

Effects of rainfall intensity and slope on interception and precipitation partitioning by forest litter layer

Jie Du^{a,b}, Jianzhi Niu^{a,b,*}, Zhaoliang Gao^{c,**}, Xiongwen Chen^d, Linus Zhang^e, Xiang Li^{a,f}, Natalie S. van Doorn^g, Ziteng Luo^{a,b}, Zhijun Zhu^a

^a School of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China

^b Beijing Collaborative Innovation Center for Eco-environmental Improvement with Forestry and Fruit Trees, Beijing 102206, China

^c Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China

^d Department of Biological and Environmental Sciences, Alabama A & M University, Normal, AL 35762, USA

^e Department of Water Resources Engineering, Lund University, Lund 233 62, Sweden

^f China National Forestry Economics and Development Research Center, National Forestry and Grassland Administration, Beijing 100714, China

^g USDA Forest Service, Pacific Southwest Research Station, Albany, CA 94710, USA

ARTICLE INFO

Keywords:

Forest litter
Interception
Precipitation partitioning
Rainfall intensity
Slope gradients

ABSTRACT

Rainfall interception and other hydrologic processes affected by the forest litter layer are usually related to litter characteristics and rainfall conditions, with limited studies that consider the influence of slope. To simulate the hydrological functions of the litter layer at different slope gradients, artificial rainfall experiments were conducted at four rainfall intensities (from 30 to 120 mm hr⁻¹) in horizontal and inclined trays (with the slope of 0°, 10°, 20° and 30°) with litter of *Pinus tabulaeformis* or *Quercus variabilis*. The results indicated that (1) the dynamic process of litter interception had 3 phases: a rapid intercepted phase within the first 5 min, a moderate intercepted phase and a post-rainfall drainage phase; (2) the maximum interception storage (C_{max}) and the minimum interception storage (C_{min}) of *Q. variabilis* were larger than those of *P. tabulaeformis*; (3) C_{max} and C_{min} were correlated with slope for both types of litter, whereas only C_{max} was correlated with rainfall intensity; and (4) lateral flow amount significantly increased with both slope gradient and rainfall intensity only for *Quercus variabilis*, whereas drainage volume showed significant correlation with rainfall intensity. Moreover, the ratio of lateral runoff and drainage was affected by slope gradient whereas percentage of litter interception had a good relationship with rainfall intensity, rather than slope, with litter interception and drainage contributing the smallest and the largest proportions, respectively. Overall, the results demonstrate the effect of rainfall and slope factors on hydrological processes in the forest litter layer.

1. Introduction

Forest litter, consisting of dead leaves, twigs, fruits and other fragmented organic materials (Sayer, 2006), has important hydrological and ecological effects on forest system. The forest litter layer can affect root water uptake and soil moisture evaporation and drainage to mineral soil (Benyon and Doody, 2015; Marin et al., 2000; Ogée and Brunet, 2002; Park et al., 2010). Furthermore, many studies have reported the litter layer functions in regulating runoff and protecting soil erosion (Kimoto et al., 2002; Liu et al., 2017; Miyata et al., 2009; J.M. Sun et al., 2016; L. Sun et al., 2016).

Litter interception is an important portion of rainfall partitioning, accounting for 2–70% of gross precipitation because of differences in

temporal scales, tree species and rainfall conditions (Brye et al., 2000; Helvey and Patric, 1965; Sun et al., 2014). The immersion test is a common method to reflect water conservation capacity of forest litter, but its condition of sufficient water supply greatly exceeds that of natural rainfall. Therefore, many authors have focused attention on simulated rainfall experiments to explore the hydrological processes of forest litter (Li et al., 2017; Putuhen and Cordery, 1996; Sato et al., 2004). Artificial rainfall tests have been conducted to investigate the characteristics of litter interception and potential influencing factors such as rainfall intensity, rainfall duration, litter type, litter mass and litter thickness, among others (Guevaraescobar et al., 2007; Marin et al., 2000; Pitman, 1989). However, most studies place the litter layer horizontally and few simulate the hydrological processes in sloping

* Correspondence to: J. Niu, School of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China.

** Corresponding author.

E-mail addresses: nexk@bjfu.edu.cn (J. Niu), gzl@ms.iswc.ac.cn (Z. Gao).

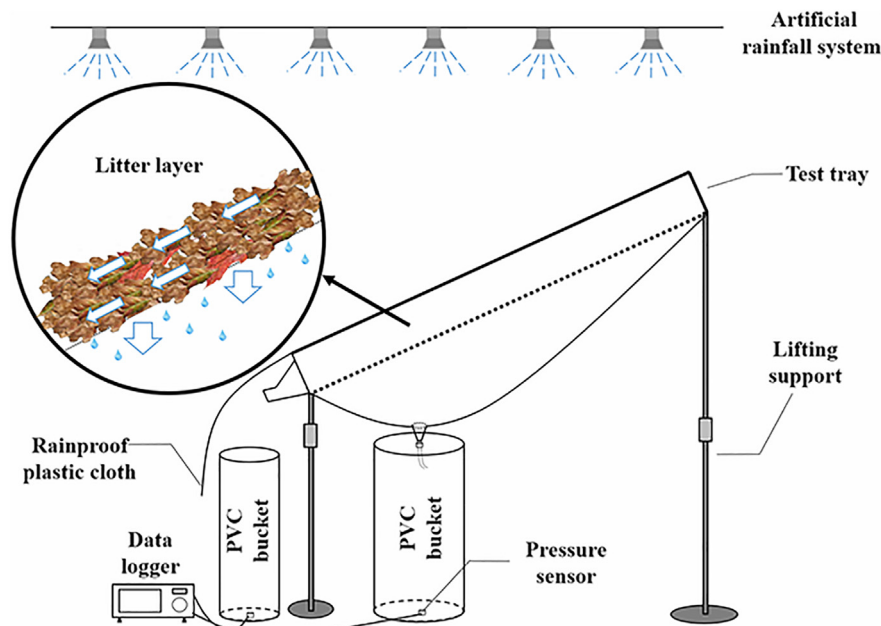


Fig. 1. Schematic of simulated rainfall experiment.

litter layers.

Overland runoff generation is potentially affected by vegetation cover because of varying infiltration capacity and slope roughness among different vegetation types (El-Hassanin et al., 1993; Mueller et al., 2007). Similarly, because of surface covers such as the litter layer, hydrologic processes on hillslopes increase complexity. For example, lateral flow in the organic horizon is regarded as a part of a linked network of preferential flow pathways (Noguchi et al., 1999; Sidle et al., 2001). Some studies found that surface runoff may be affected not only by Hortonian overland flow but also by another lateral runoff, that of biomat flow (Kim et al., 2014; Sidle et al., 2007). Sidle et al. (2007) observed that much of the rainfall was laterally transported through the upper 20 cm 'biomat layer'. By contrast, Coelho Netto (1987) found that litter-flow corresponds to a very low percentage of precipitation, with little significance as a streamflow component during a storm flow period. Most studies related to hillslope hydrology focus on the water budget of the topsoil layer including litter, humus and mineral soil, in addition to interactions among these sublayers, such as water repellency (hydrophobicity), in connection with soil moisture, soil structural stability and organic compounds, among others (Doerr et al., 2000; Mataix-Solera et al., 2011; Miyata et al., 2009; Valat et al., 1991), which complicate hydrologic processes. Hence, determining how rainwater passes in and out of the litter layer and how during this passage, rainfall might be partitioned as interception, infiltration and lateral runoff in the litter layer is of great importance.

The objectives of this study were the following: (a) to depict the dynamics of litter interception under simulated rainfall; (b) to determine the characteristics of litter interception under various rainfall intensities and on different slopes; and (c) to analyse how rainfall and slope factors affect precipitation partitioning within the litter layer.

2. Material and methods

2.1. Sample collection

The study site is located in Jiufeng National Forestry Park, Beijing, China (116°28'E, 39°34'N). Five 1 × 1 m² sample plots were selected by an S-shaped sampling method in two 20 × 20 m² areas of dominant forest types in northern China: a broad-leaf type, represented by *Quercus variabilis*, and a needle-leaf type, represented by *Pinus*

tabuliformis (Allen, 1993; Wang et al., 2015). In each plot, the two layers of forest litter were measured, and then carefully collected by hand following Johnson (1992) and Keith et al. (2010): an undecomposed litter (L) layer, including relatively freshly fallen leaves, twigs and bark; and a fermentation (F) layer, consisting of half-decomposed leaves, and other recognizable plant tissues. After collection, litter was quickly transferred to the laboratory and weighed and then spread out to dry naturally for further testing.

2.2. Rainfall simulation system

Experiments were conducted under simulated rainfall at the Capital Metropolitan Region Forest Ecosystem National Research Station in Beijing. The rainfall simulation system (QYJY-503C, Qingyuan Measurement Technology, Co. Ltd., Xi'an, China) simulates a wide range of rainfall intensities from 10 to 300 mm hr⁻¹ by controlling different nozzle valves and water pressure. The nozzles were installed at a height of 18 m, which allowed raindrops to reach the same terminal velocity as natural rainfall. The rainfall device has good controllability and performance, with rainfall uniformity > 80% (Huo et al., 2015). Based on the high requirement for precision in rainfall intensity, we chose a small test area to demarcate rainfall intensities for the tests to increase the rainfall uniformity up to 95%. Simulated rain is a useful experimental method because of its convenience and controllability, although it cannot perfectly imitate natural rainfall (Duan et al., 2004).

2.3. Experimental facility

The experimental facility is shown in Fig. 1. The sample tray used in this study had an area of 100 × 50 cm² and a height of 13 cm. The bottom side was made of nylon net composed of 2 mm diameter strands constituting a 1 × 1 cm² mesh or a 2 × 2 cm² mesh used to load needle-leaf litter or broad-leaf litter, respectively. The size of mesh was suitable to prevent leaf drop of litter and weaken surface tension between the strands of the mesh, which might affect the interception value. To avoid a drooping net after sampling, we tightened the net and inserted four metal sticks (diameter 5 mm) under the net every 20 cm along the long edge of the tray. Semi-decomposed litter (F) layer was evenly put on the tray first, and then, undecomposed litter (L) layer was placed on the F layer. For comparison, litter mass of the two types of tree species was

the same at 1.5 kg m^{-2} , and the mass of F and L layer was determined according to their weight ratios in natural condition. Additionally, four adjustable stands were fixed under each corner of the tray, and by changing the stand height, different tray slopes were used to simulate forested hillslopes. The lowest side of the tray was empty and connected to a V-shaped steel tank to converge the rainwater along the slope into a PVC bucket. In addition, there was a plastic bag below the tray for collecting the rainfall from the bottom of the litter layer into another PVC bucket. To prevent rainwater from falling into the steel tank and PVC buckets, a rainproof plastic cloth was placed above them. The bottoms of the PVC buckets were fitted with hydraulic pressure transducers (SIN-P300, Meacon Automation Technology Co. Ltd., Hangzhou, China) and the real-time bucket water pressure data were stored on an automatic data logger (SIN-R200D, Meacon Automation Technology Co. Ltd., Hangzhou, China).

2.4. Experimental procedure

Two types of interception storage were recorded: $C_{\max}$, a transitory value, the maximum interception storage capacity of the litter layer, measured as the amount of water stored in the litter layer at an instant of rainfall cessation; and $C_{\min}$, the minimum interception storage capacity of the litter layer, measured as the amount of water retained in the litter layer when drainage is finished after rain events (Pitman, 1989; Putuhena and Cordery, 1996). During the rainfall test, rainwater was partitioned into three sections after falling on the litter layer: lateral flow (LF), represented by water flow along the slope on or through the litter surface; drainage (D), represented by water flow that penetrated through the entire litter layer and dropped from the bottom of the litter; and litter interception (LI), represented by rainwater stored in the litter. According to the principle of water balance, the amount of litter interception was calculated indirectly. Evaporation was not measured and neglected, because no wind and sunlight occurred in the laboratory. During the test period, mean air temperature was 24°C in the lab, which was closed to the average understory temperature in the field.

In the experiment, we selected four rainfall intensities (30, 60, 90, 120 mm hr^{-1}) and four slopes (0° , 10° , 20° , 30°) with duration of 60 mins to observe interception characteristics of the two litter types and other hydrological functions. The dynamic data were collected every 1 min, and after rainfall, the data logger was stopped until water finished draining from the litter layer. Each test was replicated once, and therefore a total of 64 rainfall simulations were performed.

2.5. Statistical analysis

Cumulative interception storage $C_{\max}$, $C_{\min}$, drainage amount and lateral flow amount were all averaged over two replicates. To test whether the differences among different rainfall intensities and slopes were statistically significant ($P < 0.05$), one-way analysis of variance (ANOVA) was performed with a *t*-test (LSD). Pearson's correlation coefficient was used to calculate the relationships between hydrological indices (such as $C_{\max}$, $C_{\min}$ and their proportions) and independent variables (rainfall intensity and slope) with 95% confidence intervals ($P < 0.05$). Multiple linear regression and nonlinear regression were conducted to describe the relationship between hydrological index and rainfall intensity/slope. The coefficient of determination (R^2) was used to assess the model fit. All the statistical analyses and plot displays were conducted using IBM SPSS Statistics 22 and OriginPro 2016, respectively.

3. Results and discussion

3.1. Rainfall interception process

Fig. 2 shows the interception process of the two types of litter under

different rainfall intensities and tray slopes. Both *Q. variabilis* and *P. tabuliformis* had an interception trend that was categorized into three stages: rapid-growth stage in the first 5 min; slow-growth stage from the 5th minute to the end of rainfall; and the drainage stage from the rainfall cessation to the end of test. Large rainfall intensity resulted in rapid slowing down of the interception process. For example, in the 10° slope test for *Q. variabilis* and a rainfall intensity of 30 mm hr^{-1} , cumulative interception storage increased rapidly in the first 5 min of rainfall and then displayed a moderately increasing trend; whereas under rainfall intensities of 90 and 120 mm hr^{-1} , the turning point was 1–2 min from the start of the test (Fig. 2b).

After a wetting-up phase in the first stage, the cumulative interception storage increased at a relatively moderate rate, because forest litter began absorbing water. When rainfall stopped, a rapid drainage occurred from the litter layer followed by a slow down; stability was achieved at approximately 10 min after rain cessation (Fig. 2). Little variation was observed in the cumulative interception storage after drainage among different rainfall intensities.

3.2. Effects of rainfall and slope on litter interception

On average, $C_{\max}$ values of *Q. variabilis* and *P. tabuliformis* were $1.90 (\pm 0.26)$ – $2.83 (\pm 0.39) \text{ mm}$ and $1.56 (\pm 0.20)$ – $2.29 (\pm 0.36) \text{ mm}$ from 0° to 30° , respectively (Table 1). Correspondingly, $C_{\min}$ values ranged from 46 to 63% of $C_{\max}$ for the two types of litters, indicating much of the retained water was lost to the drainage process. Both $C_{\max}$ and $C_{\min}$ of *Q. variabilis* were larger than those of *P. tabuliformis*, which is consistent with previous studies that compared broad-leaf and needle-leaf litters (Li et al., 2017; Putuhena and Cordery, 1996; Sato et al., 2004).

The $C_{\max}$ of the two types of litter increased with increasing rainfall intensity at each slope, with a significant correlation of $r = 0.794$ and $r = 0.837$ for *Q. variabilis* and *P. tabuliformis*, respectively (Fig. 3, Table 2, $P < 0.05$). By contrast, no significant ($P > 0.05$) correlation was detected between litter $C_{\min}$ and rainfall intensity, although $C_{\min}$ showed an increasing trend when the slope was 0° and 10° for litter of *Q. variabilis* (Fig. 3).

The $C_{\max}$ of the two types of litter for tests at the same rainfall intensity remarkably declined from 30° to no slope (Fig. 3). Moreover, the values of $C_{\min}$ revealed the same trend in spite of some fluctuation. Pearson's correlation analysis indicated that both $C_{\max}$ and $C_{\min}$ of *Q. variabilis* and *P. tabuliformis* had a significant negative relationship with slope (Table 2, $P < 0.05$). Simultaneously, the results of multiple comparisons among different slope gradients illustrated that both $C_{\max}$ and $C_{\min}$ between 20° and 30° showed no difference, whereas a significant difference existed between the steep slopes (20° and 30°) and no slope (0°).

The effects of slope and rainfall intensity on interception capacity were combined in a multiple linear regression analysis. Eqs. (1) to (4) showed that both $C_{\max}$ and $C_{\min}$ were significantly co-determined by slope (*S*) and rainfall intensity (*RI*) for *Q. variabilis* and *P. tabuliformis*.

$$Q. \text{ variabilis } C_{\max} = 0.009RI - 0.032S + 2.112, R^2 = 0.883, P < 0.01 \quad (1)$$

$$Q. \text{ variabilis } C_{\min} = 0.002RI - 0.014S + 1.434, R^2 = 0.757, P < 0.01 \quad (2)$$

$$P. \text{ tabuliformis } C_{\max} = 0.001RI - 0.009S + 1.007, R^2 = 0.548, P < 0.01 \quad (3)$$

$$P. \text{ tabuliformis } C_{\min} = 0.009RI - 0.024S + 1.650, R^2 = 0.850, P < 0.01 \quad (4)$$

3.3. Rainfall partitioning

In the tests with slope, rainfall was partitioned into lateral flow (LF),

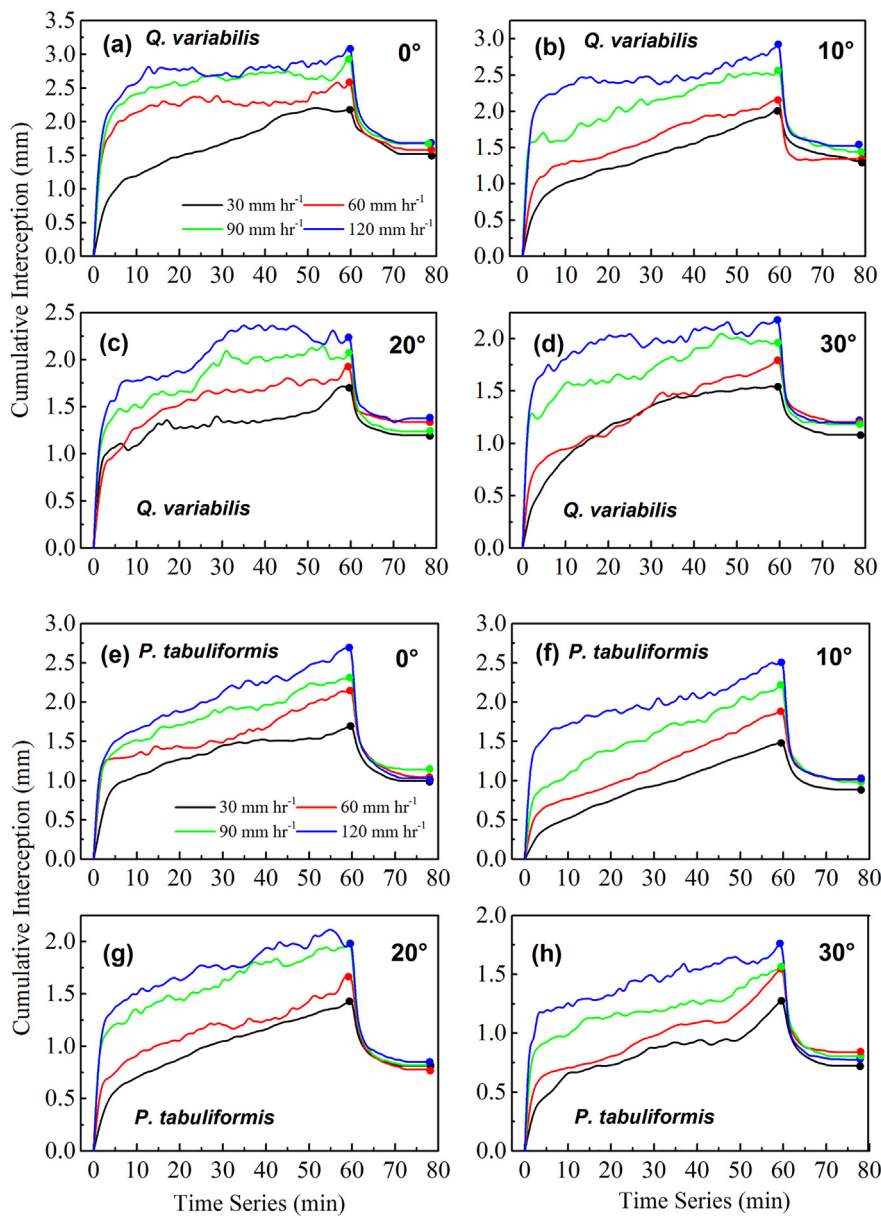


Fig. 2. Dynamic interception processes of two types of litter layer and four slopes.

Table 1
Interception storage capacity metrics $C_{\max}$ and $C_{\min}$ of *Q. variabilis* and *P. tabuliformis* at different rainfall intensities.

	Slope (°)	30 (mm hr ⁻¹)	60 (mm hr ⁻¹)	90 (mm hr ⁻¹)	120 (mm hr ⁻¹)	Mean ± STD (mm)
<i>Q. variabilis</i> $C_{\max}$ (mm)	0°	2.21 ± 0.05	2.71 ± 0.04	3.06 ± 0.12	3.22 ± 0.08	2.83 ± 0.39
	10°	2.05 ± 0.02	2.22 ± 0.2	2.69 ± 0.05	3.04 ± 0.13	2.50 ± 0.41
	20°	1.74 ± 0.2	1.92 ± 0.02	2.18 ± 0.07	2.84 ± 0.07	2.03 ± 0.24
	30°	1.56 ± 0.09	1.84 ± 0.13	2.01 ± 0.19	2.20 ± 0.06	1.90 ± 0.26
<i>Q. variabilis</i> $C_{\min}$ (mm)	0°	1.49 ± 0.01	1.56 ± 0.03	1.67 ± 0.01	1.68 ± 0.05	1.61 ± 0.08
	10°	1.29 ± 0.1	1.32 ± 0.13	1.47 ± 0.01	1.52 ± 0.02	1.40 ± 0.13
	20°	1.20 ± 0.11	1.33 ± 0.03	1.00 ± 0.07	1.23 ± 0.01	1.28 ± 0.10
	30°	1.08 ± 0.07	1.20 ± 0.03	1.19 ± 0.13	1.19 ± 0.19	1.17 ± 0.13
<i>P. tabuliformis</i> $C_{\max}$ (mm)	0°	1.74 ± 0.06	2.22 ± 0.08	2.41 ± 0.05	2.73 ± 0.21	2.29 ± 0.36
	10°	1.51 ± 0.02	1.95 ± 0.07	2.30 ± 0.02	2.64 ± 0.25	2.10 ± 0.44
	20°	1.47 ± 0.12	1.69 ± 0.02	1.98 ± 0.05	2.08 ± 0.1	1.80 ± 0.25
	30°	1.30 ± 0.14	1.58 ± 0.07	1.62 ± 0.19	1.75 ± 0.07	1.56 ± 0.20
<i>P. tabuliformis</i> $C_{\min}$ (mm)	0°	1.00 ± 0.04	1.05 ± 0.03	1.14 ± 0.04	1.00 ± 0.03	1.06 ± 0.07
	10°	0.89 ± 0.02	1.02 ± 0.05	0.97 ± 0.03	1.01 ± 0.01	0.97 ± 0.06
	20°	0.81 ± 0.04	0.78 ± 0.01	0.82 ± 0.07	0.85 ± 0.26	0.82 ± 0.14
	30°	0.72 ± 0.09	0.84 ± 0.07	0.80 ± 0.03	0.77 ± 0.08	0.79 ± 0.08

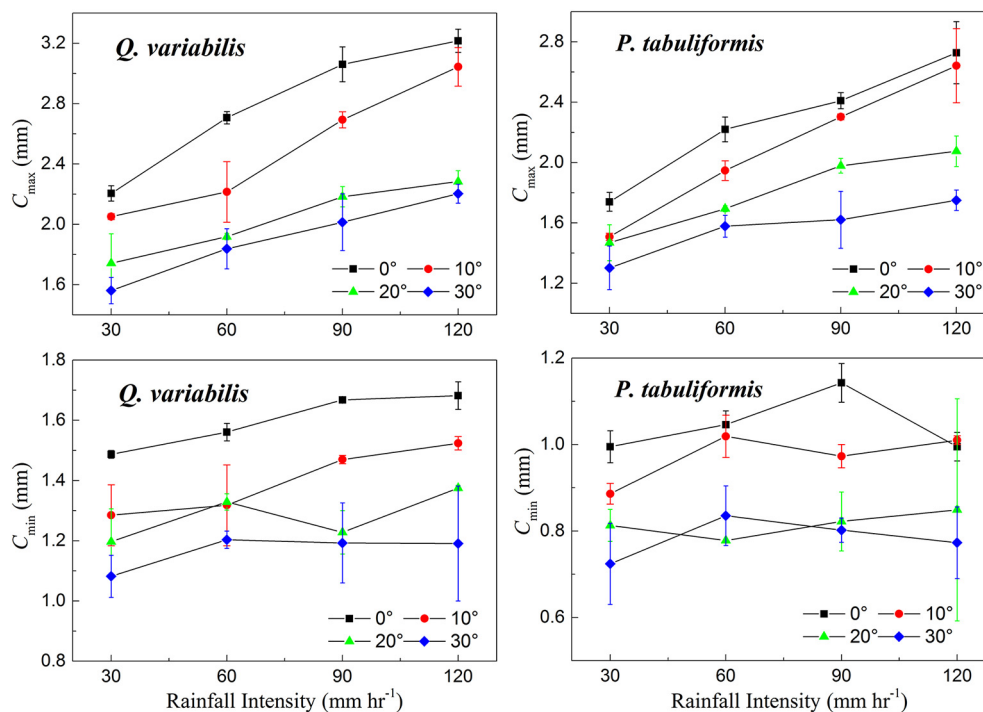


Fig. 3. Relationship between $C_{\max}/C_{\min}$ and rainfall intensities at four different slopes for *Q. variabilis* and *P. tabuliformis*.

Table 2

Pearson's correlation coefficients r between $C_{\max}/C_{\min}$ and rainfall intensity/slope for *Q. variabilis* and *P. tabuliformis*.

Interception storage capacity	Rainfall intensity (mm hr^{-1})		Slope ($^{\circ}$)	
	<i>Q. variabilis</i>	<i>P. tabuliformis</i>	<i>Q. variabilis</i>	<i>P. tabuliformis</i>
$C_{\max}$ (mm)	0.794**	0.837**	−0.856**	−0.810**
$C_{\min}$ (mm)	0.603	0.404	−0.943**	−0.944**

Note: two-tailed test of significance was used and significant correlations ($P < 0.01$) are labelled with asterisks.

drainage (D) and litter interception (LI), as stated in Section 2.4. In test with no slope, only the latter two were considered. The ratios of LF, D and LI to gross precipitation (P_g) for *Q. variabilis* and *P. tabuliformis* were calculated (Fig. 4). The proportions of LI were the lowest, at $< 5\%$ of P_g for both litter types. The percentages of LF ranged from 12.27 to 44.58% for *Q. variabilis* and from 3.59 to 20.38% for *P. tabuliformis*. The D/ P_g percentages were at least 50%; with the largest proportion exceeding 95%.

Unlike the value of LI, the LI/ P_g percentage significantly decreased with increasing rainfall intensity, whereas no significant correlation was found between LI/ P_g and slope (Table 3). A strong relationship was found between LI/ P_g and P_g (Fig. 5), which was described by a power function:

$$I = 94.16 g^{-0.96}, R^2 = 0.82, P < 0.01 \quad (5)$$

where I is the LI/ P_g percentage (%) and g is the gross precipitation (mm). The volume of LF significantly increased with rising rainfall intensity for both two types of the litter, whereas showed a significant relationship with slope for only *Q. variabilis* (Table 3). This finding suggested that leaf shape might affect the lateral movement of rainwater within the litter layer, which is supported by field tests (Kim et al., 2014). LF/ P_g percentage also had a significant correlation with slope, rather than rainfall intensity. In complete contrast to LI, the amount of D had a significant relationship with rainfall intensity, whereas its percentage of P_g showed a negative relationship with slope.

4. Discussion

4.1. Litter interception and its influencing factors

Except for rainfall and slope, the litter interception trend depends on how quickly the litter layer is saturated. Putuhen and Cordery (1996) reported that the saturation of the interception storage appeared at the 10th to 30th minute depending on litter thickness, with the entire interception process separated into wetting, saturation and drainage phases. Mo et al. (2009) found that the retained rainwater in the litter layer became constant after 3 h for *Larix principis-rupprechtii* and *Betula albosinensis* under a litter mass of 1.0 kg m^{-2} , and for a greater litter mass of 2.0 kg m^{-2} , saturation occurred after 5 h of rainfall for *Cryptomeria japonica* and *Lithocarpus edulis* (Sato et al., 2004). The variation in saturation time can be attributed to different litter types, litter mass and rainfall intensities. In our experiment, forest litter failed to become saturated within 1 h of rainfall because the litters were not fully wetted; therefore, filling void spaces within the litter layer might require more time.

The conflicting findings of current studies indicate that effects of rainfall intensity on the interception storage capacity of litter are complicated. Putuhen and Cordery (1996) found that both $C_{\max}$ and $C_{\min}$ were not correlated with rainfall intensity ($34\text{--}75 \text{ mm hr}^{-1}$), in contrast to Sato et al. (2004) who reported that both $C_{\max}$ and $C_{\min}$ increased with rainfall intensity $< 50 \text{ mm hr}^{-1}$. The small difference in rainfall intensity in these two studies led to completely opposite results, despite that litters nearly all approached the saturation point. This difference may result from the physical characteristics of forest litter such as leaf shape and leaf waxiness, among others, which should be further considered. In our experiment, rainfall intensities ranged from 30 to 120 mm hr^{-1} , but the litter layer failed to saturate because of short rainfall duration compared with that of some studies (Sato et al., 2004; Mo et al., 2009). Cumulative interception storage capacity is an instantaneous value taken during the rainfall process and, is determined by how much water can be detained in the litter layer. In this study, litter equivalent to mass per unit area of 1.5 kg m^{-2} had sufficient water-holding capacity to store rainwater under high rainfall intensity

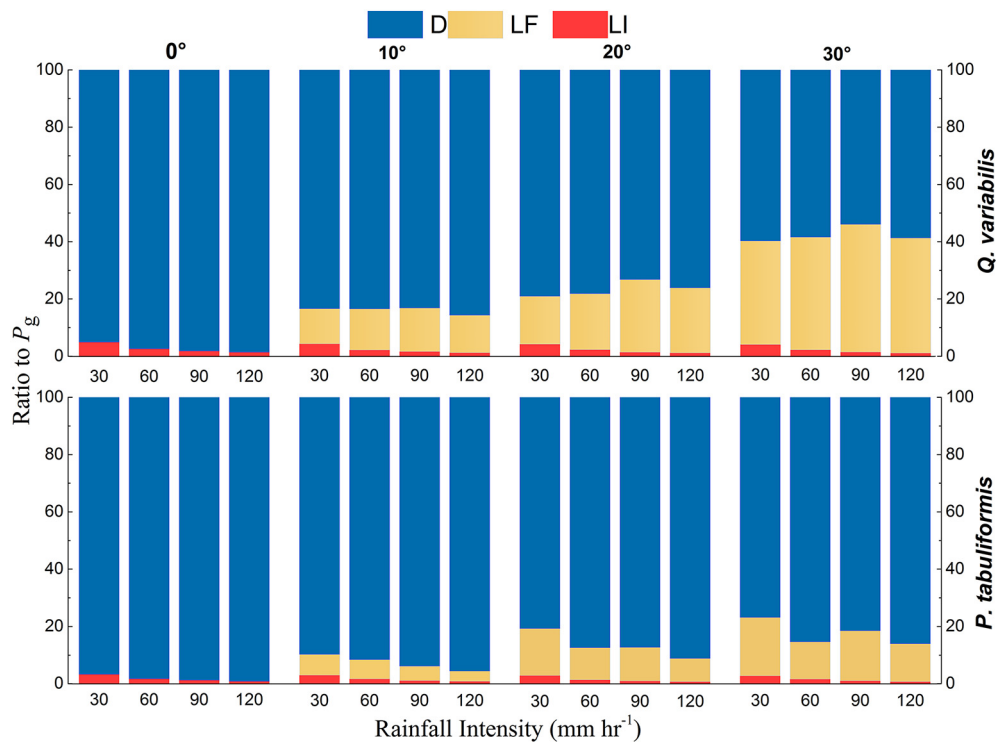


Fig. 4. Stacked columns of percentage of each hydrological portion of the forest litter layer of *Q. variabilis* and *P. tabuliformis*.

in a moment, resulting in a positive relationship between $C_{\max}$ and rainfall intensities. By contrast, $C_{\min}$ measured after drainage primarily consisted of ‘adhesion water’ held by leaf surface, correlating with litter mass rather than rainfall intensity. Our findings are similar to those in studies of Li et al. (2013) and Guevaraescobar et al. (2007).

Current studies seldom put litter sample trays on a slope. For the broad-leaf litter of *Q. variabilis*, much of intercepted water was ‘loose’ water or ‘capillary’ water as noted by Sato et al. (2004) and Guevaraescobar et al. (2007) because of the large leaf area of the species. This type of free water is stored in the bowl-shaped depression of fallen leaves and voids spaces within litters and was most likely the reason why the volume of stored water showed no significant differences between the slopes of 20° and 30°, whereas significant differences existed between steep-slope and no slope. This finding suggested that broad-leaf litter layer had a threshold angle; therefore, the effect of slope on $C_{\max}$ or $C_{\min}$ might attenuate at the steep slope (20°). For the needle-leaf litter, part of the rainwater detained on the surface of pine needles flowed down the sloped tray, which was a simpler interception process than that in the broad-leaf litter. According to previous studies, $C_{\min}$ is more important than $C_{\max}$, because $C_{\min}$ represents the real interception loss of the litter layer, which is available for evaporation (Putuhen and Cordery, 1996; Sato et al., 2004). $C_{\min}$ is also suggested for use as a specific indicator of forest litter, because it is primarily affected by the physical characteristics of litter such as leaf shape and litter mass, or location on a slope, rather than external factors such as rainfall intensity.

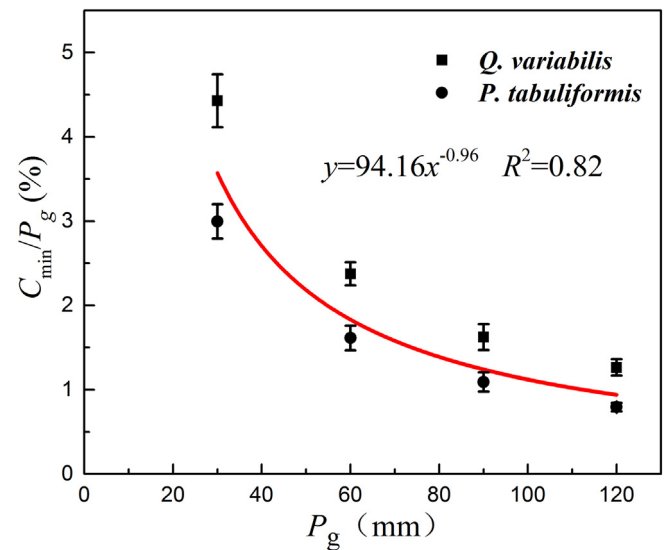


Fig. 5. Relationship between percentage of interception and gross precipitation.

Table 3
Correlations between indexes of each hydrological portion and slope/rainfall intensity.

Factors	Tree species	LI/mm	$\frac{LI}{P_g}/\%$	LF/cm ³	$\frac{LF}{P_g}/\%$	VF/cm ³	$\frac{VF}{P_g}/\%$
Slope (°)	<i>Q. variabilis</i>	−0.890**	−0.122	0.591*	0.943**	0.444	−0.978**
	<i>P. tabuliformis</i>	−0.892**	−0.124	0.695*	0.848**	−0.232	−0.898**
Rainfall intensity (mm hr ^{−1})	<i>Q. variabilis</i>	0.364	−0.923**	0.736**	0.145	0.868**	−0.007
	<i>P. tabuliformis</i>	0.163	−0.931**	0.573	−0.403	0.967**	0.347

Note: two-tailed test of significance was used and significant correlations ($P < 0.01$) are labelled with asterisks. * $P < 0.05$; ** $P < 0.01$.

4.2. Mechanisms of hydrological processes in the forest litter layer

Understanding how rainwater flows in forest litter layers is significant, because this lateral flow will contribute to surface runoff generation. Coelho Netto (1987) showed that overland flow on a litter-covered slope was contained in two primary routes: over the top layer (leaves with no evidence of decay) and within the root-litter carpet. Biomat flow, defined as stormwater flow through a near-surface layer on hillslopes, was primarily observed in the loose litter layer and decomposed organic layer (Sidle et al., 2007). Stacked litters impede water drainage from the litter layer and promote water movement within and above litter. Sidle et al. (2007) reported that biomat flow was estimated as 46.3 and 28.5% of total precipitation in hinoki and deciduous forests, respectively. In our experiment, similarly, lateral flow was calculated to be as much as 44.6 and 20.4% of total precipitation for broad-leaf litter and needle-leaf litter, respectively. Dyeing tracing tests in organic rich soils showed that this biomat flow path is short and therefore contributes more to deep percolation than Hortonian overland flow (Noguchi et al., 1999; Sidle et al., 2001; Sidle et al., 2007). Because of the small scale of our test, the proportion of lateral flow was relatively high.

To our knowledge, only a few laboratory studies have discussed lateral movement of water in the litter layer. The results of Sato et al. (2004) showed that percentages of lateral drainage increased with litter mass and the broad-leaf litter could transport more rainwater laterally than needle-leaf litter. They supplied rainfall into only a central part of the litter surface (approximately one-third of the tray) and observed lateral flow in a horizontal condition, which is not applicable in our study. Many factors affect litter flow generation, such as leaf type, rainfall and slope, among others. Because of the difference in leaf type, broad-leaf litter generated the most lateral flow in our test. Additionally, good correlation was observed between lateral water volume and rainfall intensity for broad-leaf litter, rather than for needle-leaf litter. Compared with broad-leaf litter, leaf surface area of pine needles is too small to retain much water, which led to no difference in lateral flow among changing rainfall intensities. By contrast, both LF and LF/ P_g were affected by slope gradient for the two types of litter, although the values between them were very different. Kim et al. (2014) showed that biomat flow had less effect on surface runoff generation for a thin litter layer, indicating that litter thickness or litter mass may be effective factors for litter-flow production.

As a special soil layer, the forest litter layer has unsaturated infiltration because of its porous and loose structure. Kosugi et al. (2001) found that the Richards equation applies to simulations of unsaturated water flow in the litter layer and that the broad-leaf forest floors have smaller unsaturated hydraulic conductivity than that of needle-leaf forest floors. Regardless of slope, rainwater consists of litter storage and drainage. The percolation flux from the litter layer was not steady, even under constant rainfall intensity, which might result from the alternative appearance of filling and emptying processes for litter temporary storage (Dunkerley, 2015; Walsh and Voigt, 1977). Under the condition of slope, three components are considered: interception, lateral flow and percolation, with a relationship of restricting each other among them. The litter interception constituted < 5% of rainfall in our tests; thus, both the volume and proportion of lateral water and percolation showed opposite results with rainfall intensity and slope gradient.

One limitation of our study was that effects of underlying organic and mineral soil layers on hillslope hydrology were not considered. On a forested hillslope, complex interactions exist among litter interception, infiltration and runoff. Soil water repellency, a special soil character, is well known to inhibit infiltration and promote runoff (Doerr et al., 2000; Gomi et al., 2008). Many studies have found that water repellency was not only concerned with underlying mineral soil, but also litter layer and duff layer (Neris et al., 2013; Zehetner and Miller, 2006). In this study, the absence of humus material and mineral soil might result in lower runoff values than those in the natural condition.

Neris et al. (2013) noted that the greater cohesion of the duff remnants in a pine forest has a negative effect on water infiltration and therefore promotes lateral runoff. In this regard, broken cohesion during the litter reconstruction might be another reason for influencing infiltration and lateral runoff processes. Soil water repellency is a complicated property that involves many controlling factors such as soil moisture, soil texture and chemical characteristic, etc., which require increased consideration in further study (Doerr et al., 2000; Kim et al., 2005; Kim et al., 2014). Nevertheless, we built a relatively ideal condition that could best investigate the hydrological processes in the litter layer (particularly for the L and F layers) without considering the potential influence discussed above.

Litter interception accounts for a very small part of precipitation in most individual rainfall tests; however, on longer time scales such as daily, monthly or yearly, litter interception can account for > 10%, or even > 20% of natural net rainfall in the field (Bulcock and Jewitt, 2012a; Bulcock and Jewitt, 2012b; Tsiko et al., 2012). Marin et al. (2000) conducted field observations in an Amazonia forest and found that the daily average litter drainage ranged from 25 to 93%, whereas no drainage water was collected when rainfall events yielded < 5 mm. Therefore, light rainfall intensity should receive additional attention in simulated experiments. Moreover, the two routes of litter flow could not be separately measured because of device limitations in this study. Quantifying different components of lateral water flows is necessary to better understand the mechanisms of hydrologic processes on sloped lands.

5. Conclusion

Artificial rainfall experiments were conducted to investigate the characteristics of interception, lateral runoff, and drainage of the litter layer and their responses to different rainfall intensities and slopes. Litter interception processes consisted of three dynamic phases: a rapid-growing phase, a moderate-growing phase, and a post-rainfall drainage phase. Both C_{max} and C_{min} of broadleaved litter were larger than those of needle-leaf litter regardless of precipitation or slope. Irrespective of tree species, C_{max} and C_{min} had a significant negative correlation with slope. C_{max} of the two types of litter was significantly correlated with rainfall intensity, whereas no good relationship was found between C_{min} and slope. The volume of lateral flow was significantly correlated with slope and rainfall intensity only for $Q_{variabilis}$; whereas drainage volume had a significant relationship with rainfall intensity, instead of slope. On average, the proportion of drainage water was the largest, and the lateral flow percentage was the second largest. The intercepted water accounted for the lowest part of gross rainfall, < 5%. Percentages of lateral flow and drainage showed significant correlation with slope; by contrast, litter interception proportion was remarkably affected by rainfall intensity, rather than by slope. The results of this study helped to increase our understanding of the hydrological processes within the forest litter layer on slopes.

Acknowledgements

This work was supported by the Beijing Municipal Education Commission (CEFF-PXM2018_014207_000024) and National Natural Science Foundation of China (grant no. 41671283). We also appreciate the Jiufeng National Forest Park Administration for their great help.

References

- Allen, R.B., 1993. A Permanent Plot Method for Monitoring Changes in Indigenous Forests. Landcare Research, Lincoln, pp. 24.
- Benyon, R.G., Doody, T.M., 2015. Comparison of interception, forest floor evaporation and transpiration in *Pinus radiata* and *Eucalyptus globulus* plantations. Hydrol. Process. 29, 1173–1187.
- Brye, K.R., Norman, J.M., Bundy, L.G., Gower, S.T., 2000. Water-budget evaluation of prairie and maize ecosystems. Soil Sci. Soc. Am. J. 64, 715–724.

- Bulcock, H.H., Jewitt, G.P.W., 2012a. Modelling canopy and litter interception in commercial forest plantations in South Africa using the Variable Storage Gash model and idealised drying curves. *Hydrol. Earth Syst. Sci.* 16, 4693–4705.
- Bulcock, H.H., Jewitt, G.P.W., 2012b. Field data collection and analysis of canopy and litter interception in commercial forest plantations in the KwaZulu-Natal Midlands, South Africa. *Hydrol. Earth Syst. Sci.* 16, 3717–3728.
- Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth-Sci. Rev.* 51, 33–65.
- 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.
- Dunkerley, D., 2015. Percolation through leaf litter: what happens during rainfall events of varying intensity? *J. Hydrol.* 525, 737–746.
- El-Hassanin, A.S., Labib, T.M., Gaber, E.I., 1993. Effect of vegetation cover and landslope on runoff and soil losses from watersheds of Burundi. *Agric. Ecosyst. Environ.* 43, 301–308.
- Gomi, T., Sidle, R.C., Ueno, M., Miyata, S., Kosugi, K.I., 2008. Characteristics of overland flow generation on steep forested hillslopes of central Japan. *J. Hydrol.* 361, 275–290.
- Guevaraescobar, A., Gonzalesosa, E., Ramossalinas, M., Hernandezdelgado, G.D., 2007. Experimental analysis of drainage and water storage of litter layers. *Hydrol. Earth Syst. Sci.* 11, 1703–1716.
- Helvey, J.D., Patric, J.H., 1965. Canopy and litter interception of rainfall by hardwoods of eastern United States. *Water Resour. Res.* 1, 193–206.
- Huo, Y.M., Bi, H.X., Zhu, Y.J., Xu, H.S., Wang, X.X., Chang, Y.F., 2015. Characteristics of artificial rainfall produced by QYJY-503C simulation system. *Sci. Soil Water Conserv.* 13, 31–36 (in Chinese with English Abstract).
- Johnson, E.A., 1992. *Fire and Vegetation Dynamics: Studies From the North American Boreal Forest*. Cambridge Univ. Press, Cambridge, U.K., pp. 129.
- Keith, D.M., Johnson, E.A., Valeo, C., 2010. A hillslope forest floor (duff) water budget and the transition to local control. *Hydrol. Process.* 24, 2738–2751.
- Kim, H.J., Sidle, R.C., Moore, R.D., 2005. Shallow lateral flow from a forested hillslope: influence of antecedent wetness. *Catena* 60, 293–306.
- Kim, J.K., Onda, Y., Kim, M.S., Yang, D.Y., 2014. Plot-scale study of surface runoff on well-covered forest floors under different canopy species. *Quat. Int.* 344, 75–85.
- Kimoto, A., Uchida, T., Mizuyama, T., Li, C., 2002. Influences of human activities on sediment discharge from devastated weathered granite hills of southern China: effects of 4-year elimination of human activities. *Catena* 48, 217–233.
- Kosugi, K., Mori, K., Yasuda, H., 2001. An inverse modeling approach for the characterization of unsaturated water flow in an organic forest floor. *J. Hydrol.* 246, 96–108.
- Li, X., Niu, J.Z., Xie, B.Y., 2013. Study on hydrological functions of litter layers in North China. *PLoS One* 8, e70328.
- Li, X., Xiao, Q.F., Niu, J.Z., Dymond, S., Mcpherson, E.G., van Doorn, N.S., Yu, X.X., Xie, B.Y., Zhang, K.B., Li, J., 2017. Rainfall interception by tree crown and leaf litter: an interactive process. *Hydrol. Process.* 31, 3533–3542.
- Liu, W., Luo, Q., Lu, H., Wu, J., Duan, W., 2017. The effect of litter layer on controlling surface runoff and erosion in rubber plantations on tropical mountain slopes, SW China. *Catena* 149, 167–175.
- Marin, C.T., Bouten, I.W., Dekker, S., 2000. Forest floor water dynamics and root water uptake in four forest ecosystems in northwest Amazonia. *J. Hydrol.* 237, 169–183.
- Mataix-Solera, J., Cerdà, A., Arcenegui, V., Jordán, A., Martínez-Zavala, L., 2011. Fire effects on soil aggregation: a review. *Earth-Sci. Rev.* 109, 44–60.
- Miyata, S., Kosugi, K., Gomi, T., Mizuyama, T., 2009. Effects of forest floor coverage on overland flow and soil erosion on hillslopes in Japanese cypress plantation forests. *Water Resour. Res.* 45, 192–200.
- Mo, F., Yu, P.T., Wang, Y.H., Wang, J., Xiong, W., Xu, L.H., 2009. The water-holding capacity of litter layers in the forests of *Larix principis-rupprechtii* and *Betula albo-sinensis* in Liupan Mountain and their rainfall interception process. *Acta Ecol. Sin.* 6, 2868–2876 (in Chinese with English Abstract).
- Mueller, E.N., Wainwright, J., Parsons, A.J., 2007. Impact of connectivity on the modeling of overland flow within semiarid shrubland environments. *Water Resour. Res.* 43, 1–8.
- Neris, J., Tejedor, M., Rodríguez, M., Fuentes, J., Jiménez, C., 2013. Effect of forest floor characteristics on water repellency, infiltration, runoff and soil loss in Andisols of Tenerife (Canary Islands, Spain). *Catena* 108, 50–57.
- Coelho Netto, A.L., 1987. Overlandflow production in a tropical rainforest catchment: the role of litter cover. *Catena* 14, 213–231.
- Noguchi, S., Tsuboyama, Y., Sidle, R.C., Hosoda, I., 1999. Morphological characteristics of macropores and the distribution of preferential flow pathways in a forested slope segment. *Soil Sci. Soc. Am. J.* 63, 1413–1423.
- Ogée, J., Brunet, Y., 2002. A forest floor model for heat and moisture including a litter layer. *J. Hydrol.* 255, 212–233.
- Park, A., Friesen, P., Serrud, A.A.S., 2010. Comparative water fluxes through leaf litter of tropical plantation trees and the invasive grass *Saccharum spontaneum* in the Republic of Panama. *J. Hydrol.* 383, 167–178.
- Pitman, J.I., 1989. Rainfall interception by bracken in open habitats—relations between leaf area, canopy storage and drainage rate. *J. Hydrol.* 105, 317–334.
- Putuhen, W.M., Cordery, I., 1996. Estimation of interception capacity of the forest floor. *J. Hydrol.* 180, 283–299.
- Sato, Y., Kumagai, T., Kume, A., Otsuki, K., Ogawa, S., 2004. Experimental analysis of moisture dynamics of litter layers: the effects of rainfall conditions and leaf shapes. *Hydrol. Process.* 18, 3007–3018.
- Sayer, E.J., 2006. Using experimental manipulation to assess the roles of leaf litter in the functioning of forest ecosystems. *Biol. Rev.* 81, 1–31.
- Sidle, R.C., Noguchi, S., Tsuboyama, Y., Laursen, K., 2001. A conceptual model of preferential flow systems in forested hillslopes: evidence of self-organization. *Hydrol. Process.* 15, 1675–1692.
- Sidle, R.C., Hirano, T., Gomi, T., Terajima, T., 2007. Hortonian overland flow from Japanese forest plantations—an aberration, the real thing, or something in between? *Hydrol. Process.* 21, 3237–3247.
- Sun, X., Wang, G., Lin, Y., Liu, L., Gao, Y., 2014. Intercepted rainfall in *Abies fabri* forest with different-aged stands in southwestern China. *Turk. J. Agric. For.* 37, 495–504.
- Sun, J.M., Yu, X.X., Li, H.Z., Chang, Y., Wang, H.N., Tu, Z.H., Liang, H.R., 2016. Simulated erosion using soils from vegetated slopes in the Jiufeng Mountains, China. *Catena* 136, 128–134.
- Sun, L., Zhang, G.H., Luan, L.L., Liu, F., 2016. Temporal variation in soil resistance to flowing water erosion for soil incorporated with plant litters in the Loess Plateau of China. *Catena* 145, 239–245.
- Tsiko, C.T., Makurira, H., Gerrits, A.M.J., Savenije, H.H.G., 2012. Measuring forest floor and canopy interception in a savannah ecosystem. *Phys. Chem. Earth A/B/C* 47–48, 122–127.
- Valat, B., Jouany, C., Riviere, L.M., 1991. Characterization of the wetting properties of air-dried peats and composts. *Soil Sci.* 152, 100–107.
- Walsh, R.P.D., Voigt, P.J., 1977. Vegetation litter: an underestimated variable in hydrology and geomorphology. *J. Biogeogr.* 4, 253.
- Wang, W.D., Wang, W.L., Xu, F.L., Yu, Q.M., Ma, H.L., 2015. Characteristics of soil nutrients and enzyme activities in young and middle aged *Larix principis-rupprechtii* plantation in western Qinling Mountains. *J. Plant Nutr. Fertil.* 21, 1032–1039 (in Chinese with English Abstract).
- Zehetner, F., Miller, W.P., 2006. Erodibility and runoff-infiltration characteristics of volcanic ash soils along an altitudinal climosequence in the Ecuadorian Andes. *Catena* 65, 201–213.