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

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. Poensen 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 (Poensen 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 (QY)Y-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. 2013). 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 × 0.50 × 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...
a slope of $10^\circ$ 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 50 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 $10^\circ$ slope were chosen because the rock fragment and lands with slopes between 5 and 15$^\circ$ are widely distributed in the mountain areas of North China (Ye et al. 2009; Han et al. 2012; Li & Liu 2013; Yang et al. 2015).

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

![Figure 1](https://iwaponline.com/hr/article-pdf/49/2/390/196268/nh0490390.pdf)

**Figure 1** | The simulated rainfall experimental facility.

<p>| Table 1 | Physical and chemical characteristics of the experimental soil |</p>
<table>
<thead>
<tr>
<th>Size distribution (%)</th>
<th></th>
<th>0.5–</th>
<th>0.02 mm</th>
<th>&lt; 0.02 mm</th>
<th>pH</th>
<th>TN (%)</th>
<th>TP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 0.5 mm</td>
<td>72.45 ± 1.67</td>
<td>25.35 ± 1.88</td>
<td>2.19 ± 0.23</td>
<td>6.7 ± 0.13</td>
<td>0.018 ± 0.012</td>
<td>0.0294 ± 0.016</td>
<td></td>
</tr>
<tr>
<td>0.5–</td>
<td>0.02 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 0.02 mm</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Total nitrogen (TN); total phosphorus (TP).
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 minimize 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 graduated 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 chromatography and the micro-Kjeldahl method, respectively. Total phosphorus (TP) in the runoff and sediments was measured by ion chromatography and HClO₄-H₂SO₄ 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 53% 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 regardless 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 treatments (30 mm·h⁻¹), the nutrient reduction ratios from 10 to 50% cover ranged from 17 to 41% for TN and 16 to 35% for TP. When rainfall intensity increased to 90 mm·h⁻¹, the protection 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, however, 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 fragments 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.
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).
Their coefficient of determination for a linear regression (R²) 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 5** Nutrient concentrations during a single rain at three intensities with three kinds 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.

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).
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 9–27 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,
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 2011).
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
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>
<thead>
<tr>
<th>Different treatments</th>
<th>Loss rate of sediment-associated TN (y)</th>
<th>Loss rate of sediment-associated TP (y)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equation</td>
<td>R²</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>y = 0.12x + 0.045</td>
<td>0.772**</td>
</tr>
<tr>
<td>10</td>
<td>y = 0.15x + 0.042</td>
<td>0.882**</td>
</tr>
<tr>
<td>20</td>
<td>y = 0.14x + 0.0029</td>
<td>0.698*</td>
</tr>
<tr>
<td>30</td>
<td>y = 0.10x + 0.014</td>
<td>0.183</td>
</tr>
<tr>
<td>Total</td>
<td>y = 0.16x – 0.0038</td>
<td>0.904**</td>
</tr>
<tr>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>y = 0.23x + 0.063</td>
<td>0.805**</td>
</tr>
<tr>
<td>10</td>
<td>y = 0.10x + 0.34</td>
<td>0.419*</td>
</tr>
<tr>
<td>20</td>
<td>y = 0.070x + 0.34</td>
<td>0.055</td>
</tr>
<tr>
<td>30</td>
<td>y = 0.10x + 0.22</td>
<td>0.280</td>
</tr>
<tr>
<td>Total</td>
<td>y = 0.24x – 0.0083</td>
<td>0.790*</td>
</tr>
<tr>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>y = 0.17x + 0.47</td>
<td>0.853**</td>
</tr>
<tr>
<td>10</td>
<td>y = 0.21x – 0.33</td>
<td>0.961**</td>
</tr>
<tr>
<td>20</td>
<td>y = 0.20x – 0.23</td>
<td>0.953**</td>
</tr>
<tr>
<td>30</td>
<td>y = 0.17x + 0.18</td>
<td>0.883**</td>
</tr>
<tr>
<td>Total</td>
<td>y = 0.19x + 0.0043</td>
<td>0.887**</td>
</tr>
</tbody>
</table>

*p < 0.05, **p < 0.01.
Total nitrogen (TN); Total phosphorus (TP).
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 (Tiemyer 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. 2013). 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

<table>
<thead>
<tr>
<th>Different treatments</th>
<th>Runoff-associated TP</th>
<th>Sediment-associated TP</th>
<th>Total TP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Loss amount (mg·m⁻²)</td>
<td>Loss ratio (%)</td>
<td>Reduction ratio (%)</td>
</tr>
<tr>
<td>Rainfall intensity (mm·h⁻¹)</td>
<td>Rock fragment cover (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0</td>
<td>2.88</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>2.41</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>1.88</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>2.05</td>
<td>11</td>
</tr>
<tr>
<td>60</td>
<td>0</td>
<td>5.09</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>5.08</td>
<td>5</td>
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<td></td>
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<td>4.44</td>
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<td></td>
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<td>4.25</td>
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<td>90</td>
<td>0</td>
<td>8.51</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>8.25</td>
<td>4</td>
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<tr>
<td></td>
<td>20</td>
<td>7.96</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>7.17</td>
<td>4</td>
</tr>
</tbody>
</table>

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

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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.

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**ACKNOWLEDGEMENTS**

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Ruiz-Colmenero, M., Bienes, R., Eldridge, D. J. & Marques, M. J. 2015 Vegetation cover reduces erosion and enhances soil...


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