Effect of rock fragment cover on nutrient loss under varied rainfall intensities: a laboratory study

Hanzhi Li, Dengxing Fan, Jianzhi Niu, Guodong Jia, Jiamei Sun, Xinxiao Yu and Linus Zhang

ABSTRACT

Surface rock fragments retard overland flow discharge, reduce the runoff generation rate and soil erosion as well as nutrients loss. In Northwest China, a common method for minimizing water, soil, and nutrient losses is the use of rock fragment cover. We used lab stimulation testing to evaluate rock fragment cover efficacy for nutrient conservation. Nutrient losses were determined in both the runoff and sediments under three rain intensities (30, 60 and 90 mm·h^{-1}), four rock fragment covers (0, 10, 20 and 30%) and a slope of 10°. The results showed that rock fragment cover significantly reduced the nutrient losses. Compared with the bare soil control, the rock fragment cover reduced the runoff volume and sediments by 18–38 and 11–69%, respectively, and reduced N and P losses by 9–43 and 16–70%, respectively. These results indicate that rock fragment cover is an effective method for reducing land degradation and improving local environmental conditions.

Key words | nutrient loss, rock fragment cover, simulated rainfall, soil and water conservation

Hanzhi Li
Dengxing Fan
Jianzhi Niu
Guodong Jia
Jiamei Sun
Xinxiao Yu (corresponding author)
Key Laboratory of State Forestry Administration on Soil and Water Conservation,
Beijing Engineering Research Center of Soil and Water Conservation (Beijing Forestry University),
Beijing 100083,
China
E-mail: yuxinxiao111@126.com

Linus Zhang
Department of Water Resources Engineering,
Lund University,
Box 118, SE-221 00 Lund,
Sweden

INTRODUCTION

Soil and water losses cause land degradation, productivity loss, and environmental deterioration. These are serious problems in China and across the globe (Wang *et al.* 2014a). Vegetation restoration and reconstruction are measures used to reduce soil and water losses, especially in arid and semi-arid regions with fragile environments. In North China, below ground competition for limited resources such as water and nutrients is particularly intense (Franklin *et al.* 2007) due to limited rainfall and poor soils. This poses a challenge for effective environmental conservation and restoration.

Rock fragments can modify hydrological and erosional processes of soil and influence plant growth (Nottingham *et al.* 2015). Rock fragment cover can modify soil erosion by: (1) protecting the soil from splash erosion and impeding flow-driven entrainment processes; (2) reducing overland flow velocity and reducing detachment and transport capacity of the overland flow; and (3) reducing the cross-sectional flow area and rill development, resulting in increased flow path duration and greater flow depths (Jiinshuh *et al.* 2000; Janeau *et al.* 2014). Therefore, erosion can be controlled by increasing infiltration into the protected areas around and under the rock fragments (Jomaa *et al.* 2012). However, the specific effects of rock fragment cover on erosion processes remain undocumented. Poesen *et al.* (1990) found that runoff increased with the increase of rock fragment cover. This finding was inconsistent with other reports (Martínez-Zavala & Jordán 2008; Jomaa *et al.* 2012). Rock fragment contacts could influence soil erosion by altering the initial moisture level (Poesen *et al.* 1999). The position of rock fragments can cause diversification in water erosion processes (Otero *et al.* 2011). These diverse opinions suggest that understanding of the mechanism of soil erosion would benefit from additional study.

The levels of different nutrients depend on the mechanism of loss. Nutrients, including N and P, can be lost in both runoff and sediments, but the proportions lost can vary (Tiemeyer *et al.* 2006; Joo 2011). Losses from dissolution and desorption could not only reduce soil fertility, but also cause water pollution (Wudneh *et al.* 2014). It is therefore important to determine nutrient losses in both runoff and eroded sediments. Rainfall characteristics have different effects on nutrient losses. The relationship between rainfall intensity and nutrient loss has often been studied (Zhang *et al.* 2014, 2016). Nutrient losses typically increase with increased rainfall intensity (Kleinman *et al.* 2006; Santos *et al.* 2011; Liu *et al.* 2014; Wang *et al.* 2014a; Zhang 2016). Walton *et al.* (2000) found that the relationship between nutrient levels and rainfall intensity in runoff was related to runoff yield when the slope was <2%. Mulching is an effective way of managing water and soil conservation and reducing nutrient loss (Li *et al.* 2009). Nutrient loss is also related to slope, soil texture, and nutrient content (Reddy & Venkataiah 1989; Buck *et al.* 2011; Yan *et al.* 2013; Yang *et al.* 2013; Baptista *et al.* 2015; Peng *et al.* 2017), factors which increase research complexity.

The international soil erosion model considers the influence of gravel on soil erosion. Modified cover factor and soil erodibility factor (RUSLE model), effective porosity and runoff resistance coefficient revised (WEPP model), soil saturated hydraulic conductivity, splash erosion and the Manning coefficient (EUROSEM model) are used in the models to improve the accuracy of model predictions (Poesen *et al.* 1990; Poesen & Lavee 1994; Papanicolaou *et al.* 2011). However, the nutrient losses in runoff and sediment remain poorly documented and the dynamics of N and P and sediment transport by runoff after rainstorms are unclear.

Simulated rain is a useful experimental method due to convenience and controllability, although simulated rain cannot completely mimic natural rain (Duan *et al.* 2004). Rain-simulation experiments can use different rain intensities to shorten experimental periods and to control the experimental conditions for easy observation of runoff and its evolution (Cheng *et al.* 2008). In this study, we used simulated rain to investigate the effects of rain intensity and rock fragment cover on total N and P in runoff and sediments to: (1) clarify the effects of rock fragments on the nutrient loss process both in runoff and sediment; and (2) determine the parameters influencing the nutrient loss process.

MATERIAL AND METHODS

Rain simulator and soil flumes

The experiments were conducted at the Key Laboratory of Soil and Water Conservation and Desertification Combating of the Ministry of Education. This facility belongs to the Beijing Forest University located in the Jiufeng Mountains (40°04′N, 116°06′E) in Beijing, China. The laboratory rain hall has systems for simulated rain, water supply, and soil flumes. The simulated rainfall experimental facility is shown in Figure 1.

The rainfall height of the simulated experiment was 12 m which allows raindrops to reach a rainfall terminal speed that is similar to natural rainfall speeds of between 1.3 and 2.9 m·s^{-1}. These speeds increase with rainfall intensity. The rain simulator (QYJY-503C, Xianqingyuan, Inc., Shanxi, China) is capable of generating intensities of 10–300 mm·h^{-1} and is controlled by four nozzle types. The mean diameter distribution of raindrops ranged from 0.85 to 1.33 mm, which is similar to the diameter range of natural rainfall in this region (0.15–2.63 mm) (Huo *et al.* 2015). The kinetic energy varies with rainfall intensity both in the natural and simulated rainfall. This is the dependent variable of rainfall speed and raindrop diameter. Therefore, the characteristics of the precipitation generated by the simulator were similar to those of natural precipitation (see Sun *et al.* (2016) and Li *et al.* (2016) for a description of the rainfall simulator).

Soil flumes ($2.00 \times 0.50 \times 0.30$ m, length × width × height) were constructed from sheet metal with many drain holes at the bottom to allow unrestricted drainage. The runoff and eroded soil were collected at the ends of the flumes. The slope of the soil flume could be set at 0–45° by adjusting screws.

Experiments and material

To simulate the effect of rock fragments on nutrient loss, we used rain intensities of 30, 60, and 90 mm·h^{-1}, a rock fragment coverage of 0% (control group), 10, 20 and 30%, and
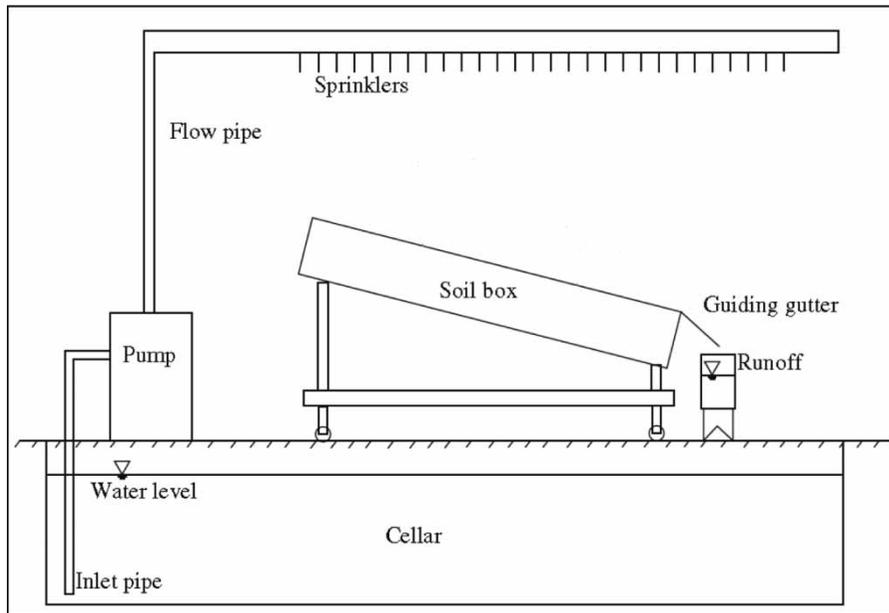
Figure 1 | The simulated rainfall experimental facility.

a slope of 10° based on the characteristics of yearly rainfall, rock fragment coverage and the characteristics of mountain slopes in the North China region. A rainfall intensity of between 30 and 90 mm h^{-1} is typical of intense storms in semiarid regions of China that are dominated by a monsoon climate (Gebel et al. 2014; Moiwo & Tao 2014). A rock fragment coverage from 0 to 30% and a 10° slope were chosen because the rock fragment and lands with slopes between 5 and 15° are widely distributed in the mountain areas of North China (Ye et al. 2009; Han et al. 2012; Li & Liu 2013; Yang et al. 2013).

All treatments used fertilization to study the effects of rock fragments on nutrient loss after rainfall. All of the rainfall durations were 60 min long. A total of 24 rainfall simulations consisting of different rainfall intensities and rock fragments were performed and all experiments were repeated twice under the same conditions.

In the fertilization experiments, we fertilized the surface soil in the flumes before each treatment with a compound fertilizer containing N and P at the 20 g·m^{-2} fertilization level according to local fertilization practices. Knowing the original and added contents of N and P allowed us to calculate the losses.

Cinnamon soil was used in this study, collected from the 0–20 cm surface layer of a local forest to simulate field conditions. Cinnamon soil is the most common soil type in the mountainous districts. Soil samples were air-dried and passed through a 1 cm aperture square-hole sieve to remove coarse rocks and organic debris such as roots and leaves. The physical and chemical characteristics of the sieved soil are listed in Table 1. The dried soil was packed into the soil flumes at a bulk density of 1.34 g·cm^{-3}. It was packed in 10 cm layers to ensure consistent bulk densities for each layer. Each soil layer was raked lightly before adding the next layer to reduce discontinuities between the layers. The rock fragments used were collected from the Jiu Feng Mountains and had sieved diameters between 20 and 60 mm. The rock fragments were uniformly distributed on top of the soil surface (Figure 2). Determination of rock fragment coverage was made using a digital camera to produce an image of the

Table 1 | Physical and chemical characteristics of the experimental soil

Size distribution (%)

> 0.5 mm	0.5–0.02 mm	< 0.02 mm	pH	TN (%)	TP (%)
72.45 ± 1.67	25.35 ± 1.88	2.19 ± 0.23	6.7 ± 0.13	0.018 ± 0.012	0.0294 ± 0.016

Total nitrogen (TN); total phosphorus (TP).

Figure 2 │ Illustration of the superficial rock fragment cover.

distribution of the rock fragments. The coverage was obtained using color analysis in Photoshop. We could then adjust the rocks to achieve the desired target coverage.

The soil-water content was controlled by a preliminary experiment rather than the ring method to avoid damaging the soil surface in the flume (Sun *et al.* 2016). We preliminarily operated the simulator at 10 mm·h^{-1} to increase the

soil-water content until the emergence of runoff and to mini-mize differences in soil-water contents among the treatments.

Measurements and methods

Triplicate samples of runoff with sediments were collected for each treatment in buckets every 2 min for the first 10 min and then every 5 min for the next 50 min. In each treatment, the runoff velocity was measured every 10 min from start of runoff until the end of rainfall duration using the Dye Tracer Method (Lei *et al.* 2013). The velocities observed in this research were modified by the measured velocity multiplied correction coefficient of 0.75 (Poesen *et al.* 1999). We measured the volume of runoff with a gradu-ated cylinder. We took runoff samples with a dropper after the collected runoff stood in the bucket for 24 hours. We dried the sediment samples at 105°C in a drying oven and weighed and sieved the dried samples. Total nitrogen (TN) in the runoff and sediments was measured by ion chromato-graphy and the micro-Kjeldahl method, respectively. Total phosphorus (TP) in the runoff and sediments was measured by ion chromatography and $HClO_4$-H_2SO_4 digestion, respectively.

RESULTS

Runoff rates, sediment and runoff velocity

Rainfall and subsequent runoff are the main forces causing soil erosion and loss of soil nutrients. The velocity of overland flow and the kinetic energy of raindrops are directly dependent on rain intensity (Steiner & Smith 2000). Nutrients in our study were lost at different levels in the runoff and sediments. The runoff rate increased with time before stabilizing, but the rate of sediment transport was higher at the beginning and then decreased with time until stabilizing (Figure 3). Runoff rates and sediment transport increased with rain intensity due to the increased raindrop energy and scouring by the runoff. Runoff rates and sediment transport decreased with increased rock fragments at the various rain intensities. In the 30 mm·h^{-1} treatments, rock fragment cover reduced runoff volume and sediment yield by 18–38 and 11–69% from 10–30% cover,

respectively. As rainfall intensity increased, the capability of rock fragments for soil and water conservation decreased. At 60 and 90 mm·h^{-1} the reduction ratios ranged from 6–26 and 18–43%, respectively, for runoff. At 60 and 90 mm·h^{-1} the reduction ratios ranged from 7–19 and 9–29%, respectively, for sediment. Runoff velocity was also sensitive to rainfall intensity and rock fragments. Velocity increased when rainfall intensity increased and decreased when rock fragments increased. Rock fragments reduced the mean runoff velocity by 13, 24 and 33% for 10, 20 and 30% cover at various rainfall intensities, respectively.

TN and TP loss in the runoff

Rock fragments can effectively decrease nutrient loss regard-less of rainfall intensity. Although nutrient loss rates for TN and TP differ, the efficiency of rock fragments in protecting them from loss is similar. In the lower rainfall intensity treat-ments (30 mm·h^{-1}), the nutrient reduction ratios from 10 to 30% cover ranged from 17 to 41% for TN and 16 to 35% for TP. When rainfall intensity increased to 90 mm·h^{-1}, the protec-tion efficiency decreased by 6 to 9% for TN and 3 to 16% for TP.

The rate of TN loss in the runoff remained stable at low intensity rainfall (≤60 mm·h^{-1}) but decreased with time at high intensity rainfall (90 mm·h^{-1}). The rate of TP loss was higher at the beginning of the rain and then gradually decreased at all intensities (Figure 4). The loss rates, how-ever, differed greatly between the two nutrients, indicating differences in the processes determining N and P runoff loss.

To illustrate the erosion process of each treatment, the concentrations of runoff-associated nutrients are presented in Figure 5. The greatest losses occurred in the initial erosion process followed by descent to a stable value. Rock frag-ments increased the concentration of runoff-associated nutrients, however the loss rate decreased. At 30 mm·h^{-1} rainfall intensity, the concentrations of TN and TP increased from 11.29 to 11.73 and 0.116 to 0.147 mg·L^{-1}, respectively for cover that varied from 0 to 30%. At 60 mm·h^{-1} rainfall, this increased from 10.53 to 11.49 and 0.108 to 0.121 mg·L^{-1}, respectively. At 90 mm·h^{-1} rainfall, the values increased from 9.98 to 11.31 and 0.117 to 0.123 mg·L^{-1}, respectively for TN and TP.

Rock fragments on the soil surface slowed the runoff rate and extended the contact time (Figure 3). Rain intensity,
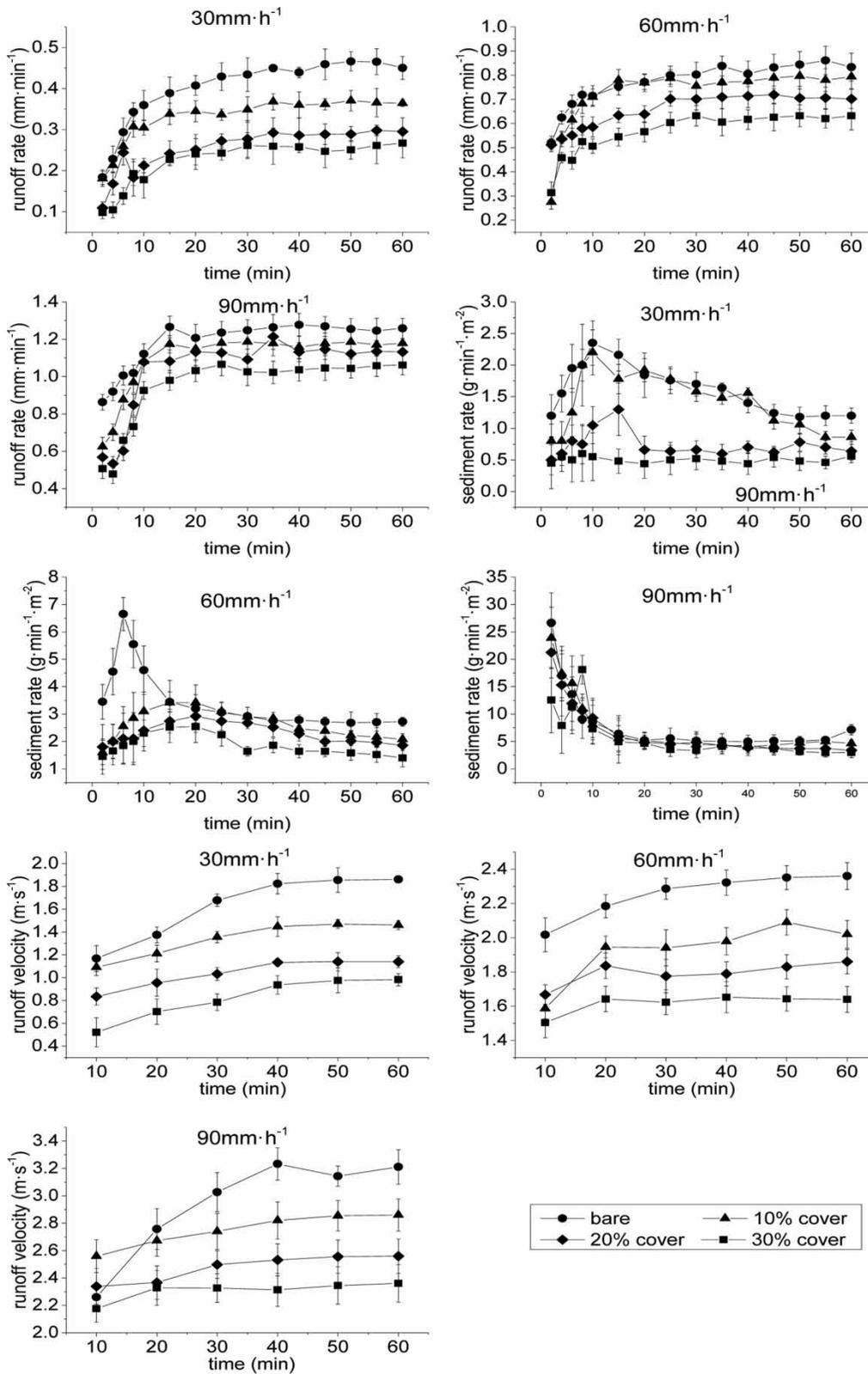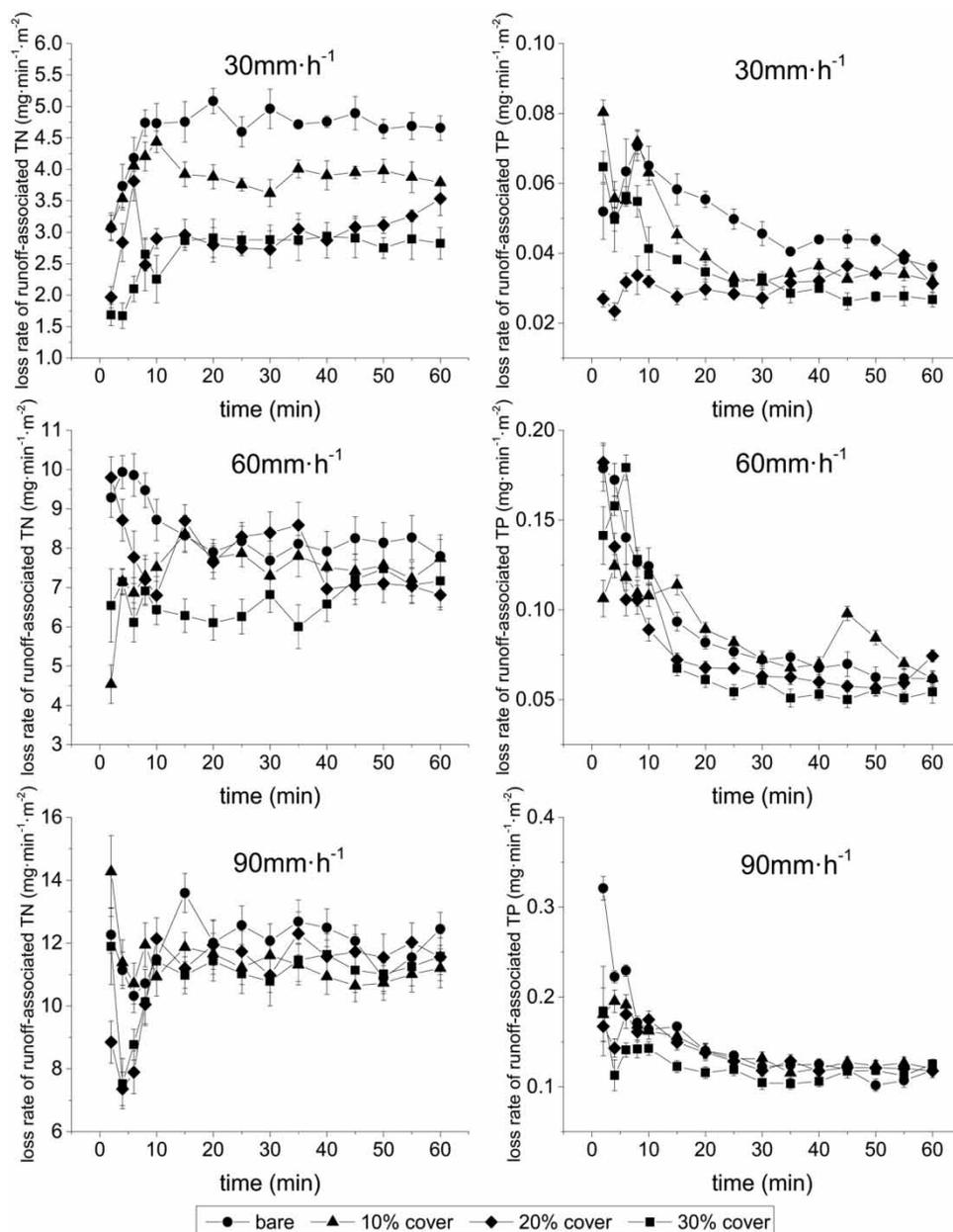
Figure 3 | Rates of runoff, sediment transport, and runoff velocity during a single rain event at three intensities with three levels of rock fragment cover.
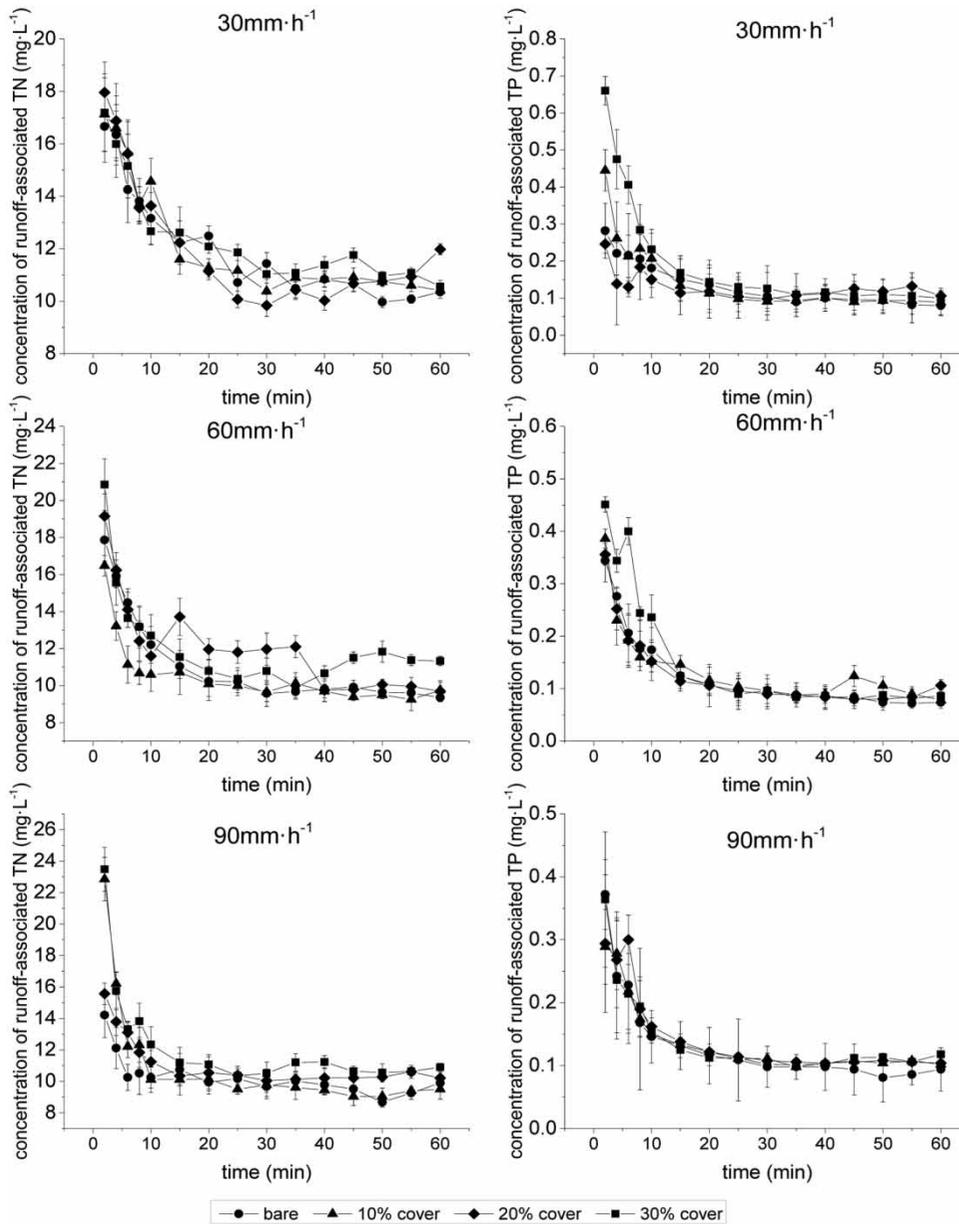
Figure 4 │ Loss rates of runoff-associated nutrients during a single rain event at three intensities with three levels of rock fragment cover. Total nitrogen (TN); total phosphorus (TP).

however, did not have a significant effect on the nutrient concentrations, perhaps due to limitation of the nutrient load capacity in the runoff.

The relationship between nutrient concentration and runoff contact time was analyzed to study the nutrient loss mechanism. The contact time was derived from the runoff velocity. It was measured every 10 minutes using a dye tracer method and the corresponding nutrients were also determined at 10 minute intervals. The significant fit between them showed that nutrient loss was caused by fertilizer dissolved in the initial runoff (Figure 6 and Table 2).

To further examine the influence factors of runoff-associated nutrients under experimental conditions, we determined linear regression relationships between nutrient concentration and contact time (Table 2). Most equations were significant (except 90 mm·h^{-1}, control treatment).
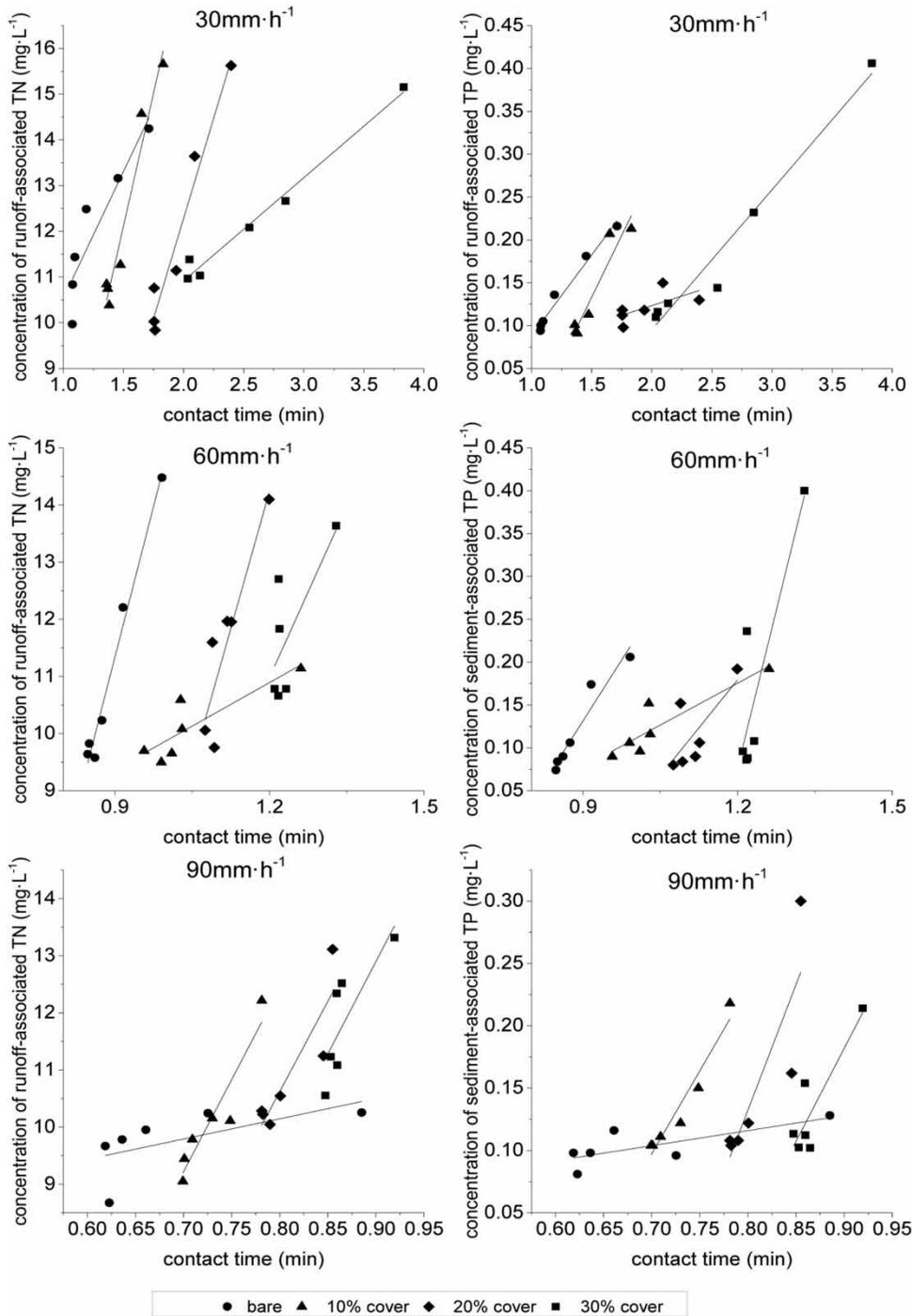
Figure 5 | Nutrient concentrations during a single rain at three intensities with three kinds of rock fragment cover. Total nitrogen (TN); total phosphorus (TP).

Their coefficient of determination for a linear regression (R^2) ranged from 0.426 to 0.983. The regression line slopes of TN and TP showed substantial variability.

TN and TP losses in sediments

Rock fragment cover can effectively reduce loss of sediment-associated nutrients. Rock fragments are most effective at relatively light rainfall intensities. Under 30 mm·h^{-1}

conditions, the nutrients reduction ratios were 7–74 and 16–71% from 10 to 30% cover, respectively, for TN and TP. At 60 mm·h^{-1}, the nutrients reduction ratios were 24–51 and 22–49% from 10 to 30% cover, respectively, for TN and TP. At 90 mm·h^{-1}, the protection efficiency decreased by 34–40 and 24–31% for TN and TP, respectively. Based on the sediment-associated nutrient loss process (Figure 7), nutrient loss was mainly concentrated in the initial stage of rainfall and this is similar to the process of sediment loss.

Figure 6 | Correlation between nutrient concentration and contact time at three intensities with three levels of rock fragment cover. Total nitrogen (TN); total phosphorus (TP).

Unlike runoff-associated nutrients, the relationship between nutrient concentration and contact time was less obvious. The regression analysis of the relationship between the rate of nutrient loss and sediment rate is presented in Figure 8 and Table 3. The effect of sediment rate on the sediment-associated nutrient loss rate reached significance ($p < 0.05$) under a certain rainfall intensity with varied rock fragment cover.

Table 2 | Relationship between nutrient concentration (y) and contact time (x) under different treatments

Different treatments		Concentration of runoff-associated TN (y)		Concentration of runoff-associated TP (y)	
Rainfall intensity (mm·h^{-1})	Rock fragment cover (%)	Equation	R^2	Equation	R^2
30	0	y = 5.53x + 5.00	0.841*	y = 0.18x − 0.10	0.975**
	10	y = 11.62x − 5.32	0.954**	y = 0.28x − 0.29	0.911**
	20	y = 8.75x − 5.23	0.954**	y = 0.044x + 0.033	0.426*
	30	y = 2.25x + 6.40	0.983**	y = 0.16x − 0.23	0.968**
60	0	y = 35.15x − 20.30	0.980**	y = 0.94x − 0.72	0.932**
	10	y = 5.07x + 4.80	0.744**	y = 0.32x − 0.21	0.812*
	20	y = 32.01x − 24.17	0.827*	y = 0.74x − 0.71	0.542*
	30	y = 19.99x − 13.01	0.549*	y = 2.45x − 2.86	0.774**
90	0	y = 3.53x + 7.31	0.387	y = 0.12x + 0.019	0.557*
	10	y = 32.20x − 13.32	0.881**	y = 1.33x − 0.83	0.936**
	20	y = 31.54x − 14.61	0.794*	y = 2.01x − 1.47	0.744*
	30	y = 32.32x − 16.19	0.654*	y = 1.48x − 1.15	0.783*

*$p < 0.05$, **$p < 0.01$.
Total nitrogen (TN); total phosphorus (TP).

Proportions of TN and TP lost in runoff and sediments

TN and TP have distinctive loss characteristics. TN loss occurs mainly in the runoff, while TP loss mainly occurs with sediment, regardless of rainfall intensity. Tables 4 and 5 show that the runoff-associated TN loss accounted for 88–98% of the TN lost, while sediment-associated TP loss accounted for 89–97% of the TP lost. With rock fragments, the reduction ratios for TN and TP reached 9–43 and 16–70%, respectively. Additionally, a decreased amount of rainfall increased the efficiency of rock fragment cover for nutrient conservation.

DISCUSSION

Nutrients are lost from soil during rainfall events by dissolving in rainwater or by being physically moved with the sediments. The amount of nutrient loss thus depends on the amounts of runoff and sediments and the nutrient concentrations in each.

Effect of rock fragment cover on runoff rates, sediment transport and runoff velocity

Runoff rate and sediment transport in our study were not significantly correlated in contrast to the findings by Wang *et al.* (2014a) who reported that the two factors had a significant linear relationship. Different experimental conditions can lead to different results (Wang *et al.* 2014b). Sediment transport here was mainly affected by erosion from raindrop splash and scouring by shallow flow. Erosion from raindrop splashes decreased and the scouring force of the runoff increased as the rain continued. The saturated soil was loosened, easily transported, and reached a peak of sediment transport. The sediment transport rate decreased and then stabilized after the loose surface soil had been transported by the flow. The rock fragments protected the soil from erosion by reducing the direct contact of raindrops and reducing the splash erosion. The flow depth varied with rock fragment proportion, as reported by Renard *et al.* (1997), which was a key parameter controlling the flow characteristics around obstacles. Runoff velocity may be a composite index explaining runoff variation and a key parameter for calculation of other hydraulic parameters. The reduced runoff velocity associated with rock fragments produced less runoff scouring.

The effects of rock fragment coverage as mulch on soil hydrological processes have been inconsistent in the field experiments. The results in this study were consistent with Guo *et al.* (2010) and Wang *et al.* (2012) who determined that soil erosion and runoff generation decreases with rock fragment coverage ranging from 0 to 40%. However,
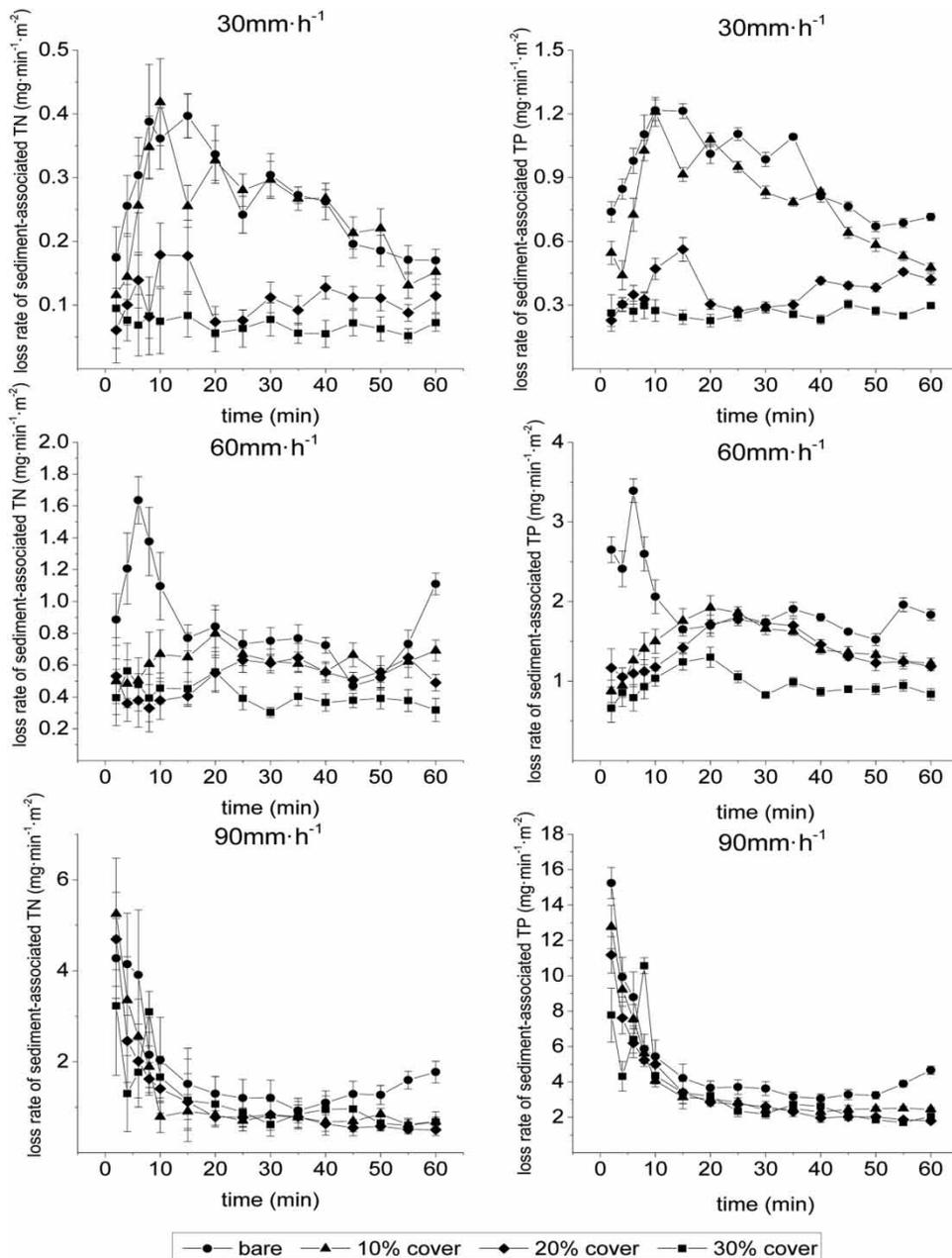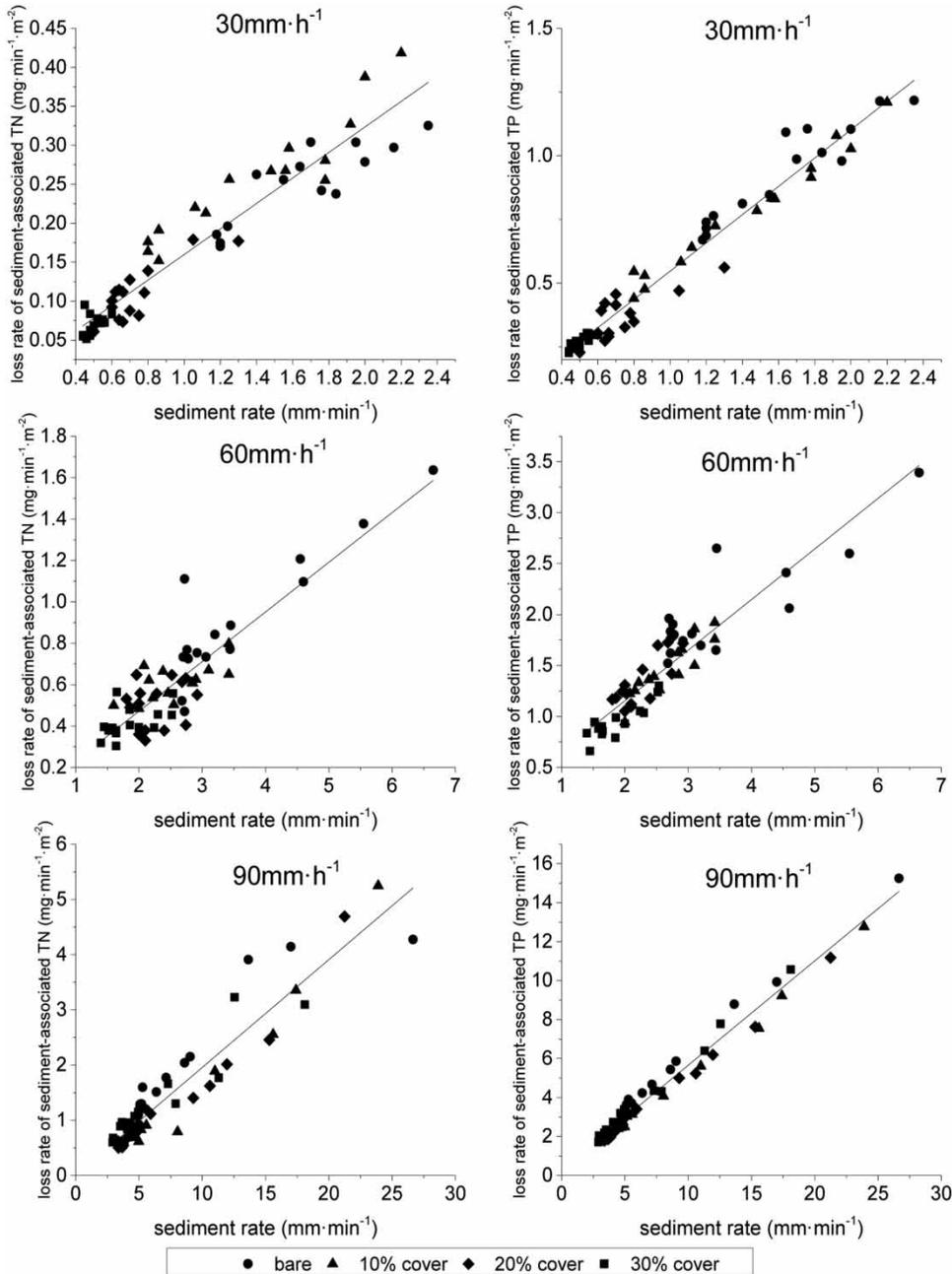
Figure 7 | Loss rates of sediment-associated nutrients during a single rain at three intensities with three levels of rock fragment cover. Total nitrogen (TN); total phosphorus (TP).

Zavala *et al.* (2010) and Gordillo-Rivero *et al.* (2015) found that soil erosion and runoff generation increased with an increase in rock fragment cover. The differences may result from complex field conditions such as rock fragments position, rock fragment size, distribution of soil macropores, rock fragments spatial heterogeneity, and the microclimate of experiment plots (Bunte & Poesen 2010; Chen *et al.*

2011; Dang *et al.* 2012; Schreiber & Killingback 2013; Warren *et al.* 2013; Mukhlisin & Naam 2015).

The results in this research also showed that rock fragments have protective benefits similar to other mulching practices. The runoff and sediment reduction reported for other vegetative mulching practices varied between 7.19–37.30 and 45.32–75.75%, respectively (Robichaud

Figure 8 │ Correlation between the rates of nutrient loss and sediment rate at three intensities with three levels of rock fragment cover. Total nitrogen (TN); total phosphorus (TP).

et al. 2013; Sadeghi *et al.* 2015; Prosdocimi *et al.* 2016). Compared with other vegetative mulching practices, rock fragment mulching was a long-lasting treatment that would resist decomposition. Also, rock mulch had the additional advantage of being readily available in the study region.

Effect of rock fragment cover on TN and TP loss in runoff

Our results demonstrated that the level of soluble reactive nutrients in the runoff increased significantly within 24 hours after fertilization, a finding consistent with previous research (Shuman 2002). Granular fertilizer may not

Table 3 | Relationship between the rates of nutrient loss (y) and sediment rate (x) under different treatments

Different treatments		Loss rate of sediment-associated TN (y)		Loss rate of sediment-associated TP (y)	
Rainfall intensity (mm·h^{-1})	Rock fragment cover (%)	Equation	R^2	Equation	R^2
30	0	$y = 0.12x + 0.045$	0.772**	$y = 0.47x + 0.16$	0.885**
	10	$y = 0.15x + 0.042$	0.882**	$y = 0.49x + 0.083$	0.975**
	20	$y = 0.14x + 0.0029$	0.698*	$y = 0.35x + 0.10$	0.631*
	30	$y = 0.10x + 0.014$	0.183	$y = 0.44x + 0.043$	0.736**
	Total	$y = 0.16x - 0.0038$	0.904**	$y = 0.55x - 0.0083$	0.964**
60	0	$y = 0.23x + 0.063$	0.805**	$y = 0.36x + 0.74$	0.740*
	10	$y = 0.10x + 0.34$	0.419*	$y = 0.52x + 0.067$	0.858**
	20	$y = 0.070x + 0.34$	0.055	$y = 0.58x + 0.037$	0.683*
	30	$y = 0.10x + 0.22$	0.280	$y = 0.38x + 0.23$	0.761*
	Total	$y = 0.24x - 0.0083$	0.790*	$y = 0.49x + 0.16$	0.839**
90	0	$y = 0.17x + 0.47$	0.853**	$y = 0.55x + 0.66$	0.994**
	10	$y = 0.21x - 0.33$	0.961**	$y = 0.51x + 0.14$	0.994**
	20	$y = 0.20x - 0.23$	0.953**	$y = 0.50x + 0.15$	0.995**
	30	$y = 0.17x + 0.18$	0.883**	$y = 0.57x + 0.23$	0.991**
	Total	$y = 0.19x + 0.0043$	0.887**	$y = 0.30x + 0.54$	0.976**

*$p < 0.05$, **$p < 0.01$.
Total nitrogen (TN); Total phosphorus (TP).

Table 4 | Proportions of runoff-associated TN and sediment-associated TN under different treatments

Different treatments		Runoff-associated TN			Sediment-associated TN			Total TN	
Rainfall intensity (mm·h^{-1})	Rock fragment cover (%)	Loss amount (mg·m^{-2})	Loss ratio (%)	Reduction ratio (%)	Loss amount (mg·m^{-2})	Loss ratio (%)	Reduction ratio (%)	Loss amount (mg·m^{-2})	Reduction ratio (%)
30	0	279.70	95		15.65	5		295.35	
	10	232.09	94	17	14.61	6	7	246.70	16
	20	178.65	96	36	6.54	4	58	185.19	37
	30	164.27	98	41	4.04	2	74	168.31	43
60	0	497.35	91		49.54	9		546.89	
	10	449.33	92	10	37.64	8	24	486.97	11
	20	463.32	94	7	31.99	6	35	495.31	9
	30	400.98	94	19	24.28	6	51	425.26	22
90	0	723.57	88		98.85	12		822.42	
	10	679.37	91	6	65.46	9	34	744.83	9
	20	675.33	92	7	59.74	8	40	735.07	11
	30	660.88	91	9	64.17	9	35	725.05	12

combine with soil particles and may be directly transported away with runoff (Withers *et al.* 2003). The rock fragment cover in our study increased the nutrient concentrations in the runoff, which may have been associated with the rate of nutrient desorption and the contact time between the runoff and soil surface. The rock fragments on the soil surface could slow the runoff rate (Figure 3) and extend the contact time because of the longer flow path (Zhou *et al.*

2009). Rain intensity, however, did not have a significant effect on the concentrations of the nutrients, perhaps due to limitations of the nutrient load capacity in the runoff. Nutrient concentrations were linearly correlated with contact time (Figure 6). The slopes of the regression lines differed significantly between the two nutrients. Contact time influenced the TN concentration in the runoff more than the TP concentration. The differences of the intercepts

Table 5 │ Proportions of runoff-associated TP and sediment-associated TP under different treatments

Different treatments		Runoff-associated TP			Sediment-associated TP			Total TP	
Rainfall intensity (mm·h^{-1})	Rock fragment cover (%)	Loss amount (mg·m^{-2})	Loss ratio (%)	Reduction ratio (%)	Loss amount (mg·m^{-2})	Loss ratio (%)	Reduction ratio (%)	Loss amount (mg·m^{-2})	Reduction ratio (%)
30	0	2.88	5		55.06	95		57.94	
	10	2.41	5	16	46.01	95	16	48.43	16
	20	1.88	8	35	22.34	92	59	24.22	58
	30	2.05	11	29	15.92	89	71	17.98	69
60	0	5.09	4		113.93	96		119.02	
	10	5.08	5	0.3	88.90	95	22	93.97	21
	20	4.44	5	13	85.03	95	25	89.47	25
	30	4.25	7	17	57.81	93	49	62.06	48
90	0	8.51	3		273.30	97		281.82	
	10	8.25	4	3	208.98	96	24	217.23	23
	20	7.96	4	7	188.35	96	31	196.31	30
	30	7.17	4	16	187.80	96	31	194.97	31

suggest that the rock fragments affected the runoff rate and nutrient concentration (Table 2).

The position of rock fragments can influence soil hydrological process during the erosion process (Otero *et al.* 2011). The surface rock fragments in our study decreased the runoff rate but increased the nutrient concentration in the runoff. The rock cover, however, decreased the amounts of TN and TP lost in the runoff, indicating that the runoff rate played a more important role than the concentration, rather than a change of soil properties. The slopes of the regression lines were much greater for TN than TP, indicating that TN was more influenced by runoff than TP.

Effect of rock fragment cover on TN and TP losses in sediments

The linear relationship observed between sediment rate and sediment-associated nutrients has also been observed under different vegetation types and coverages (Ruiz-Colmenero *et al.* 2013). For nutrients such as TN or TP, no significant differences were observed in rock coverage between the treatments. All of the treatments for each specific nutrient could be fit by a single regression equation. The results indicated that nutrient concentration was not affected by the rock fragments. Other research has demonstrated that nutrient loss is more dependent on soil properties (Tiemeyer *et al.* 2007; Baptista *et al.* 2015). However, rock fragment cover can

reduce the sediment rate (Figure 3) so rock fragments could reduce nutrient losses by controlling sediment loss.

The slopes of the relationship between the rates of nutrient and sediment loss can differ in different soil types (Otero *et al.* 2011; Wong *et al.* 2015). However, compared with the different coverage in cinnamon soil used here, the correlation coefficient was small. Thus, the ability to transport nutrients would be predicted to change little with rain intensity or cover.

Effect of rock fragment cover on proportions of TN and TP lost in runoff and sediments

Rain intensity and vegetation have the most influence on runoff volume in North China. Vegetation has the greatest effect on reducing nutrient loss (Zhang *et al.* 2011, 2012), because the thin soil (usually <30 cm) limits the impact of the soil on runoff. Rock fragment cover could protect sloping land against runoff scouring, thereby reducing nutrient losses. Vegetation can also decrease nutrient loss because it effectively slows the rate of runoff, reduces soil erosion, and increases crop nutrient use (Dillaha 1989; Udawatta *et al.* 2006). Studies on the effects of rock fragments on nutrient loss have focused on the physical aspects of surface erosion, but we found that a rock fragment cover could decrease sediment loss more effectively than runoff loss and decrease the loss of P more effectively than the loss of

N because of the different transportation forms. These findings indicate that unique conservation measures should be taken for different nutrients because of the different loss mechanisms of TN and TP.

CONCLUSIONS

Simulated rainfall experiments were used to study the effect of rock fragment cover on the loss of nutrients by water erosion. The effects of four rock fragment coverages (0, 10, 20 and 30%) were tested under three rainfall intensities (30, 60, and 90 mm h^{-1}) with a common slope (10°). The results indicate that surface rock fragment cover may impact runoff, soil loss, and nutrients transport on the slope lands of North China.

Runoff rate generally increased in the initial 20 min for each rock fragment cover treatment and then reached a plateau or slightly decreased. Runoff-associated nutrients were controlled both by runoff rate and runoff-associated nutrient concentrations. Concentrations of nutrients in the runoff were higher in the rock fragment cover treatments but the total nutrient losses were lower relative to bare soil because of the lower runoff rate. Regression equations described the relationships between the concentration of nutrients and contact time to help explain the runoff-associated nutrients loss mechanism. Finally, rock fragment cover (from 10 to 30%) could decrease runoff by 6–43%, and the nutrient reduction ratio was 6–42% and 3–35%, respectively for TN and TP.

Sediment transport increased sharply at the beginning of rainfall and then decreased with time until stabilizing. However, there was no significant relationship between rock fragment cover and sediment-associated nutrient concentrations, so the sediment-associated nutrient loss depends on sediment transport. Regression equations between them explain the different nutrient loss relationships between runoff and sediment. However, rock fragment cover was still an effective measure that could decrease sediment loss by 7–69%, and the nutrient reduction ratio was 7–74 and 16–71%, respectively, for TN and TP.

Rock fragment cover decreased TN and TP losses by 9–43 and 16–70%, respectively, relative to the bare soil. Additionally, the loss dynamics differed between the two nutrients. Most of the TN was lost in the runoff, and most of the TP was lost in the sediments. These findings have implications for controlling soil erosion, modeling soil surface nutrients transport, and conserving soil and water resources on the slope lands of North China. It also helps us to understand the effectiveness of rock fragment cover in semi-arid regions.

REFERENCES

Baptista, I., Ritsema, C. & Geissen, V. 2015 Effect of integrated water-nutrient management strategies on soil erosion mediated nutrient loss and crop productivity in Cabo Verde drylands. *Plos One* **10**, e0134244.

Buck, B. J., King, J. & Etyemezian, V. 2011 Effects of salt mineralogy on dust emissions: Salton Sea California, USA. *Soil Sci. Soc. Am. J.* **75**, 1958–1972.

Bunte, K. & Poesen, J. 2010 Effects of rock fragment size and cover on overland flow hydraulics, local turbulence and sediment yield on an erodible soil surface. *Earth Surf. Process. Landforms* **19**, 115–135.

Chen, H., Liu, J., Wang, K. & Zhang, W. 2011 Spatial distribution of rock fragments on steep hillslopes in karst region of northwest Guangxi, China. *Catena* **84**, 21–28.

Cheng, F., Xu, X., Gao, J. & Xue, Y. 2008 Advance of research on the rainfall simulators for soil erosion. *Sci. Soil Water Conserv.* **6**, 107–112.

Dang, H., Chen, H. & Shao, M. A. 2012 Effects of laminated rock fragments on soil infiltration processes in Karst regions. *Trans. Chinese Soc. Agric. Eng.* **28**, 38–43.

Dillaha, T. A. 1989 Vegetative filter strips for agricultural non-point source pollution control. *Trans. Am. Soc. Agric. Eng.* **32**, 513–519.

Duan, Y. H., Zhang, N. M. & Zhang, Y. J. 2004 Effect of fertilizer application on controlling nitrogen and phosphorus pollution loading from farmland runoff. *J. Soil Water Conserv.* **18**, 130–132.

Franklin, D., Truman, C., Potter, T., Bosch, D., Strickland, T. & Bednarz, C. 2007 Nitrogen and phosphorus runoff losses from variable and constant intensity rainfall simulations on

loamy sand under conventional and strip tillage systems. *J. Environ. Qual.* **36**, 846–854.

Gebel, M., Uhlig, M., Halbfass, S., Meissner, R. & Duan, S. 2014 Predicting erosion and sediment yield in a mesoscale basin in the semiarid monsoon region Miyun/China. *Ecol. Process.* **3**, 5.

Gordillo-Rivero, Á. J., Garcia-Moreno, J., Jord, N. A., Zavala, L. M. & Granja-Martins, F. M. 2015 Fire severity and surface rock fragments cause patchy distribution of soil water repellency and infiltration rates after burning. *Hydrol. Process.* **28**, 5832–5843.

Guo, T., Wang, Q., Li, D. & Jie, Z. 2010 Effect of surface stone cover on sediment and solute transport on the slope of fallow land in the semi-arid loess region of northwestern China. *J. Soils Sediments* **10**, 1200–1208.

Han, S., Yang, Y., Fan, T., Xiao, D. & Moiwo, J. P. 2012 Precipitation-runoff processes in Shimen hillslope micro-catchment of Taihang Mountain, north China. *Hydrol. Process.* **26**, 1332–1341.

Huo, Y., Bi, H., Zhu, Y., Xu, H., Wang, X. & Chang, Y. 2015 Characteristics of artificial rainfall produced by QYJY-503c simulation system. *Sci. Soil Water Conserv.* **13**, 31–36. (in Chinese).

Janeau, J. L., Gillard, L. C., Grellier, S., Jouquet, P., Le, T. P. Q., Luu, T. N. M., Ngo, Q. A., Orange, D., Pham, D. R. & Tran, D. T. 2014 Soil erosion, dissolved organic carbon and nutrient losses under different land use systems in a small catchment in northern Vietnam. *Agric. Water Manage.* **146**, 314–323.

Jiinshuh, J., Ai, K. F., Kaimin, S. & Chaochi, H. 2000 Stone cover and slope factors influencing hillside surface runoff and infiltration: laboratory investigation. *Hydrol. Process.* **14**, 1829–1849.

Jomaa, S., Barry, D. A., Heng, B. C. P., Brovelli, A., Sander, G. C. & Parlange, J. Y. 2012 Influence of rock fragment coverage on soil erosion and hydrological response: laboratory flume experiments and modeling. *Water Resour. Res.* **48**, 213–223.

Joo, J. H., Kangwon National University, Chuncheon, Republic Of Korea 2011 Assessment of nutrient losses in different slope highland soils amended with livestock manure compost. *Korean J. Soil Sci. Fertilizer* **44**, 361–367.

Kleinman, P. J., Srinivasan, M. S., Dell, C. J., Schmidt, J. P., Sharpley, A. N. & Bryant, R. B. 2006 Role of rainfall intensity and hydrology in nutrient transport via surface runoff. *J. Environ. Qual.* **35**, 1248–1259.

Lei, T., Yan, Y., Shi, X., Chuo, R. & Zhao, J. 2013 Measuring velocity of water flow within a gravel layer using an electrolyte tracer method with a pulse boundary model. *J. Hydrol.* **500**, 37–44.

Li, Z. J. & Liu, Q. Q. 2013 Causes and its impacts of soil erosion in the rocky mountain area of Northern China. *Adv. Mater. Res.* **731**, 3807–3810.

Li, M., Yao, W., Ding, W., Yang, J. & Chen, J. 2009 Effect of grass coverage on sediment yield in the hillslope-gully side erosion system. *J. Geogr. Sci.* **19**, 321–330.

Li, X., Xiao, Q., Niu, J., Dymond, S., Doorn, N. S. V., Yu, X., Xie, B., Lv, X., Zhang, K. & Li, J. 2016 Process-based rainfall interception by small trees in Northern China: the effect of rainfall traits and crown structure characteristics. *Agric. Forest Meteorol.* **218–219**, 65–73.

Liu, R., Wang, J., Shi, J., Chen, Y., Sun, C., Zhang, P. & Shen, Z. 2014 Runoff characteristics and nutrient loss mechanism from plain farmland under simulated rainfall conditions. *Sci. Total Environ.* **468–469**, 1069–1077.

Martínez-Zavala, L. & Jordán, A. 2008 Effect of rock fragment cover on interrill soil erosion from bare soils in Western Andalusia, Spain. *Soil Use Manage.* **24**, 108–117.

Moiwo, J. P. & Tao, F. 2014 Groundwater recharge and discharge analysis for land use conditions suitable for the hydrology and ecology of semiarid regions. *Hydrol. Res.* **45**, 563–574.

Mukhlisin, M. & Naam, S. I. 2015 Effect of rock fragments on pore water pressure and slope stability at a hillslope. *J. Geol. Soc. India* **86**, 337–343.

Nottingham, A. T., Turner, B. L., Stott, A. W. & Tanner, E. V. J. 2015 Nitrogen and phosphorus constrain labile and stable carbon turnover in lowland tropical forest soils. *Soil Biol. Biochem.* **80**, 26–33.

Otero, J. D., Figueroa, A., Munoz, F. A. & Pena, M. R. 2011 Loss of soil and nutrients by surface runoff in two agro-ecosystems within an Andean paramo area. *Ecol. Eng.* **37**, 2035–2043.

Papanicolaou, A. N., Dermisis, D. C. & Elhakeem, M. 2011 Investigating the role of clasts on the movement of sand in gravel bed rivers. *J. Hydrol. Eng.* **137**, 871–883.

Peng, X., Dai, Q., Li, C., Yuan, Y. & Zhao, L. 2017 Effect of simulated rainfall intensities and underground pore fissure degrees on soil nutrient loss from slope farmlands in Karst Region. *Trans. Chinese Soc. Agric. Eng.* **33**, 131–140.

Poesen, J. & Lavee, H. 1994 Rock fragments in top soils: significance and processes. *Catena* **23**, 1–28.

Poesen, J., Ingelmosanchez, F. & Mucher, H. 1990 The hydrological response of soil surfaces to rainfall as affected by cover and position of rock fragments in the top layer. *Earth Surf. Process. Landforms* **15**, 653–671.

Poesen, J., Luna, E. D., Franca, A., Nachtergaele, J. & Govers, G. 1999 Concentrated flow erosion rates as affected by rock fragment cover and initial soil moisture content. *Catena* **36**, 315–329.

Prosdocimi, M., Cerd, A. & Tarolli, P. 2016 Soil water erosion on Mediterranean vineyards: a review. *Catena* **141**, 1–21.

Reddy, M. V. & Venkataiah, B. 1989 Influence of microarthropod abundance and climatic factors on weight loss and mineral nutrient contents of Eucalyptus leaf litter during decomposition. *Biol. Fertil. Soils* **8**, 319–324.

Renard, K. G., Foster, G. R., Weesies, G. A., McCool, D. K. & Yoder, D. C. 1997 Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). In: *US Department of Agriculture Handbook, No. 703*. US Government Printing Office, Washington, DC.

Robichaud, P. R., Wagenbrenner, J. W., Lewis, S. A., Ashmun, L. E., Brown, R. E. & Wohlgemuth, P. M. 2013 Post-fire mulching for runoff and erosion mitigation part II: effectiveness in reducing runoff and sediment yields from small catchments. *Catena* **105**, 93–111.

Ruiz-Colmenero, M., Bienes, R., Eldridge, D. J. & Marques, M. J. 2013 Vegetation cover reduces erosion and enhances soil

organic carbon in a vineyard in the central Spain. *Catena* **104**, 153–160.

Sadeghi, S. H. R., Gholami, L., Homaee, M. & Khaledi Darvishan, A. 2015 Reducing sediment concentration and soil loss using organic and inorganic amendments at plot scale. *Solid Earth Discuss.* **6**, 63–89.

Santos, J. C. N. D., Palacio, H. A. D. Q., Andrade, E. M. D., Meireles, A. C. M. & Araujo Neto, J. R. D. 2011 Runoff and soil and nutrient losses in semiarid uncultivated fields. *Rev. Ciên. Agronôm.* **42**, 45–48.

Schreiber, S. J. & Killingback, T. P. 2013 Spatial heterogeneity promotes coexistence of rock-paper-scissors metacommunities. *Theor. Popul. Biol.* **86**, 1–11.

Shuman, L. M. 2002 Phosphorus and nitrate nitrogen in runoff following fertilizer application to turfgrass. *J. Environ. Qual.* **31**, 1710–1715.

Steiner, M. & Smith, J. A. 2000 Reflectivity, rain rate, and kinetic energy flux relationships based on raindrop spectra. *J. Appl. Meteorol.* **39**, 1923–1940.

Sun, J., Yu, X., Li, H., Chang, Y., Wang, H., Tu, Z. & Liang, H. 2016 Simulated erosion using soils from vegetated slopes in the Jiufeng Mountains, China. *Catena* **136**, 128–134.

Tiemeyer, B., Kahle, P. & Lennartz, B. 2006 Nutrient losses from artificially drained catchments in North-Eastern Germany at different scales. *Agric. Water Manage.* **85**, 47–57.

Tiemeyer, B., Frings, J., Kahle, P., Kohne, S. & Lennartz, B. 2007 A comprehensive study of nutrient losses, soil properties and groundwater concentrations in a degraded peatland used as an intensive meadow – implications for re-wetting. *J. Hydrol.* **345**, 80–101.

Udawatta, R. P., Motavalli, P. P., Garrett, H. E. & Krstansky, J. J. 2006 Nitrogen losses in runoff from three adjacent agricultural watersheds with claypan soils. *Agric. Ecosyst. Environ.* **117**, 39–48.

Walton, R. S., Volker, R. E., Bristow, K. L. & Smettem, K. R. J. 2000 Experimental examination of solute transport by surface runoff from low-angle slopes. *J. Hydrol.* **233**, 19–36.

Wang, X., Li, Z., Cai, C., Shi, Z., Xu, Q., Fu, Z. & Guo, Z. 2012 Effects of rock fragment cover on hydrological response and soil loss from Regosols in a semi-humid environment in South-West China. *Geomorphology* **s151–152**, 234–242.

Wang, G., Wu, B., Zhang, L., Jiang, H. & Xu, Z. 2014a Role of soil erodibility in affecting available nitrogen and phosphorus losses under simulated rainfall. *J. Hydrol.* **514**, 180–191.

Wang, G. Z., Tian, Y. C., Qu, J. G., Xu, J. Z., Liu, Z. X. & Yan, D. F. 2014b The characteristics of runoff and sediment yield in different land use types in southwest mountains of Henan Province. *Adv. Mater. Res.* **1065–1069**, 3267–3271.

Warren, K., Eppes, M. C., Swami, S., Garbini, J. & Putkonen, J. 2013 Automated field detection of rock fracturing, microclimate, and diurnal rock temperature and strain fields. *Geosci. Instrum. Methods Data Syst. Discuss.* **3**, 371–406.

Withers, P. J. A., Ulen, B., Stamm, C. & Bechmann, M. 2003 Incidental phosphorus losses – are they significant and can they be predicted? *J. Plant Nutr. Soil Sci.* **166**, 459–468.

Wong, J. X. W., Colen, C. V. & Airoldi, L. 2015 Nutrient levels modify saltmarsh responses to increased inundation in different soil types. *Mar. Environ. Res.* **104**, 37–46.

Wudneh, A., Erkossa, T. & Devi, P. 2014 Sediment and nutrient lost by runoff from two watersheds, Digga district in Blue Nile basin, Ethiopia. *J. Environ. Sci. Technol.* **8**, 498–510.

Yan, Y., Xin, X., Xu, X., Wang, X., Yang, G., Yan, R. & Chen, B. 2013 Quantitative effects of wind erosion on the soil texture and soil nutrients under different vegetation coverage in a semiarid steppe of northern China. *Plant Soil* **369**, 585–598.

Yang, J., Zheng, H., Chen, X. & Shen, L. 2013 Effects of tillage practices on nutrient loss and soybean growth in red-soil slope farmland. *Int. Soil Water Conserv. Res.* **1**, 49–55.

Ye, Z., Liu, B., Fu, S. & Zeng, X. 2009 Review of research on enrichment ratio of nutrient in soil erosion process. *Sci. Soil Water Conserv.* **7**, 124–130.

Zavala, L. M., Jord N, A., Bellinfante, N. & Gil, J. 2010 Relationships between rock fragment cover and soil hydrological response in a Mediterranean environment. *Soil Sci. Plant Nutr.* **56**, 95–104.

Zhang, G. 2016 Characteristics of runoff nutrient loss and particle size distribution of eroded sediment under varied rainfall intensities. In: *4th International Conference on Machinery, Materials and Computing Technology, ICMMCT*, Atlantis Press, The Netherlands.

Zhang, G. H., Liu, G. B., Wang, G. L. & Wang, Y. X. 2011 Effects of vegetation cover and rainfall intensity on sediment-associated nitrogen and phosphorus losses and particle size composition on the Loess Plateau. *J. Soil Water Conserv.* **66**, 192–200.

Zhang, W., Li, H., Sun, D. & Zhou, L. 2012 A statistical assessment of the impact of agricultural land use intensity on regional surface water quality at multiple scales. *Int. J. Environ. Res. Public Health* **9**, 4170–4186.

Zhang, J. Q., Wang, H., Zhang, R. F., Zhou, D. M. & Zhang, A. J. 2014 Effect of rain intensity on nutrient loss of runoff in sloping gneiss area. *J. Soil Water Conserv.* **28**, 42–41.

Zhang, Y., Zhang, M., Niu, J., Li, H., Xiao, R., Zheng, H. & Bech, J. 2016 Rock fragments and soil hydrological processes: significance and progress. *Catena* **147**, 153–166.

Zhou, B. B., Shao, M. A. & Shao, H. B. 2009 Effects of rock fragments on water movement and solute transport in a Loess Plateau soil. *C. R. Géosci.* **341**, 462–472.