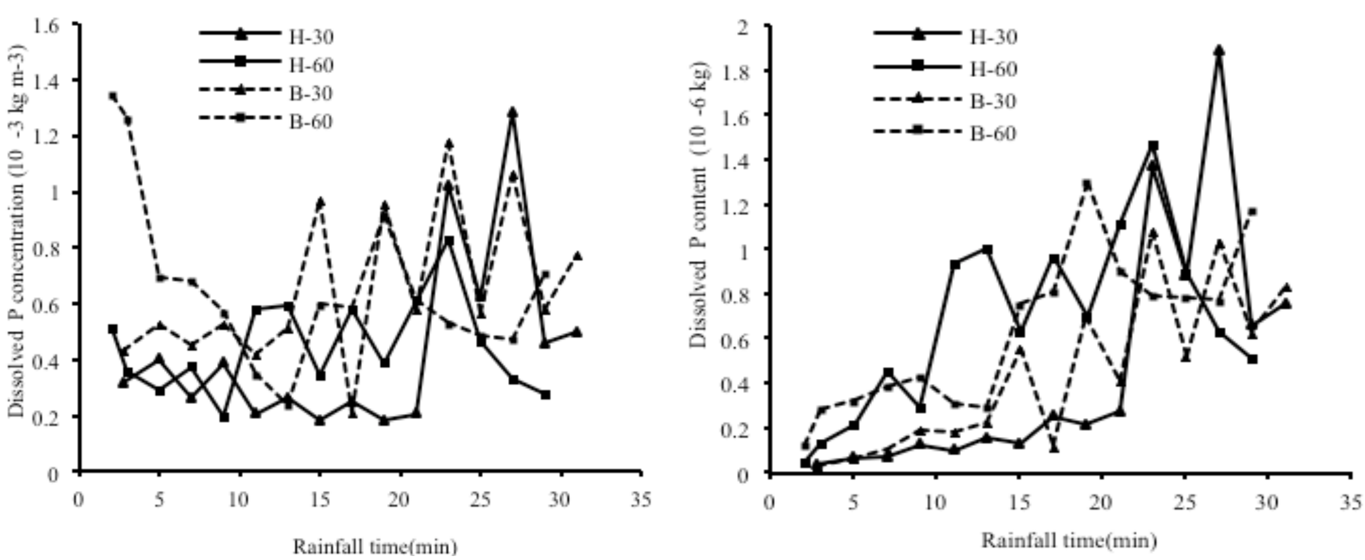

Figure 4. The trends of DP concentration and content with the increasing rainfall time under different rainfall intensities on brown soil and Huang-mian soil.

Increasing rainfall intensity had different impacts on nitrogen loss in two types of soils, especially for the different nitrogen forms. The total contents of nitrate N loss under 60×10^{-3} m hr^{-1} in brown soil was 2.3 times more than under 30×10^{-3} m hr^{-1}; the total contents of ammonia N loss under 60×10^{-3} m hr^{-1} in Huang-mian soil was 2.21 times more than under 30×10^{-3} m hr^{-1}. It shows that increasing rainfall intensity had more impact on nitrate N content in brown soil than ammonia N loss content in Huang-mian soil.

As DP was concerned, the difference in the content and concentration between brown soil and Huang-mian soil was less, as well as under higher and lower rainfall intensity.

Based on the above results and discussions, suggestions on reducing the harm of N and P loss in brown soil and Huang-mian soil regions are given as follows: at areas with heavier rainfalls, focus on the nitrate N loss as well as sediment content loss in brown soil and ammonia N loss in Huang-mian soil; at areas with weaker rainfalls, focus on the sediment content loss in Huang-mian soil.

CONCLUSIONS

Simulated rainfalls were designed for brown and Huang-mian soils to investigate the different characteristics of N, P loss, and impacts of rainfall intensity on runoff and sediment between the two types of soils.

Higher percentages of clays in Huang-mian soil stopped the water to filter into soil. Huang-mian soil under 60×10^{-3} m hr^{-1} had the shortest runoff occurrence time, while brown soil under 30×10^{-3} m hr^{-1} had the longest time. Huang-mian soil under 30×10^{-3} m hr^{-1} had the most sediment. Runoff had a closer relationship with NO_3^--N concentration than NH_4^+-N. Huang-mian soil has less loss of P in concentration than brown soil, which could explain why Loesse Plateau has huge soil and water loss but less eutrophication than the Yimeng mountainous area. Under the same rainfall intensity, Huang-mian soil had more runoff volume than brown soil, but higher rainfall intensity will decrease the difference. Increasing rainfall intensity had more impact on sediment content in brown soil than Huang-mian soil. Increasing rainfall intensity had more impact on nitrate N content in brown soil than ammonia N loss content in Huang-mian soil.

This study also produced essential information that will help with an understanding how the characteristics of N and P loss in brown soil and Huang-mian soil were affected by rainfall intensity. Suggestions on reducing harm of N and P loss in brown soil and Huang-mian soil regions were given.

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