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Hydraulic characteristics of varying slope gradients, rainfall intensities and litter cover on vegetated slopes

Jiamei Sun, Dengxing Fan, Xinxiao Yu and Hanzhi Li

ABSTRACT

Litter produced by forests performs crucial functions in rainfall interception and soil conservation, particularly in the condition that larger raindrops formed by canopy accelerate soil erosion. To explore how forest litter exerts runoff hydrological characteristics and sediment yield processes, experiments on forest covered (*Vitexnegundo* var. *heterophylla*) slopes were conducted under various combinations of rainfall intensities and slope gradients. The results showed that litter reduced runoff yield rate by 9–31% and reduced sediment yield rate by 65–90%, with mean runoff and sediment reductions of 18% and 76% for all treatments. On forest covered slopes, Reynolds number and runoff power generally increased with the increase in both rainfall intensity and slope gradient. Litter layer reduced Reynolds number and runoff power with 8–29% and 56–80%, respectively. Darcy–Weisbach resistance coefficient decreased by increasing rainfall intensity and slope gradient. Litter layer increased Darcy–Weisbach resistance coefficient by three to nine times. Relationships between sediment yield rate and Reynolds number, runoff power, Darcy–Weisbach resistance coefficient were described by exponential, linear, power functions, respectively. The critical runoff power values for slopes with and without litter were 0.0027 and 0.0010 m/s, respectively. Reynolds number was the best hydrodynamic parameter for dynamic erosion characterizing.

Key words | forest, hydraulic, litter, runoff, sediment

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INTRODUCTION

Soil erosion is severely depleting environmental resources and degrading land quality in many areas of China (Liu *et al.* 2013). Soil erosion has led to a direct decline in local agricultural productivity, and it also has impacts on nature, economy, society, and sustainable development (Cattan *et al.* 2009). To avoid the negative effects caused by soil erosion, the Chinese Government established soil and water conservation as a basic national policy from 1993 (Huo *et al.* 2015). A series of measures and projects were implemented to combat soil erosion (Shen *et al.* 2016). One of the most famous measures was the Three Norths Forest Shelterbelt program, started in 1978. This program aimed to improve forest coverage from 5% to 15% in Northeast, North, and Northwest China (Huang *et al.* 2013). Forest cover is an effective method that can help in controlling runoff and soil erosion processes (Marques *et al.* 2007; Mohammad & Adam 2010). As well, cover factor, slope gradient, rainfall intensity, rainfall duration, soil type, soil texture, etc., are also important factors in determining the degree of soil erosion (Hartanto *et al.* 2003). The Universal Soil Loss Equation (USLE) places all the factors into five dominate factors: rainfall pattern, soil type, topography, crop system, and management practices (Stone & Hilborn 2000).

During the soil erosion process, runoff is the main driver of sediment detachment and transportation (Kinnell 2005).

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Cover can reduce the runoff amount and slow down runoff velocity (Ellis *et al.* 2006), so that the soil transportation capacity of runoff is weakened. Simultaneously, cover can protect the soil surface from break up by raindrops (Van Dijk *et al.* 2002). Generally, cover has been the most widely used measure in soil and water conservation (Nanko *et al.* 2008). More importantly, dead leaves or branches produced by forests can also protect the soil surface. Litter layer is an important component in ecosystems, helping to limit soil moisture loss and protect the soil surface (Bristow *et al.* 1986; Ikiensinma & Manoj 2013).

Slope gradient and rainfall intensity are also dominant factors in influencing the erosion process (Pan & Shangguan 2006). Previous studies showed that runoff generate time advanced if slope gradient increased (Coblentz & Muck 2012). Slope gradient is a main factor in change infiltration and runoff velocity characteristics. It has a positive relationship with erosion rate (Chamizo *et al.* 2012). Rainfall intensity is the key factor for determining runoff amount (Cerdan *et al.* 2002). Rainfall intensity increase not only leads to runoff amount increase, but also leads to number and raindrops' kinetic energy increase which aggravates splash erosion (Keim *et al.* 2006). Cover has the effect of weakening raindrops' kinetic energy and protecting the soil surface from detaching directly (Van Dijk *et al.* 2002). To quantify the effects of these factors and their combinations to erosion, experiments under different conditions were performed in this study. *Vitexnegundo* var. *heterophylla* (VN) studied in this research is a common forest type in North China. It has been commonly planted, and can produce around 9.3 t litter per ha (Zheng *et al.* 1993). The effects of original litter from VN forests to soil erosion were also explored. To date, numerous litter researches have been conducted on litter's capacity of intercepting and rainwater storage (Tobon-Marin *et al.* 2000). Relatively little information is available on how the litter layer influenced runoff hydrodynamic characteristics, such as runoff velocity, depth, resistance, etc., and their relationships with erosion rate (Abrahams *et al.* 1986; Brown 2003; An *et al.* 2012). Therefore, the original VN litter was collected to explore the erosion process of VN litter covered slopes in comparison with slopes only with VN cover. Simulated rainfall is the most convenient method to perform experiments in various conditions. It was initially used in soil erosion research in the 1930s (Martínez-Murillo *et al.* 2013). Nowadays, with technical developments, it is widely used in scientific research, due to the experimental conditions being easy to control, so that a variety of conditions can be simulated within a short time (Coblentz & Muck 2012).

With the rainfall simulation method, erosion processes under various experimental conditions were investigated, mainly focused on the erosion and hydraulic property responses of cover, rainfall intensity, and slope gradient. The objectives of this study were to: (1) evaluate the effects of litter layer on runoff and sediment yield rates; (2) explore runoff characteristics by quantifying Reynolds number, runoff power, and resistance coefficient under litter covered slopes; (3) quantify the relationships between hydraulic parameters and sediment yield rate. This research provided data for slope erosion prediction and quantitatively emphasized the importance of litter layer to ecosystem.

MATERIALS AND METHODS

Site description

The experiments were conducted at the Key Laboratory of Soil & Water Conservation and Desertification Combating, located in Jiufeng National Forestry Mountains (40°04′N, 116°06′E, 145 m a.s.l.), Beijing, China. The laboratory belongs to Beijing Forestry University.

Rainfall simulator

All experiments were performed using the rainfall simulator inside the laboratory. Its rainfall area was 256 m^2 and separated into four zones. Each zone was 8 m long and 8 m wide, and the four rainfall zones could be controlled either together or separately. The rainfall simulator was made up of three main components: adjustable soil boxes, water sprinkler system, and control system. The schematic diagram is shown in Figure 1.

The soil boxes were 2 m long, 0.5 m wide, and 0.4 m deep, and were adjustable to gradients of 0–45°. There were evenly distributed holes in the bottom of soil boxes for rainwater seepage. The water sprinkler system included cellar, pump, pipes, and sprinklers. The cellar was used to store

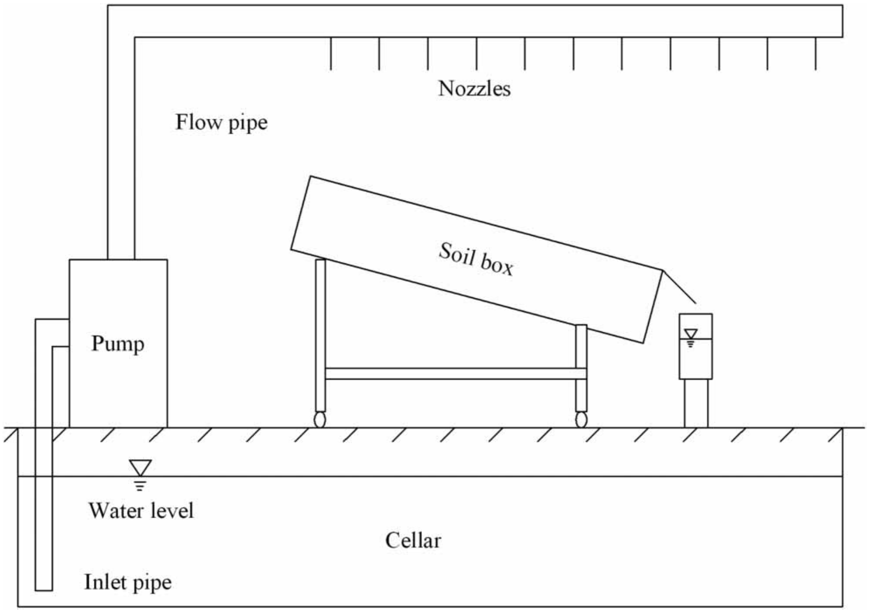

Figure 1 | The schematic diagram of the rainfall simulator.

and supply water. There was a pump to transport water from the cellar to sprinkler nozzles through pipes (Figure 1). Sprinkler nozzles were 12 m high. The technical parameters of the rainfall simulator are presented in Table 1. Rainfall was conducted in a completely indoor environment to minimize the influence caused by wind. Water used in the rainfall simulation was drinking water from Beijing Waterworks Group, which met the requirements of drinking water standards. Rainfall uniformity was around 85%, mean raindrop diameter was 0.9334 mm, 1.0397 mm, and 1.1135 mm when rainfall intensity was 30 mm/h, 60 mm/h, and 90 mm/h, respectively. The QYJY-503C rainfall simulator could simulate the natural rainfall well (Huo *et al.* 2015).

Table 1 | Technical details of the rain simulator

Technical details	Value
Maximum rain area (m)	16 × 16
Maximum rain height (m)	12
Rainfall intensity (mm/h)	0–300
Coefficient of uniformity (%)	>85
Raindrop diameter (mm)	1.47 ± 0.64
Raindrop velocity (m/s^2)	4.78 ± 0.25
Rain kinetic energy ($J/m^2/s$)	0.2193 ± 0.12

Experimental design

Cinnamon soil (Chinese Soil Taxonomy) was used in this research. It is the most common soil in rocky mountainous areas of North China. It corresponds to Haplustalfs in the Soil Taxonomy of America. Haplustalfs have a lithic contact within 50 cm of the mineral soil surface. They are cinnamon color and gradually become lighter with increasing soil depth. The main properties of the experimental soil are shown in Table 2. Soil particles were passed through a

Table 2 | Main properties of the experimental soil

Particle-size distribution (%)						
<2 μm	2–50 μm	>50 μm	Bulk density (g/cm^3)	pH	Total N content (%)	Total P content (%)
13.8	56.38	27.36	1.34	6.7 ± 0.13	0.018 ± 0.012	0.029 ± 0.016

10 mm sieve to remove the stones and trash, then air-dried to an initial water content of approximately 10%. Soil materials were packed into boxes at the soil bulk density of 1.34 g/cm^3 (natural soil bulk density is between 1.3 and 1.4 g/cm^3). They were packed into the boxes in layers, and each layer was 10 cm. Before adding the next layer, the last soil layer was raked lightly to reduce any discontinuities between the layers. After packing, the boxes were left for six months to allow natural compaction, which could render soil properties similar to natural conditions.

Vitexnegundo var. *heterophylla* (VN) saplings were collected from a natural forest and transplanted into the soil boxes. Simultaneously, the original litter layer was also collected, including decomposed, partly decomposed, and undisturbed litter. Therefore, two cover treatments were obtained: VN alone and VN with original litter, combined with rainfall intensities of 30, 60, and 90 mm/h and slope gradients of 10, 15, and 20° (Table 3). One bare soil box served as a blank control. Each cover type had two replicates. Soil boxes were used multiple times for the various combinations of rainfall intensity and slope gradient. To minimize the influence of soil loss to the erosion process, the experiments were conducted once a month to ensure complete soil recovery under the premise that there was no obvious rill erosion (Huang *et al.* 2013). Mean growth parameters of four slopes were measured and shown in Table 4. The leaf area index (LAI) of VN was measured using a LAI-2200 Plant Canopy Analyzer (LI-COR Biosciences).

Table 3 | Experimental combinations of cover type, rainfall intensity, and slope gradient

Slopes with litter		Slopes without litter	
Slope gradient (°)	**Rainfall intensity (mm/h)**	**Slope gradient (°)**	**Rainfall intensity (mm/h)**
10	30	10	30
10	60	10	60
10	90	10	90
15	30	15	30
15	60	15	60
15	90	15	90
20	30	20	30
20	60	20	60
20	90	20	90

Table 4 | Growth parameters of the *Vitexnegundo* var. *heterophylla* planted in the soil boxes

Box number	Basal diameter (cm)	Tree height (m)	Crown width (m)	LAI
1	1.31	1.83	1.1 × 1.2	0.762
2	1.35	1.79	1.2 × 0.9	0.782
3	1.38	1.82	1.3 × 0.9	0.763
4	1.32	1.82	1.1 × 1.1	0.742

Experimental procedure

Each rainfall event lasted for 60 minutes from runoff generation. In the first 10 minutes, samples were collected every 2 minutes, and then samples were collected every 5 minutes. Runoff volume was measured by cylinders. After volume measurement, runoff samples with sediment were dried in an oven at 105°C for 24 hours to measure the sediment weight. Runoff velocity was measured during the rainfall simulation by adding $KMnO_4$ coloration to the top of the soil box and recording the required time for the dye to reach the bottom. It was measured every 5 minutes after runoff generation at five parallel locations along the slope to obtain the mean velocity.

Data processing method

Runoff was too thin to measure the depth directly. Thus, runoff depth was calculated by unit width flux and runoff velocity. In light of the fact there was no obvious horizontal and vertical runoff concentration except areas around VN trunk, we measured the actual runoff width along the slope repeatedly, and took the mean value as runoff cross-sectional width. Assuming that runoff was distributed along the slope uniformly, depth was calculated by Equation (1) (Sun *et al.* 2015):

$$h = \frac{q}{V} = \frac{Q}{(V \cdot B \cdot t)} \tag{1}$$

where h is runoff depth (m), q is unit width flux (m^3/(min·m)), Q is the runoff amount in the sampling interval (m^3), t is the runoff sampling interval (min), V is the mean runoff velocity (m/min), and B is the runoff cross-sectional width (m).

Reynolds number (*Re*) represented runoff regime condition by the ratio of runoff inertial force to viscous force. *Re* is calculated by Equation (2) (Sun *et al.* 2015):

$$Re = \frac{Vh}{v} \quad (2)$$

where v is the viscosity coefficient of water movement ($7.0 \times 10^{-5}\ m^2/s$).

Runoff power (ω) is runoff ability to transport sediment along an open channel of length x and height y. Runoff power is calculated by Equation (3) (Wu *et al.* 2014):

$$\omega = \frac{dy}{dt} = \frac{dx}{dt} \cdot \frac{dy}{dx} = V \cdot S \quad (3)$$

where ω is runoff power (m/s), y is height (m), t is time (s), x is horizontal distance (m), V is mean runoff velocity (m/s), and S is the hydraulic gradient.

The Darcy–Weisbach resistance coefficient (f) is calculated by Equation (4) (Wu *et al.* 2014):

$$f = \frac{8gRJ}{V^2} \quad (4)$$

where g is gravitational acceleration (m/s^2), R is the hydraulic radius (m), V is the mean runoff velocity (m/s), and J is the hydraulic gradient.

Statistical analysis

Tests for significant differences between slopes with and without litter under different treatments were evaluated by the analysis of variance (ANOVA) method, the SPSS v.17.0 (SPSS Inc., Chicago, IL, USA) was used to perform the ANOVA method. The significance level was set at $\alpha < 0.05$ (significant) and $\alpha < 0.01$ (very significant).

RESULTS AND DISCUSSION

Variation in runoff yield

Runoff yield rate ranged from 0.5 to 1.6 $L/min/m^2$ in VN single covered slopes, and mean runoff yield rate was 1.0 $L/min/m^2$ (Figure 2(a)). In VN with litter covered slopes, runoff yield rate ranged from 0.4 to 1.3 $L/min/m^2$, with mean runoff yield rate of 0.8 $L/min/m^2$ (Figure 2(a)). Litter had a significant effect on runoff generation ($\alpha = 7.13 \times 10^{-5}$). Litter of VN reduced runoff yield rate by 9–31% (Table 5). Litter had the largest runoff reduction when rainfall intensity was 90 mm/h and slope gradient was 20°, and the least runoff reduction when rainfall intensity was 60 mm/h and slope gradient was 15°.

Litter reduced sediment concentration in runoff by 56–85% (Table 5). This was mainly caused by the transportation capacity of runoff. Runoff was the driving force for soil particle transportation (Stone & Hilborn 2000). With the decrease of runoff yield rate, the ability of runoff to transport sediment became weaker (Hartanto *et al.* 2003). VN and litter both impeded overland runoff and increased infiltration rate, thus causing runoff to be reduced. Simultaneously, litter cover consumed raindrops' kinetic energy so as to prevent soil detachment (Coblentz & Muck 2012); the root of VN improved the soil infiltration rate (Pan & Shangguan 2006).

Variation in sediment yield

Sediment yield rates on slopes with litter layer were significantly lower than those on slopes without litter layer ($\alpha = 0.002$) (Figure 2(b)). Our results indicated that litter layer reduced sediment yield rate by 65–90%, while the mean sediment yield rate reduction was 76% (Table 5). In the treatment where rainfall intensity was 30 mm/h and slope gradient was 10°, sediment yield rate reduction was up to 90%. Litter cover reduced soil erosion by intercepting rainwater, protecting soil surface, and reducing splash erosion (Huang *et al.* 2013). Soil particles were detached by multiple processes, mainly by the hydraulic forces of raindrops (Polyakov & Nearing 2003). Litter protected soil surface significantly, particularly in the condition that larger raindrops formed by canopy accelerated soil erosion (Wirtz *et al.* 2012). In addition to litter, other covers such as wheat-straw mulch, temporary grass materials have also been applied widely to reduce soil erosion (Fullen 1998; Zhang *et al.* 2009).

Sediment yield rate generally increased with the increase in both rainfall intensity and slope gradient (Figure 2(b)). When rainfall intensity increased from 30 to 60 mm/h, sediment yield rates in slopes with litter layer increased by 1.4, 2.1, and 1.1 $g/min/m^2$ for slope gradients of 10°, 15°, and 20°, respectively. On slopes without litter,

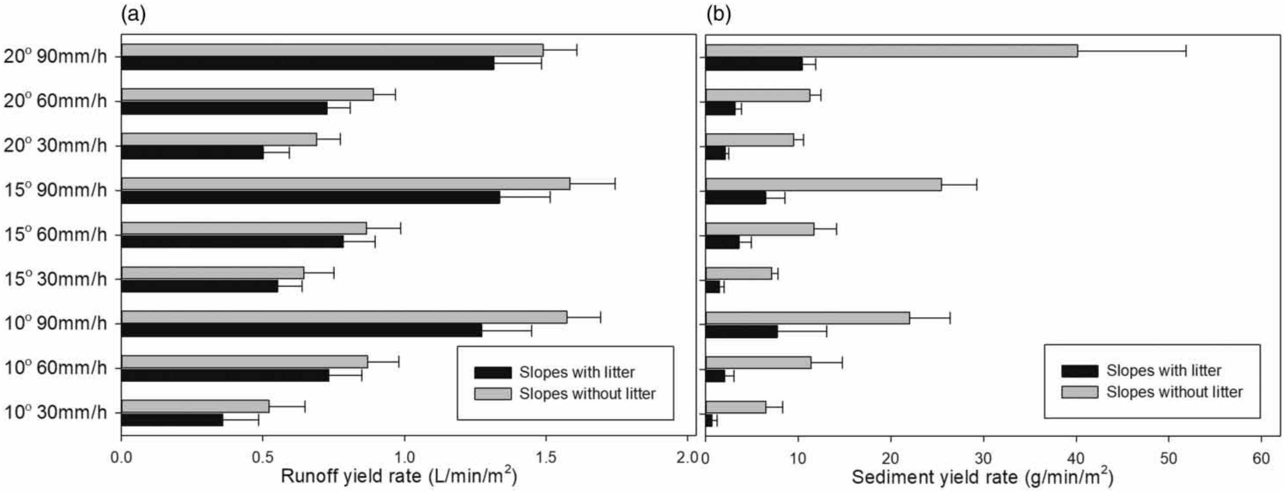

Figure 2 | Runoff and sediment yield rates in different experiment conditions. Error bars represent standard deviations for each indicator.

sediment yield rates increased by 4.9, 4.6, and 1.7 $g/min/m^2$ for slope gradients of 10°, 15°, and 20°, respectively. These results implied that both litter and slope gradient could reduce sediment yield rate. Previous studies reported that sediment yield rate increased with increasing rainfall intensity and slope gradient. Rainfall intensity had greater influence on sediment yield rate than slope gradient did (Huang *et al.* 2013). Sediment yield rate increased substantially with rainfall intensity increase due to the increased raindrops' number and kinetic energy, which caused heavier disturbance to soil surface and greater splash erosion (Nanko *et al.* 2008). In addition to this, heavier rainfall intensity also increased runoff velocity and amount (Savat 1980). Faster runoff velocity improved runoff shear stress and led to greater disturbance to the soil surface (Polyakov & Nearing 2003). Slope gradient also impacted on the runoff velocity. Increasing slope gradient increased runoff velocity and strengthened the scouring force on the soil surface (Emmett 1970; Marques *et al.* 2007). Additionally, slope gradient increase led to the increase of soil particle gravity along the slope from the mechanical perspective. Therefore, soil particles were more easy to be carried out of the slope by runoff (Shen *et al.* 2016).

Table 5 | Runoff yield rate, sediment concentration, and sediment yield rate reductions caused by litter layer in different experimental conditions

Experimental conditions	Runoff yield rate reduction (%)	Sediment concentration reduction (%)	Sediment yield rate reduction (%)
20° 90 mm/h	31	85	90
20° 60 mm/h	16	79	82
20° 30 mm/h	19	56	65
15° 90 mm/h	14	75	79
15° 60 mm/h	9	66	69
15° 30 mm/h	16	70	74
10° 90 mm/h	27	69	77
10° 60 mm/h	18	65	71
10° 30 mm/h	12	71	74

Sediment yield rate did not uniformly increase with increasing rainfall intensity and slope gradient (Huang *et al.* 2013). This was due to there being critical values for rainfall intensity and slope gradient in influencing erosion (Shen *et al.* 2016). After they reached their critical values, erosion rate began to slow down (Léonard & Richard 2004). In our study, rainfall intensity had greater influence on sediment yield than slope gradient did. This finding was consistent with studies from Huang *et al.* (2013) and Berger *et al.* (2010).

Reynolds number

Litter decreased *Re* by 8–29% in comparison to slopes without litter ($\alpha = 9.76 \times 10^{-5}$) (Figure 3). Among all the treatments, litter had the largest impact on *Re* when rainfall intensity was 30 mm/h and slope gradient was 10°, mean reduction was 29%. Litter had the least impact on *Re* when rainfall

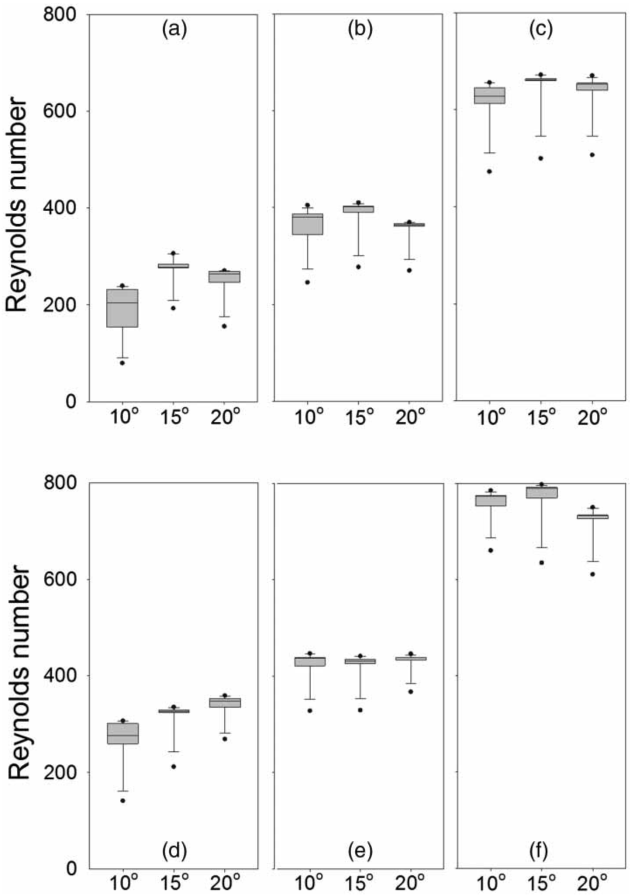

Figure 3 | Reynolds numbers under various experimental conditions: (a), (b), and (c) indicate 30, 60, and 90 mm/h rainfall intensities on slopes with litter, respectively; (d), (e), and (f) indicate 30, 60, and 90 mm/h rainfall intensities of slopes without litter, respectively. The horizontal line in each box indicate the median value, the bottom and top indicate the lower and upper quartile value, respectively, and 5% and 95% are shown by dots.

intensity was 60 mm/h and slope gradient was 15°, mean reduction was 8%. *Re* generally increased with the increase in both rainfall intensity and slope gradient (Figure 3). On the slope at 10°, when rainfall intensity increased from 30 to 60 mm/h and then from 60 to 90 mm/h, *Re* increased by 59–79% on slopes without litter and by 62–70% on slopes with litter. On the slope at 15°, *Re* increased by 33–82% on slopes without litter and by 42–68% on slopes with litter. On the slope at 20°, *Re* increased by 27–68% on slopes without litter and by 42–80% on slopes with litter.

Re is the ratio of inertial forces to viscous forces that describes flow conditions. Hydraulic theory states that runoff is turbulent flow when *Re* is greater than 500, runoff is laminar flow when *Re* is less than 500, and excessive flow when *Re* is around 500 (Reichert & Norton 2013). *Re* is a dimensionless number in fluid mechanics which represents flow regime conditions. Based on this, *Re* is an important parameter for measuring the soil disturbance caused by runoff. When rainfall intensities were 30 and 60 mm/h, *Re* values were less than 500, runoff was laminar flow. *Re* values were greater than 500 when rainfall intensity was 90 mm/h, runoff was turbulent flow. Larger *Re* value representing inertial force is stronger than viscous force, and runoff led to greater soil erosion (Shen *et al.* 2016).

Analysis on hydraulic parameters of thin sheet flow in erosion process is necessary to characterize soil erosion quantitatively (Wirtz *et al.* 2012). Rainfall intensity increase caused greater disturbance to the soil surface (Woo & Brater 1961; Léonard & Richard 2004). Rainfall intensity and slope gradient affected *Re* value significantly. *Re* increased as rainfall intensity increased (Figure 3). This indicated that the increase rainfall intensity increased both *Re* and soil disturbance degree caused by runoff, thereby increasing the sediment yield rate. Shen *et al.* (2016) reported similar results. When rainfall intensity increased to 90 mm/h, mean *Re* values on 10, 15, and 20° gradient slopes without litter were 760, 771, and 722, respectively; while on slopes with litter, mean *Re* values were 618, 649, and 639, respectively. Litter reduced *Re* significantly, however, due to the heavy rainfall intensity, runoff was still turbulent flow. Slope gradient increase also increased *Re* values. An *Re* increment of 10–15° was greater than that of 15–20°, which was due to the critical slope gradient (Pan & Shangguan 2006). When the slope gradient exceeded the critical gradient, the influence of slope gradient increment caused to *Re* value would not be sensitive. Huang *et al.* (2013) confirmed the critical slope gradient in the Loess Plateau.

Runoff power

Runoff power (ω) ranged from 0.002 to 0.015 m/s on slopes with litter and from 0.010 to 0.043 m/s on slopes without litter (Figure 4). Litter reduced runoff power by 56–80% in comparison to the slopes without litter ($\alpha = 5.63 \times 10^{-5}$). Litter had the largest runoff power reduction when slope gradient was 10° and rainfall intensity was 30 mm/h. The reduction caused by litter was the least when rainfall intensity was 90 mm/h and slope gradient was 20°.

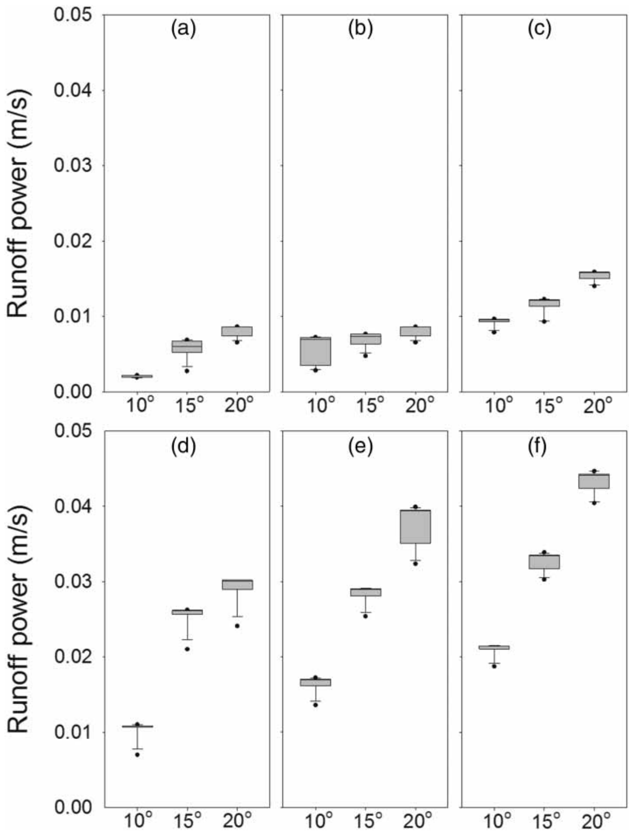

Figure 4 | Runoff power under various experimental conditions (T test; $\alpha = 0.05$): (a), (b), and (c) indicate 30, 60, and 90 mm/h rainfall intensities on slopes with litter, respectively; (d), (e), and (f) indicate 30, 60, and 90 mm/h rainfall intensities on slopes without litter, respectively. The horizontal line in each box indicates the median value, the bottom and top indicate the lower and upper quartile value, respectively, and 5% and 95% are shown by dots.

When rainfall intensity increased from 30 to 60 mm/h and then from 60 to 90 mm/h, ω increased from 0.005 to 0.007 m/s and then from 0.007 to 0.012 m/s on the slopes with litter. On slopes without litter, ω increased from 0.022 to 0.028 m/s (30 to 60 mm/h) and then from 0.028 to 0.032 m/s (60 to 90 mm/h). When the slope gradient increased from 10 to 15° and then from 15 to 20°, ω increased from 0.006 to 0.008 m/s and then from 0.008 to 0.011 m/s on the slopes with litter. On the slopes without litter, ω increased from 0.016 to 0.029 m/s (10 to 15°) and then from 0.029 to 0.037 m/s (15 to 20°).

In the conventional sediment-transport equation, runoff power was calculated from the runoff volume and velocity, slope gradient, and shear force, but these parameters do not represent sediment transport on a hillslope (Bagnold 1966). Yang (1973) therefore proposed the theory of unit runoff power, defined as the product of runoff velocity and slope gradient. Our study was based on this theory and supported the application of the theory to the hydrodynamic calculation of soil erosion. Soil erosion process is the runoff energy dissipation process (Van Dijk *et al.* 2002). Runoff power is the time rate of energy supplied by runoff to the soil surface (Yang 1973). Runoff erodes soil particles by dissipating energy when flowing through the slope (Cerdan *et al.* 2002). Thus, greater ω led to greater erosion. In this research, ω increased with both increasing rainfall intensity and slope gradient (Figure 4), and increasing runoff power implied larger capacity of sediment transportation. Litter decreased ω significantly making the runoff contain less energy, and thereby reducing the sediment yield rate.

Darcy–Weisbach resistance coefficient

Darcy–Weisbach resistance coefficient (f) varied from 0.27 to 1.54 on slopes without litter and 1.18 to 6.47 on slopes with litter (Figure 5). Under various experimental conditions, litter increased f by three to nine times ($\alpha = 3.12 \times 10^{-4}$).

f decreased with the increasing rainfall intensity and slope gradient (Figure 5). When rainfall intensity was 30 mm/h, f decreased from 6.5 to 2.5 on slopes without litter as slope gradient increased from 10 to 20°. On the slopes with litter, f decreased from 1.5 to 0.6 in the same situation. When rainfall intensity increased to 60 mm/h, f decreased from 4.7 to 2.2 on slopes without litter as slope gradient increased from 10 to 20°, and on the slopes with litter, f decreased from 1.1 to 0.5 with litter. For the 90 mm/h rainfall intensity, f did not differ significantly among the three slope gradients. When the slope gradient increased from 10 to 20°, f decreased from 2.7 to 1.2 and 0.9 to 0.3 on slopes without and with litter, respectively. However, f increased with increasing slope gradient and significantly differed among all the experimental slope gradients.

f calculation equation is a phenomenological equation in fluid dynamics which is related to the head loss or pressure loss (Manning & Thompson 1995). The equation was named after Henry Darcy and Julius Weisbach (Brown 2003). A description of previous studies involving the resistance coefficient on agricultural slopes was provided by Engman (1986), who found that the hydraulic resistance coefficient was developed from runoff plot data

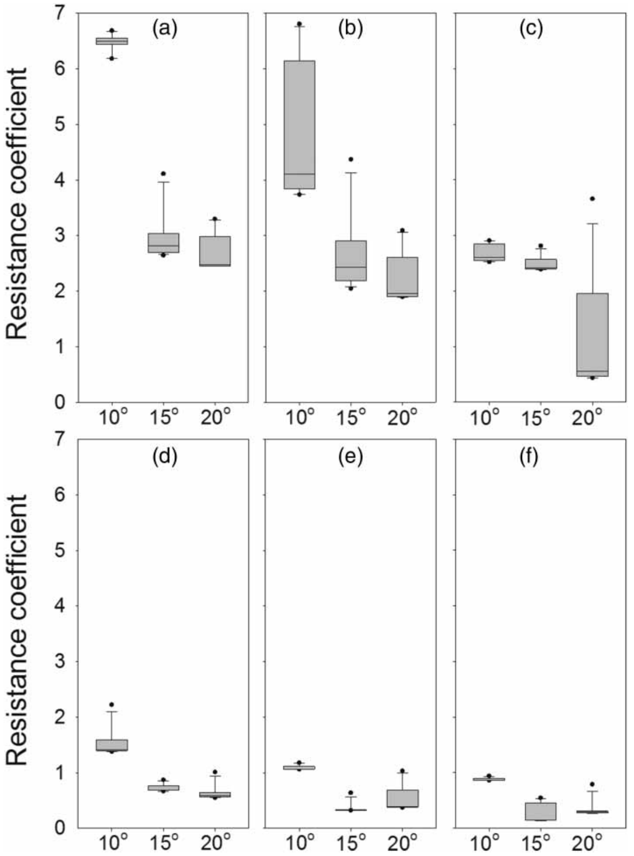

Figure 5 | Resistance coefficient under different experiment controls (T test; $\alpha = 0.05$): (a), (b), and (c) indicate 30, 60, and 90 mm/h rainfall intensities on slopes with litter, respectively; (d), (e), and (f) indicate 30, 60, and 90 mm/h rainfall intensities of slopes without litter, respectively. The horizontal line in each box indicates the median value, the bottom and top indicate the lower and upper quartile value, respectively, and 5% and 95% are shown by dots.

collected in erosion studies. Friction factor was presented in a tabular format with the description of various surfaces and land uses, which reflect erosion amount in a scientific way (Savat 1980). Laboratory measurements of roughness coefficients on covered surfaces were made by Woo & Brater (1961), Emmett (1970), and Savat (1980). Similar tests were performed under field conditions on natural landscapes by Abrahams *et al.* (1986). In these studies, f decreased with increasing slope gradients, while sediment yield rates decreased as f increased. Among all of the hydraulic parameters, f is the best variable parameter for describing resistance of runoff (Reichert & Norton 2013).

Relationships

The relationships between sediment yield rate and these hydrodynamic parameters (Re, ω, and f) were well described by linear, exponential, and power functions (Table 6). Re and runoff power had positive correlation relationships with sediment yield rate, while f had a negative correlation relationship with sediment yield rate. Therefore, sediment yield rate increased as Re and runoff power increased, and decreased as f increased. The critical runoff power could be obtained when no sediment was transported, i.e., $y = 0$. The critical runoff power values on slopes with and without litter were 0.0027 and 0.0010 m/s, respectively.

Soil particle detachment and transportation by runoff are energy-intensive processes (An *et al.* 2012). Therefore, runoff dynamic mechanisms that influence sediment yield rate are important to get a clear understanding of erosion (Shen *et al.* 2016). Rainfall intensity and slope gradient are two dominate factors that influence the sediment yield rate; rainfall intensity has greater influence than slope gradient (Sun *et al.* 2015). Results in this study indicated that the impacts of rainfall intensity on sediment yield rate and hydrodynamic characteristics of erosion were greater than those of slope gradient. The relationships established between sediment yield rate and the hydrodynamic parameters indicated that runoff hydraulic research was suitable for characterizing the mechanisms of soil erosion.

Table 6 | Relationships between sediment yield rate and hydrodynamic parameters

Surface feature	Hydrodynamic parameter	Function	R^2
Slopes with litter	Reynolds number	$y = 0.5\ e^{0.0046 \cdot Re}$	0.88
	Runoff power	$y = 783.7\omega - 2.15$	0.83
	Resistance coefficient	$y = 13.0\ f^{-1.472}$	0.77
Slopes without litter	Reynolds number	$y = 3.4\ e^{0.0028 \cdot Re}$	0.87
	Runoff power	$y = 626.1\omega - 0.61$	0.78
	Resistance coefficient	$y = 5.59\ f^{-0.869}$	0.86

y, sediment yield rate; *Re*, Reynolds number; ω, runoff power; *f*, Darcy–Weisbach resistance coefficient.

Re, *ω*, and *f* were sufficiently sensitive to estimate the hydraulic characteristics of runoff. *Re* was the best hydrodynamic parameter (Reichert & Norton 2013) for characterizing erosion.

This research was processed with the method of rainfall simulation. Simulation experiments were effective for evaluating the effects of various parameters on soil erosion on small scales. It was an effective method to show the reaction of soil in various experimental conditions. However, data in simulation experiment for the sediment yield rates and associated processes were not easily extrapolated to field scale directly (Coblentz & Muck 2012). Artificial rain was designed to simulate natural rain in terms of identical rainfall intensity, rainfall uniformity, raindrop diameter and velocity. However, due to properties of rainfall changing, simulated rain cannot be the same as natural rain completely. In this condition, it was necessary to find the relationship between simulated rain and natural rain. In this study, using the QYJY-503C rainfall simulator, a good linear relationship between simulated and measured rainfall kinetic energy was reported (Huo *et al.* 2015). It could simulate natural rainfall well and reflect the results to soil and water conservation measurement technology.

CONCLUSION

Simulated rainfall was used to process the erosion experiments on forest covered slopes in this study. Erosion processes on *Vitexnegundo* var. *heterophylla* (VN) covered slopes were performed under rainfall intensities of 30, 60, and 90 mm/h combined with gradients of 10, 15, and 20°. In North China, VN is a common shrub type distributed in mountainous areas. Litter of VN also had significant impacts on the soil erosion. The results showed that litter reduced runoff yield rate by 9–31% and reduced sediment yield rate by 65–90%. Sediment yield rates in VN covered slopes generally increased with increasing rainfall intensity and slope gradient. Litter reduced *Re* by 8–29%. Simultaneously, *Re* increased with increasing rainfall intensity and slope gradient. Runoff was turbulent flow when rainfall intensity was 90 mm/h, and laminar flow when rainfall intensities were 30 and 60 mm/h. Litter reduced runoff power by 56–80%, and runoff power increased as rainfall intensity and slope gradient increased. Litter increased *f* by three to nine times in comparison to slopes without litter. Relationships between *Re*, runoff power, *f*, and sediment yield rate were described by exponential, linear, and power functions, respectively. The critical runoff power values on VN slopes with and without litter were 0.0027 and 0.0010 m/s, respectively. *Re* and runoff power had positive correlation relationships with sediment yield rate, while *f* had a negative correlation relationship with sediment yield rate.

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