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Effects of forest litter cover on hydrological response of hillslopes in the Loess Plateau of China

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ABSTRACT

Forest litter layer plays an important role in controlling water and soil loss; however, few studies have examined how litter cover affects hydrological processes. In this research, the effects of forest litter cover on interception, runoff, infiltration and soil erosion were investigated using rainfall simulation on a loess hillslope in China. Field experimental plots (10 m × 1.5 m, 5°) with two litter species (needle-leaf species and broad-leaf species) and three litter masses (300, 500 and 800 g m^{-2}) were exposed to two rainfall intensities (30 and 60 mm h^{-1}) for 40 min. A modified Merriam interception model as well as a WEPP (Water Erosion Prediction Project) Hillslope model were subsequently employed to analyze the experimental data of litter interception as well as runoff generation and soil erosion, respectively. Results showed that litter interception storage capacity ranged from 0.55 to 2.10 mm; thus, 1.8–9.2% of total rainfall was intercepted by the litter layer. Interception storage increased with increasing litter mass and rainfall intensity, and broad-leaf litter could intercept more rainwater than needle-leaf litter. Litter cover reduced runoff rates from plots covered with needle-leaf and broad-leaf litter by 18.6% and 25.9%, respectively, compared to the bare plot. Although runoff rates were slightly lower in litter-covered plots than in the bare plot, soil loss was effectively controlled when litter mass levels reached a threshold value of 500 g m^{-2}. Compared to that from the bare plot, the mean soil loss rate for litter-covered plots was lowered by 58.5%, 74.5% and 78.3% for litter masses of 300, 500 and 800 g m^{-2}, respectively. These results indicate that the litter layer was more conducive to controlling soil loss than runoff generation. Furthermore, the determination coefficient and Nash-Sutcliffe efficiency coefficient of the modified Merriam model ranged between 0.838–0.998 and 0.912–0.998, respectively, indicating that this model could successfully simulate the litter interception process. The WEPP model predictions also agreed well with the measured runoff and soil loss rates, but may have under-estimated the measured data in low rainfall intensity events and over-estimated the measured data in high rainfall intensity events. The performance of the WEPP model could be obviously improved by reducing the effective hydraulic conductivity and soil erodibility. Overall, this study will enable the development of more accurate modeling approaches and lead to a better understanding of hydrological processes under litter cover conditions.

1. Introduction

The losses of soil and water are serious eco-environmental problems in semi-arid and arid regions, resulting in reductions in local productivity of agricultural areas (Zuazo and Pleguezuelo, 2008; Duan et al., 2016; Zhang et al., 2016). More information is urgently needed to enable the development of strategies and solutions to address the eco-environmental risks in these regions. Many studies worldwide have demonstrated that vegetation cover is a key approach to controlling runoff and soil erosion (Wang et al., 2012; Li and Pan, 2018). Keesstra (2007) showed that vegetation canopy cover was one of the most important factors affecting soil erosion in forested landscapes. Oudenhoven et al. (2015) also noted that soil loss and runoff decreased with increasing canopy cover on dry rangelands. Most of these studies have recognized the important role of canopy cover in hydrological processes; however, the effects of vegetation litter cover in reducing runoff and soil erosion have not been paid enough attention.

The Loess Plateau of China has long been known to be a very fragile eco-region that suffers from severe droughts and water shortages, and is one of the most serious soil erosion regions in the world (Yu et al., 2014; Gao et al., 2016; Wu et al., 2016). Since the 1950s, implementation of large-scale soil and water conservation forests has

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played an important role in controlling soil and water losses and improving the ecological environment in this region. However, local policymakers believed that these effects depended on the protection of vegetation canopy and ignored the protection of the surface litter layer. The litter layer under the vegetation canopy was often removed and burned for fuel by local people. These activities often exposed the soil with little or no surface cover, thus increased runoff generation and reduced soil water, caused the loss of soil and nutrients, and eventually led to severe degradation or even eradication of large areas of planted forestland (He et al., 2017). Recent studies have also revealed that many of the afforested areas, characterized by a thin or absent underground cover or litter cover, are still suffering moderate or even intense soil and water loss (Cao et al., 2015). Geißler et al. (2012) believed that the forest canopy could increase splash erosion by 259% compared to open environment when there was little or no litter cover on the forest floor. This phenomenon is known as "erosion under forest" and it has the potential to cause serious erosion in the forested land (Liang et al., 2010).

Therefore, some recent studies have examined the effects of litter layer on hydrological processes. Litter not only protects the soil from direct raindrop splash by intercepting rainfall, but also prevents the clogging of soil pores by filtering splashed soil particles, thus increasing infiltration and decreasing surface runoff and soil erosion (Valentin et al., 2008). Miyata et al. (2009) reported that the primary effect of litter cover on the reduction of erosion was inhibiting the degree of raindrop impact rather than reducing overland flow or reducing sediment transport. In addition, decomposed litter could increase humus in soils, improve soil properties, and thus decrease soil erodibility (Nanko et al., 2008; Prosdocimi et al., 2016; Sun et al., 2016b). Liu et al. (2016) showed the litter-covered plots had lower runoff generation and sediment yield compared to a bare plot in the red soil region. Sun et al. (2016a) also noted that litter layers significantly reduced the rates of sediment yields in rocky mountainous areas. However, a few inconsistent results remain with regard to the influence of litter on hydrological processes. Contrary to general consensus, Cerdà and Jurgensen (2011) and Seitz et al. (2015) demonstrated that the presence of a litter layer decreased surface runoff but increased sediment loss. The divergent results reported in previous studies are likely due to differences in initial conditions, including litter characteristics, rainfall intensity, surface roughness, soil properties and slope.

Among the factors that affect soil erosion, rainfall intensity is particularly important in China's Loess Plateau (Wei et al., 2007). The kinetic energy of raindrops increases with rainfall intensity and increases the amount of runoff and erosion (Keim et al., 2006). Rainfall simulation experiments are suitable for the study of infrequent heavy rainfall events because they are more rapid, efficient, controlled (i.e., repeatable) and adaptable than natural rainfall experiments (Xia et al., 2018). However, low rainfall intensity events, which commonly occur in natural conditions, have been rarely studied. Moreover, previous studies have mainly examined litter coverage as a dominant influential factor in surface runoff and soil erosion (Blanco and Aguilar, 2015; Liu et al., 2017). However, other important litter characteristics, such as litter mass and litter species, have rarely been regarded as critical factors in this field. These factors were proved to be effective in rainfall interception (Sato et al., 2004), thus possibly exerting strong impacts on infiltration, runoff and soil erosion. All of these findings suggest that the mechanism of litter cover affecting hydrological processes is still poorly understood.

Li et al. (2013) highlighted that the roles of the litter layer were usually underestimated or even disregarded in hydrological models despite the importance of its hydrological functions. Although the canopy interception processes were often taken into account in hydrological models (such as the Gash, Rutter and Merriam models), few models were developed to represent litter interception processes for forested land (Bulcock and Jewitt, 2012). However, due to the similarity of the two processes, canopy interception models may be a good starting point for incorporating litter interception functions. In addition, only rarely have hydrological models been applied to evaluate the impacts of litter cover in controlling runoff generation and soil erosion. The Water Erosion Prediction Project (WEPP) Hillslope model is a process-based model that computes soil loss and sediment deposition from overland flow on hillslopes (Grønsten and Lundekvam, 2006; Pandey et al., 2016); however, it has a surface residue cover module. The amount of residue in the residue addition condition can highlight the effects of the litter layer on runoff and soil loss. However, the WEPP Hillslope model has not been used for the situation where the soil is covered by a litter layer. It is therefore appropriate to test the model for this case.

The aims of this study were (1) to quantify how the forest litter layer affects the hydrological processes on a loess hillslope under different conditions (two litter species, three litter masses and two rainfall intensities), (2) to develop equations and quantify parameters that can aid in predicting the litter interception process, and (3) to determine whether the WEPP Hillslope model can represent experimental data of runoff generation and soil erosion.

2. Materials and methods

2.1. Study area

The experiments in this study were conducted in the Nanxiaohegou small watershed (107°30′–107°37′ E, 35°41′–35°44′ N; between 1050 m and 1423 m above mean sea level), located in Gansu Province, China, during the period from July to October 2017. The study area is characterized by a semi-arid monsoonal climatic zone and an average annual rainfall of 507.4 mm, with 83.4% of this rainfall occurring between May and September; the annual mean temperature is 8.1 °C. The geological structure is relatively singular, which is covered almost entirely with the Quaternary loess; thus, soil erosion is serious in this watershed and the soil erosion area accounted for 89.7% of the total watershed area in 1954 (Xia et al., 2017). To curb serious soil and water loss, the watershed has been implementing comprehensive watershed management since 1952. The forest coverage has increased from 1.3% in 1954 to 31.6% in 2015 and the main tree species are *Pinus tabulaeformis*, *Robinia pseudoacacia* and *Platycladus orientalis.*

2.2. Litter

Two plantation stands were selected as the source of litter to be used in the experiments. The first stand, selected to be representative of an evergreen coniferous tree species producing needle-leaf litter, had been planted on a hillslope with an area (625 m^2) of a 30-year-old *P. tabulaeformis* plantation (Fig. 1a). *P. tabulaeformis* is a major greening species for landscape engineering and is widely planted in China. It is also a good species for soil and water conservation in the arid region of northwest China. The second stand was *R. pseudoacacia*, which was representative of a broad-leaf tree species. *R. pseudoacacia* has good drought resistance and has a good effect on reducing soil erosion. The general characteristics of each stand are shown in Table 1.

In each stand, litter samples were collected using plastic bags at 20 randomly selected points (1 m^2 each), including half-decomposed and undecomposed litter (Fig. 1b). Then the samples were air dried in the laboratory for use in the experiments. The litter thickness and mass were estimated by random sampling in each stand. The average thickness of *P. tabulaeformis* litter (*PTL*) and *R. pseudoacacia* litter (*RPL*) was 14 mm (SD = 6) and 25 mm (SD = 15), respectively. The average dry weight of *PTL* and *RPL* was 523 g m^{-2} (SD = 334) and 586 g m^{-2} (SD = 304), respectively.

2.3. Experimental setup

Field experiments were performed using two rainfall simulators

Fig. 1. Site diagram: (a) The selected *P. tabulaeformis* plantation stand for litter collecting; (b) litter layer covering on the *P. tabulaeformis* plantation stand; (c) calibration of rainfall intensity in the field plots; (d) rainfall simulation experiment conducted under a *P. tabulaeformis* litter mass of 500 g m^{-2}.

Table 1
Basic characteristics of *P. tabulaeformis* and *R. pseudoacacia* plantation stands.

Species	Age (year)	Area (m^2)	Density (trees ha^{-1})	DBH (cm)	Height (m)
P. tabulaeformis	30	625	1340	10.8	9.0
R. pseudoacacia	45	1350	700	14.6	8.3

Note: Diameter at breast height (DBH).

(manufactured by Northwest Agriculture and Forestry University, Yangling, China), which produced simulated rainfall from a 3.5 m fall height that was 90% uniform (Xia et al., 2018). Rainfall intensity could be varied by regulating pressure gauges and was measured using eight plastic basins uniformly distributed over the field plot (Fig. 1c). According to the precipitation data in Nanxiaohegou watershed over 24 years from 1993 to 2016, the maximum 30-min rainfall intensities of 30 mm h^{-1} and 60 mm h^{-1} approximately representing 2-yr and 10-yr return intervals, respectively; thus the two rainfall intensities were selected for the experiments to represent natural rainstorm conditions. To minimize the influence of wind on the simulated rainfall, the experiments were usually conducted at 6:00 am and 5:00 pm.

Twelve field plots (each 10 m × 1.5 m) were built on a hillslope in 2015 and allowed to lie fallow for two years. These plots were separated from each other with asbestos wall boards inserted vertically into the soil surface. We then selected two plots for simulation experiments that had average slopes of 5°, and tested the effects of soil loss and changes in the characteristics of the soil surfaces. Pre-testing indicated that gully erosion was so weak that the soil surface could recover to its pre-existing state after an experiment, and that the results would not be influenced by sequential experiments on the same plot. The two plots were rested for approximately 15 days to allow soil consolidation prior to the first simulation experiment. In addition, the topsoil in each plot was leveled and smoothed before each experiment to create similar surface conditions. Three time-domain reflectometry access tubes were installed in each plot for monitoring soil moisture and to ensure the

Table 2
Basic properties of the soil in the field plots.

Clay (%) < 2 μm	Silt (%) 2–50 μm	Sand (%) 50–2000 μm	Soil texture	Bulk density ($g\,cm^{-3}$)	Organic carbon ($g\,kg^{-1}$)	pH
10.8 ± 1.2	32.3 ± 2.2	56.9 ± 2.7	Sandy loam	1.3 ± 0.1	6.4 ± 0.9	8.5 ± 0.3

Note: Values of the mean ± standard deviations (SDs) are presented for each two replicates.

consistency of initial soil moisture conditions (i.e., average volumetric soil moisture should be almost 15% at depths between 20 cm and 40 cm). The characteristics of topsoil are summarized in Table 2.

To accurately place the desired amounts of litter in the plots, litter mass instead of litter thickness was used as the determinant. Three litter masses of 300, 500 and 800 $g\,m^{-2}$ were applied to reflect natural underlying surface conditions that would occur in a forest, and the corresponding litter coverages were close to 40%, 75% and 95%, respectively.

2.4. Field measurements

Two types of field experiments were conducted. The first type measured the interception storage capacity of litter by placing plastic sheeting under the litter to cover the soil surface. Natural rainfall cannot create a sufficient water supply condition as soaking-in water, therefore, litter interception storage capacity (C) must be considered to change with rainfall conditions instead of soaking-in water. Previous studies usually measured C using the sample tray method (Li et al., 2013); however, this approach ignored the impacts of hillslope overland flow on C. In contrast, this study measured C under various simulated rainfall intensities by using plastic sheeting beneath the litter to cover the soil surface and prevent drainage from the litter infiltrating into the soil profile. According to Sato et al. (2004), two different litter interception storage capacities exist: the amount of water detained in the litter layer at the cessation of rainfall (denoted C) and the amount of water detained in the litter layer when free drainage ceases after rainfall (denoted $C_{\min}$). Considering that free drainage from litter generally has little influence on soil erosion, this study mainly identified the impacts of C on the hydrological response. The litter interception storage capacity, therefore, was calculated as the difference between the rainfall input and the runoff output. The second type of field experiment was conducted without the plastic sheeting to analyze hydrological and hydraulic parameters of the natural soil surface and profile beneath the litter. All experimental conditions were the same between the two types of field experiments except for the underlying surface conditions.

Rainfall simulations lasting for 40 min were conducted for each treatment. During each simulated rainfall event, the runoff containing sediment was collected from the lower end of each field plot using 500 mL graduated cylinders (Fig. 1d) and measured every 2 min for the first 10 min and every 3 min for the last 30 min. These samples were dried at 110 °C for 24 h and weighed to determine sediment yield. Within 30 min after the cessation of rainfall, by which the gravitational water had drained out of the litter, the litter was removed from the soil manually. Infiltration rate was calculated by subtracting runoff rate and interception rate from the measured rainfall intensity. Soil loss rate was then calculated as the sediment yield per unit area per period of time.

Flow velocity was measured using the dye method with a $KMnO_4$ solution (Abrahams et al., 1986) over a distance of 0.5 m at upper, middle and lower plot positions. These measurements were then used to calculate the mean surface flow velocity (V_m). Afterwards the profile mean flow velocity (V) in each treatment was calculated from the mean surface flow velocity using a conversion factor of 0.67 ($V = 0.67V_m$) (Abrahams et al., 1986; Guo et al., 2010). Although flow depth was too shallow to be measured, it could be calculated using Eq. (1):

$$h = \frac{q}{Vbt} \tag{1}$$

in which h is the flow depth (mm), q denotes the runoff volume (L) within measurement period t (s), while V is profile mean flow velocity ($m\,s^{-1}$), and b is effective flow width (m).

According to hydraulic principles, the Reynolds number (R_e) can be used to discriminate overland flow regimes, as described by Eq. (2):

$$R_e = \frac{Vh}{\nu} \tag{2}$$

where ν is kinematic viscosity (0.00000101 $m^2\,s^{-1}$) and the other variables are as previously defined.

The surface resistance to overland flow was quantified using the Darcy-Weisbach friction factor (f) as described by Eq. (3):

$$f = \frac{8gRJ}{V^2} \tag{3}$$

where g is gravitational acceleration (9.8 $m^2\,s^{-1}$), R is the hydraulic radius (m), and J is the gradient.

In addition, the stream power (w) was used to evaluate the erosive power of overland flow, as described by Eq. (4):

$$w = \gamma_m gRJV \tag{4}$$

where w denotes the stream power ($N\,m^{-1}\,s^{-1}$) and γ_m denotes the density of muddy water ($kg\,m^{-3}$).

2.5. Modified Merriam interception model

Although the canopy interception processes were often considered in hydrological models, few models have been applied to represent litter interception processes for forested land. Considering the similarity between the litter interception and the canopy interception, previous canopy interception models seemed to be a good guide for litter interception functions. The Merriam interception model (Merriam, 1960), which was used for the simulation of canopy interception, can be described as:

$$E_{ci} = (C - \theta)\cdot(1 - e^{-cP}) + kP \tag{5}$$

where E_{ci} is the canopy interception (mm), θ is the initial water content of litter (mm), c is the effective interception coefficient and k is the evaporation capacity. The first component of the model is the "wetting up" of the canopy and the second component is the evaporation.

Then the model described by Eq. (5) was modified based on the experimental data to simulate the litter interception process with time. The modified model was defined as:

$$C_t = (C - \theta)\cdot\left(1 - e^{-\frac{Itc}{(C-\theta)}}\right) + kP \tag{6}$$

where C_t is cumulative interception (mm) at time t (h).

The Nash-Sutcliffe efficiency coefficient (NSE) and determination coefficient (R^2) were used to evaluate this model performance, respectively. The R^2 could be obtained by regression analysis, while the NSE was calculated as follows (Yesuf et al., 2015):

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{7}$$

where O_i and S_i are the observed and simulated values for the ith pair, n is the total number of paired values, and $\overline{O}$ is the mean of observed values. It is noteworthy that NSE can range between $-\infty$ and 1; thus, the closer the NSE is to 1, the more accurate the model is.

2.6. WEPP Hillslope model

Development of the WEPP Hillslope model was initiated in 1985 by the U.S. Department of Agriculture to provide a process-based model that could compute runoff and soil loss along a hillslope. This model can be used both in single-event and continuous simulation modes. The continuous-storm mode requires at least one year's daily meteorological data while the single-event mode requires precipitation data of one storm (Fu et al., 2012). Therefore, the single-event mode of WEPP Version 2012.8 was used to model data from the simulated rainfall experiments. The main processes in the WEPP Hillslope model have been described in detail previously (Shen et al., 2009; Maalim et al., 2013).

The WEPP Hillslope model requires four major inputs: climate data, topography data, management conditions and soil attributes. Climate data required by the model includes precipitation, temperature, solar radiation, wind speed and wind direction, and from these the data file can be created using the "Breakpoint Climate Data Generator" for WEPP. Except for precipitation data, all data were obtained from a meteorological station near the experimental plots. For topography data, the projective slope lengths of field plots were both 10 m, and the slope gradients were both 5°.

The management file is the most complicated of all input files. For bare plot, the initial conditions were set as fallow and default values were used for all parameters except bulk density. For the litter-covered plots, the initial conditions were set the same as for the bare plot, but an operation type of "residue addition" was added to supplement the initial conditions. The amount of residue and interrill cover were controlled to highlight the effects of the litter layer on runoff and soil loss.

The primary soil attributes, including soil texture, organic content, albedo and initial saturation level, were obtained by analyzing soil samples from the field. The values of the WEPP Hillslope model basic input parameters are shown in Table 3. The other four soil parameters, including effective hydraulic conductivity (K_e), critical shear stress (τ_c), interrill erodibility (K_i) and rill erodibility (K_r) are the key runoff and soil erosion parameters in WEPP Hillslope model. Two methods were utilized to compute the values of these parameters, which led to two simulation schemes (scheme A and scheme B). In scheme A, these four key parameters were calculated using WEPP-recommended equations based on measured soil properties. In scheme B, the parameters were calibrated artificially by applying sensitivity analysis (Han et al., 2016) to fit the model to the experimental data.

The Nash-Sutcliffe efficiency coefficient (NSE), the mean absolute relative error (R_e) and the paired sample t-test were utilized to evaluate the WEPP Hillslope model performance, respectively. The R_e is given by the following equation (Shen et al., 2009):

$$R_e = \left| \frac{S_i - O_i}{O_i} \right| \times 100\% \tag{8}$$

The smaller the value of R_e is, the better the model results are.

2.7. Data analysis

The experimental design was a factorial of 2 (underlying surface conditions) × 2 (litter species) × 3 (litter masses) × 2 (rainfall intensities) as well as controlled trial (bare plot), with two replicates of each treatment. The Kolmogorov-Smirnov test was used to determine whether the experimental data was normally distributed ($p < 0.05$). The Pearson correlation analysis was carried out to evaluate the relationship between soil loss rate and hydraulic parameters for 0.05 and 0.01 levels of significance. The paired sample t-test was used to evaluate the WEPP Hillslope model performance in simulating runoff and soil loss rate ($p < 0.05$). In addition, the analysis of variance (ANOVA) for significant differences in hydrological parameters among influencing factors was restricted due to the experimental designs (no independent observations and insufficient number of replicates). All the statistical analyses and graphical displays were made using SPSS 22.0 and ORIGIN 9.0 (Cao et al., 2015), respectively. The variances of the data were not shown in some tables and figures in order to improve clarity.

3. Results and discussion

3.1. Interception response

The typical interception duration curves for litter mass of 500 g m^{-2} are presented in Fig. 2. Results show that litter interception storage capacity increased with higher rainfall intensity regardless of litter types, and the broad-leaf litter (*R. pseudoacacia*) could intercept more rainwater than the needle-leaf litter (*P. tabulaeformis*) under the same rainfall condition. In addition, the interception process could be divided into two stages according to the slope of the curve: a quick wetting stage and a saturated stable stage. During the quick wetting stage, interception rate decreased rapidly with the rapid increase of litter moisture, especially in the higher rainfall intensity condition. Subsequently, the interception rate decreased slowly to a fairly constant value due to high litter moisture.

The C value of each litter species under different rainfall intensities and litter mass are summarized in Table 4. Results show that C ranged from 0.55 to 2.10 mm and the maximum value of C occurred at a rainfall intensity of 60 mm h^{-1} under the *RPL* mass of 800 g m^{-2}. C increased with increasing litter mass and rainfall intensity, which was comparable to some previous findings (Guevara-Escobar et al., 2007). Putuhena and Cordery (1996), on the other hand, believed no clear relationship existed between C and rainfall intensity. This difference is probably because their results were obtained under extremely high rainfall intensities, at which the litter layers may be almost fully saturated. However, as demonstrated in the present study, litter interception becomes more important hydrologically at lower rainfall intensities in natural conditions. The results also show that broad-leaf litter (*RPL*) could intercept and store more rainwater than needle-leaf litter (*PTL*) regardless of rainfall intensity and litter mass, which was consistent with the findings of Li et al. (2013). This effect can mostly be explained by the fact that the larger leaf area and smaller pore space of broad-leaf litter enabled this material to intercept rainwater effectively.

Table 3
The values of basic input parameters used in WEPP Hillslope model for the bare plot and litter-covered plot.

Cover type	Rainfall intensity (mm h^{-1})	Rainfall duration (min)	Slope length (m)	Slope gradient (°)	Operation type	Litter mass (g m^{-2})	Interrill cover (%)	Albedo	*SAT* (%)
Bare plot	30 and 60	40	10	5	Fallow	0	0	0.2	45
Litter-covered plot					Falllow + residue addition	300, 500 and 800	40, 75 and 95		

Note: Initial saturation level (*SAT*).

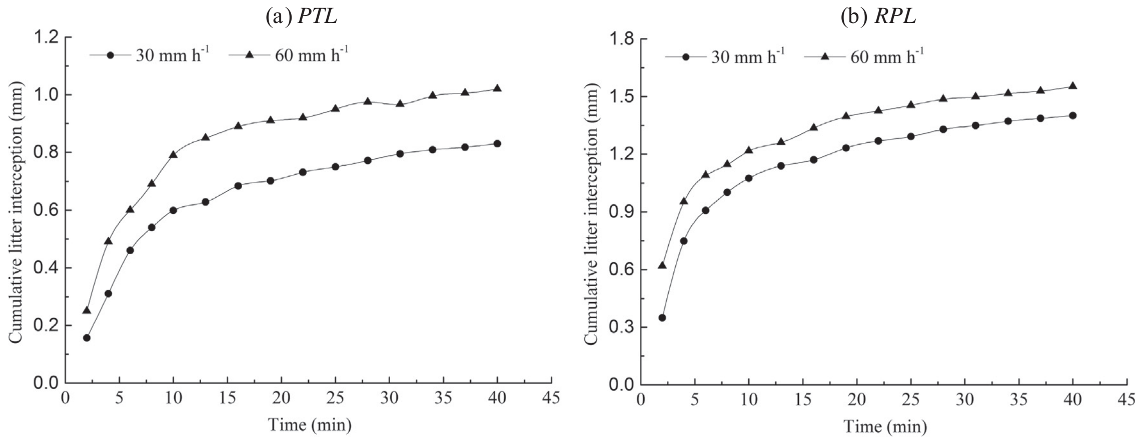

Fig. 2. Time series of litter interception of *P. tabulaeformis* litter (*PTL*) and *R. pseudoacacia* litter (*RPL*) under two rainfall intensities (litter mass: 500 g m^{-2}).

Table 4
The interception storage capacity of litter under different conditions.

Litter species	Litter mass (g m^{-2})	C (mm)	
		I = 30 mm h^{-1}	I = 60 mm h^{-1}
PTL	300	0.55 ± 0.18	0.72 ± 0.22
	500	0.83 ± 0.09	1.02 ± 0.18
	800	1.15 ± 0.26	1.33 ± 0.23
RPL	300	1.03 ± 0.07	1.19 ± 0.27
	500	1.40 ± 0.30	1.55 ± 0.25
	800	1.83 ± 0.20	2.10 ± 0.11

Note: Values of the mean ± standard deviations (SDs) are presented for each two replicates; rainfall intensity (*I*); litter interception storage capacity (*C*); *P. tabulaeformis* litter (*PTL*); *R. pseudoacacia* litter (*RPL*).

3.2. Runoff response

The effects of different litter cover conditions on runoff rate are shown in Table 5. The runoff rates varied between 11.66 and 45.45 mm h^{-1}. The fastest runoff rate was obtained on the bare plot and the slowest was found in *RPL* of 800 g m^{-2} under rainfall intensity of 30 mm h^{-1}. Results show that the runoff rate was slightly lower in litter-covered plots than in the bare plot; the average runoff rates in *PTL* and *RPL* were lowered by 18.6% and 25.9% compared to the bare plot, respectively. Meanwhile, the greater the litter mass, the lower the runoff generated. This was likely because litter cover was able not only to intercept and store rainwater, but also increase water infiltration into the soil by preventing the soil surface from sealing and increasing surface roughness, thus decreasing runoff generation (Li et al., 2014).

Results also show that runoff rate was distinctly increased with higher rainfall intensity, and litter cover was more effective in controlling runoff generation at a lower rainfall intensity than at a higher rainfall intensity. These results clearly indicate a large difference in runoff response when the rainfall intensities varied. In addition, the runoff rates for *PTL* were higher than those for *RPL* regardless of rainfall intensity and litter mass.

Table 5
Runoff response in plots under different litter cover conditions.

Cover type	Litter mass (g m^{-2})	Runoff rate (mm h^{-1})	
		I = 30 mm h^{-1}	I = 60 mm h^{-1}
Bare plot	0	22.12 ± 1.24	45.45 ± 2.09
PTL	300	19.80 ± 0.92	40.99 ± 2.46
	500	17.39 ± 1.42	38.33 ± 1.21
	800	14.35 ± 2.32	34.13 ± 1.67
RPL	300	17.75 ± 1.75	40.84 ± 2.32
	500	14.61 ± 1.23	34.60 ± 0.80
	800	11.66 ± 1.98	30.82 ± 1.22

Note: Values of the mean ± standard deviations (SDs) are presented for each two replicates; rainfall intensity (*I*); *P. tabulaeformis* litter (*PTL*); *R. pseudoacacia* litter (*RPL*).

As the litter species had slight effects on runoff rate, only the typical runoff duration curves for *PTL* under different litter mass and rainfall intensity conditions are presented in Fig. 3. The trend of the four runoff duration curves was generally similar: runoff rate increased rapidly in the early stage of rainfall (0–20 min), and then gradually stabilized to reach a peak value. However, the time taken to reach a fairly stable runoff rate was 8 min for 60 mm h^{-1} compared to 16 min for 30 mm h^{-1}. It was also found that bare plot reached the saturated stable stage faster than the litter-covered land. Moreover, runoff rate exhibited a smooth increase during the entire rainfall simulation under higher litter mass or lower rainfall intensity. These results suggest that litter cover treatments were indeed more conducive to controlling runoff generation at a lower rainfall intensity, especially in the early stage of rainfall.

3.3. Partitioning of rainwater

On plots covered by litter, rainfall was first intercepted by the litter layer; some of the rainfall that exceeded interception infiltrated into the soil, and some became surface runoff. The coefficients of interception, infiltration and runoff under different conditions are presented in

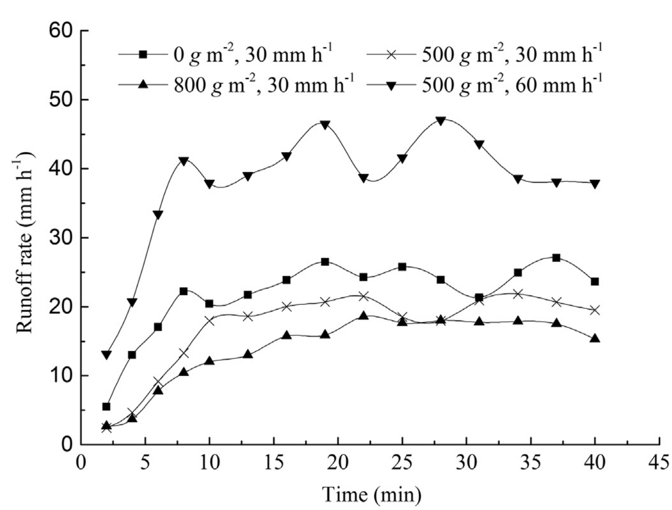

Fig. 3. Variation in runoff rate with time for different *P. tabulaeformis* litter cover treatments.

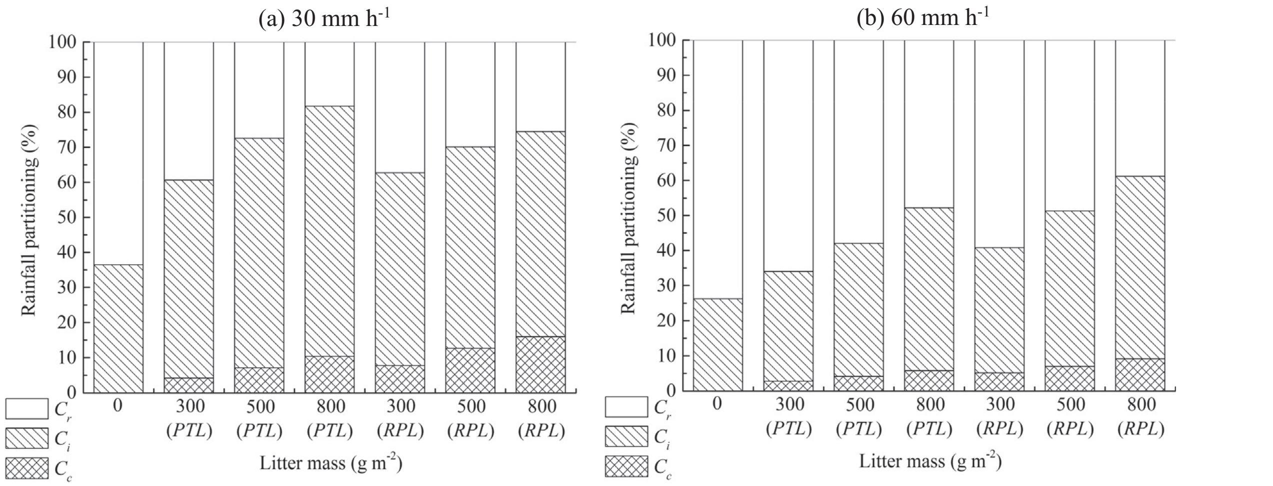

Fig. 4. Effects of litter cover on rainwater partitioning: runoff coefficient (C_r), infiltration coefficient (C_i) and interception coefficient (C_c) under rainfall intensities of 30 mm h^{-1} (a) and 60 mm h^{-1} (b). *PTL* and *RPL* represent *P. tabulaeformis* litter and *R. pseudoacacia* litter, respectively.

Fig. 4. Results show that the runoff coefficient was positively correlated with rainfall intensity and negatively associated with litter mass, while the opposite relationships existed for the interception coefficient and infiltration coefficient. At the rainfall intensity of 30 mm h^{-1}, infiltration was the main hydrological process in litter-covered plots of 800 g m^{-2}, and runoff was the dominant process in other cases. As the rainfall intensity increased to 60 mm h^{-1}, rainfall intensity gradually exceeded the infiltration capacity and the interception effects of litter cover decreased. Therefore, runoff became the main process, followed by the infiltration process, and then the interception process.

For the litter-covered plots under the rainfall intensity of 30 mm h^{-1}, 5.7% of total rainfall was intercepted by the litter layer. The remaining water was infiltrated into the soil (41.3%) or formed surface runoff (53.1%); these proportions were 57.1% larger and 28.0% smaller, respectively, compared to those of the bare plot. Similarly, at rainfall intensity of 60 mm h^{-1}, litter layer increased infiltration coefficients by 47.1% and reduced surface runoff coefficients by 19.4%, compared to those for the bare plot. These results indicated that the effects of litter cover in controlling runoff generation were due mainly to the increase of infiltration capacity. In addition, plots covered by *PTL* had higher runoff coefficients, but lower interception coefficients and infiltration coefficients, than plots covered by *RPL*.

3.4. Soil erosion process

Litter cover also had an important influence on soil erosion. Table 6 shows that the soil loss rate was distinctly lower in litter-covered plots than in the bare plot. The difference was mainly because the litter layer reduced splash erosion by protecting the soil surface against raindrop detachment, and decreased sheet erosion by reducing runoff generation and increasing surface roughness. However, the litter layer was more important in protecting the soil surface against erosion than it was in reducing runoff, corroborating findings reported by Liu et al. (2017). For example, the average soil loss rate for litter-covered plots was 66.3% and 58.3% lower compared to that for the bare plot at rainfall intensities of 30 mm h^{-1} and 60 mm h^{-1}, respectively; the corresponding runoff reduction efficiency was 28.0% and 19.4%, respectively.

Table 6
The effects of different litter cover conditions on soil loss rate.

Cover type	Litter mass (g m^{-2})	Soil loss rate (g m^{-2} min^{-1})	
		I = 30 mm h^{-1}	I = 60 mm h^{-1}
Bare plot	0	4.47 ± 0.38	18.02 ± 1.31
PTL	300	2.38 ± 0.46	7.16 ± 0.77
	500	1.14 ± 0.19	4.26 ± 0.29
	800	0.92 ± 0.13	3.56 ± 0.16
RPL	300	2.20 ± 0.26	6.93 ± 0.54
	500	1.31 ± 0.09	4.75 ± 0.20
	800	1.07 ± 0.22	4.21 ± 0.13

Note: Values of the mean ± standard deviations (SDs) are presented for each two replicates; rainfall intensity (I); *P. tabulaeformis* litter (*PTL*); *R. pseudoacacia* litter (*RPL*).

Results also show that the soil loss rate decreased with higher litter mass. Litter cover reduced the soil loss rate by 58.5%, 74.5% and 78.3% for litter masses of 300 g m^{-2}, 500 g m^{-2} and 800 g m^{-2}, respectively, compared to that of the bare plot. The litter cover at a mass of 500 g m^{-2} could substantially reduce soil erosion on loess hillslopes and that this threshold could be effective for proper erosion control. Rainfall intensity also had a direct influence on the rate of soil loss. The soil loss rate was positively correlated with rainfall intensity for all treatments. Moreover, soil loss rate was slightly lower in *RPL* plots than in *PTL* plots.

Very few previous studies have addressed the effects of litter cover on hydraulic characteristics (Dunkerley et al., 2001). Nevertheless, research on hydraulic parameter characteristics and their variations has the potential to further reveal the mechanisms of soil erosion. The results of different litter cover treatments on variations in hydraulic parameters are shown in Table 7. Litter cover had a remarkable effect on slowing the mean velocity of flow, which was decreased by 23.3%, 36.7% and 49.6% for litter masses of 300 g m^{-2}, 500 g m^{-2} and 800 g m^{-2}, respectively, compared to the mean runoff velocity from the bare plot. These differences occurred because the litter layer increased surface roughness and more flow energy was expended with higher litter mass. The Reynolds number ranged from 32.058 to 125.009, indicating that the flow regime of each treatment was predominantly laminar. In addition, the Reynolds number decreased with the increase of litter mass while the Darcy-Weisbach friction factor increased with higher litter mass; thus the soil loss rate showed the same trend with higher litter mass. Stream power is also an important hydraulic parameter affecting soil erosion, and can be used to indicate the erosion capacity of runoff (Kinnell, 2005). Results presented in Table 7 revealed a negative relationship between stream power and litter mass, which showed the same trend with soil loss rate.

Pearson correlation analysis was conducted to study the relationship between the soil loss rate and hydraulic parameters. The mean flow velocity, Reynolds number, Darcy-Weisbach friction factor and stream

Table 7
Hydraulic parameters due to various litter cover conditions on loess hillslope.

Cover type	Litter mass	Mean flow velocity ($m\,s^{-1}$)		Reynolds number		Darcy-Weisbach friction factor		Stream power ($N\,m^{-1}\,s^{-1}$)	
	($g\,m^{-2}$)	$30\,mm\,h^{-1}$	$60\,mm\,h^{-1}$	$30\,mm\,h^{-1}$	$60\,mm\,h^{-1}$	$30\,mm\,h^{-1}$	$60\,mm\,h^{-1}$	$30\,mm\,h^{-1}$	$60\,mm\,h^{-1}$
Bare plot	0	0.094	0.123	60.836	125.009	0.509	0.466	0.0531	0.1096
PTL	300	0.072	0.102	54.457	112.737	1.025	0.741	0.0473	0.0981
	500	0.053	0.088	47.831	105.413	2.213	1.050	0.0414	0.0915
	800	0.041	0.078	39.468	93.880	3.961	1.342	0.0342	0.0815
RPL	300	0.067	0.092	48.808	112.321	1.142	0.983	0.0424	0.0976
	500	0.052	0.081	40.191	95.150	2.014	1.244	0.0348	0.0826
	800	0.036	0.062	32.058	84.773	4.633	2.407	0.0278	0.0735

Note: *P. tabulaeformis* litter (*PTL*); *R. pseudoacacia* litter (*RPL*).

power were all significantly correlated with the soil loss rate, and the order of Pearson correlation coefficient was $V > w > Re > f$, ranging from −0.541 to 0.845. Each parameter has its corresponding physical meaning and plays an important role in the study of slope erosion processes and mechanisms.

3.5. The effects of litter cover on controlling runoff generation and soil erosion

The litter layer can be characterized by its key eco-hydrological functions (i.e., intercepting rainfall, increasing infiltration, decelerating surface runoff, and preventing soil loss) (Dunkerley, 2015; Liu et al., 2018). In this study, the species and mass of litter were considered to be the main controlling factors that affect the degrees to which the litter layer can help conserve soil and water.

Litter layers from different vegetation types present different responses to rainfall in terms of reducing runoff and soil erosion (Pannkuk and Robichaud, 2003). Results from the present study showed that broad-leaf litter could intercept more rainfall and reduce more runoff generation than needle-leaf litter. This agrees with previous studies conducted in plot experiments (Li et al., 2014). For example, Neris et al. (2013) noted that mean runoff in the pine needle litter-covered plots was twice that in broad-leaf litter-covered plots. On one hand, the needle-leaf litter layer promotes formation of runoff channels due to the large gaps between needles, thus leading to faster flow velocity and a lower Darcy-Weisbach friction factor. On the other hand, the broad-leaf litter promotes formation of micro-terraces due to the large area of each leaf; the micro-terraces can slow and spread overland flow and thus enhance infiltration (Ellis et al., 2006). These factors lead to diverse hydrological responses and therefore different results.

Generally, runoff and soil loss decreased with higher litter mass (i.e., litter layer coverage). Although runoff rates were slightly lower in litter-covered plots than in the bare plot, soil loss was effectively controlled when litter mass levels reached a threshold value of 500 $g\,m^{-2}$ in the present study (the corresponding litter coverage was 75%). This is consistent with studies by Blanco and Aguilar (2015) who found that the erosion threshold value was between 60 and 65% of the litter layer coverage; when the litter layer decreased to 35%, the intensity of soil erosion increased distinctly. Liu et al. (2017) also conducted that when litter coverage exceeded 70%, runoff and soil erosion in litter-covered plots were distinctly lower compared to that from bare soil plots. However, when litter coverage was < 40%, runoff and soil erosion in the litter-covered plots were no longer distinctly lower than that from bare soil plots. These results indicated that a thick, intact leaf litter layer is an important soil protection agent.

Since litter cover can have large effects in controlling soil erosion, particular attention should be given to the functions of litter layer in practical soil conservation activities. Local farmers should be advised to leave plant residue in place rather than removing and burning the litter. The litter layer should be maintained to provide a cover of 500 $g\,m^{-2}$ in order to control soil erosion effectively. Furthermore, solely from the point of view of increasing infiltration and maintaining soil water, planting broad-leaf litter tree species may result in better soil and water conservation effects than planting needle-leaf tree species.

3.6. Modeling the litter interception considering the controlling factors

Litter interception is an important element of the water balance and has a significant effect on reducing soil loss by reducing the kinetic energy of the raindrops and the amount of rainfall hitting the soil (Sun et al., 2016a). According to our field experiments, 2–9% of rainfall was intercepted by the litter layer. Previous studies also reported that interception loss by litter ranged from 1 to 2% to 50–70% of rainfall (Stan et al., 2017). However, litter interception is typically considered to constitute only a small portion of total rainfall, and in some models litter interception is not considered as a separate process (Savenije, 2004) or is even disregarded completely (Gerrits et al., 2010). Litter interception should be one of the first processes to consider in hydrologic modeling before successive processes such as infiltration and runoff are addressed (Bulcock and Jewitt, 2012). Therefore, in modeling the hydrological process on litter-covered hillslopes, it is necessary to simulate litter interception rather than disregard it.

In this study, the litter species, litter mass and rainfall conditions were recognized as the main controlling factors of litter interception storage capacity. Because litter species has large effects on C, we used litter mass (M) and total precipitation (P) to simulate C for PTL and RPL. Among all the relationships considered, the power function equation had a higher determination coefficient (R^2) and Nash-Sutcliffe efficiency coefficient (NSE) than other kinds of equations. Thus, power function equations of C with M and P were established as follows:

$$PTL: C = 0.006M^{0.665}P^{0.262}\ (R^2 = 0.991, NSE = 0.982) \tag{9}$$

$$RPL: C = 0.021M^{0.587}P^{0.185}\ (R^2 = 0.993, NSE = 0.986) \tag{10}$$

The high values of R^2 and NSE showed that the predictions of the models closely matched the measured data and attained the desired accuracy. Furthermore, according to the models C is zero when M or P is zero; that is, there will be no litter interception when no litter or rainfall is present, which is consistent with the actual conditions. Therefore, the two models can reflect the variation of litter interception storage capacity as a function of litter mass and different rainfall conditions in this study.

To further study the mechanics of litter interception, the modified Merriam interception model (Eq. (6)) was used to describe the measured interception duration curves. Because litter samples were air dried before the experiments and the evaporation could be disregarded during the rainfall events of 40 min, the initial water content of litter and the evaporation were both set to 0 mm. The fitting results for the interception duration processes are presented in Table 8.

The data presented in Table 8 reveal that R^2 ranged between 0.838 and 0.998, while NSE ranged between 0.912 and 0.998; these results show that the litter interception predicted using Eq. (6) was extremely

Table 8
Prediction results of interception processes under different litter cover conditions.

Litter species	Litter mass	c		R^2		NSE	
	($g\,m^{-2}$)	$I = 30\,mm\,h^{-1}$	$I = 60\,mm\,h^{-1}$	$I = 30\,mm\,h^{-1}$	$I = 60\,mm\,h^{-1}$	$I = 30\,mm\,h^{-1}$	$I = 60\,mm\,h^{-1}$
PTL	300	0.227	0.188	0.996	0.991	0.998	0.996
	500	0.161	0.143	0.983	0.981	0.988	0.993
	800	0.115	0.102	0.846	0.853	0.933	0.912
RPL	300	0.524	0.339	0.998	0.997	0.998	0.998
	500	0.341	0.271	0.984	0.838	0.995	0.985
	800	0.263	0.217	0.952	0.956	0.940	0.951

Note: Effective interception coefficient (c); determination coefficient (R^2); Nash-Sutcliffe efficiency coefficient (NSE); rainfall intensity (I); *P. tabulaeformis* litter (PTL); *R. pseudoacacia* litter (RPL).

close to the observed data. The very good performance of the modified Merriam interception model means that it can be used with confidence to describe the interception variation with time for different litter cover conditions.

3.7. Application of WEPP hillslope model to simulate the effects of litter cover on runoff and soil loss

The values of the four key soil parameters in two schemes and the corresponding model performance are listed in Table 9. In scheme A, the NSE for runoff and soil loss were both negative and the R_e were both > 40% when these soil parameters were calculated using WEPP-recommended equations, indicating that the WEPP model performed very poorly in predicting the experimental observations. In scheme B, the calibrated K_e, K_i and K_r were much smaller than the values calculated by the model-recommended equations, and reasonably high NSE values (0.781 and 0.814) and small R_e values (18.2% and 31.0%) for runoff and soil loss, respectively, showed that the model performed satisfactorily. It was obvious that the simulation results were distinctly improved in scheme B when values for the four key soil parameters were reduced.

Grønsten and Lundekvam (2006) utilized the WEPP Hillslope model to predict daily runoff and soil loss, and found that the WEPP-recommended soil parameter equations were not suitable for the two Norwegian soils. Larsen and Macdonald (2007) also pointed out that the performance of the WEPP Hillslope model for simulating soil erosion could be improved by reducing the effective hydraulic conductivity (K_e) on post-fire hillslopes. Moffet et al. (2007) confirmed this conclusion and suggested modifying the rill erodibility (K_r) equation by applying WEPP to predicting soil erosion on sagebrush rangeland. Therefore, here and in other studies, the four soil parameters could not be computed by the WEPP-recommended equations with sufficient accuracy. The reason for this may be that the empirical or physically based equations could not adequately represent key processes under different conditions (Larsen and Macdonald, 2007). It seems reasonable that litter cover conditions could have led to decreased soil erodibility in the present study, while the WEPP Hillslope model had no mechanism to incorporate this effect.

The simulated values (scheme B) and measured values of runoff and soil loss rate were compared to understand the adaptability of the WEPP Hillslope model in simulating litter-cover conditions (Fig. 5). Results show that runoff and soil loss predictions were relatively consistent with the observed values (quite close to the equality line 1:1), however, the predictions for soil loss rates exceeding $6\,g\,m^{-2}\,min^{-1}$ showed an evident deviation from the observed values. In addition, the WEPP Hillslope model usually under-estimated the runoff and soil loss rate in low rainfall intensity events ($30\,mm\,h^{-1}$) while over-estimated the runoff and soil loss rate in high rainfall intensity events ($60\,mm\,h^{-1}$), which was comparable to the model's performance in the earlier work of Fu et al. (2012). On one hand, soil erosion was often limited due to the short slope length used in the WEPP Hillslope model (Zhang et al., 1996), which led to the under-predictions for low rainfall events. On the other hand, the WEPP Hillslope model assumed that the whole plot would generate runoff, whereas only parts of the plot were contributing to runoff under litter-cover conditions. The over-estimated effects of the whole plot generating runoff exceeded the under-estimated effects of the slope limitation to soil erosion in the case of high rainfall events, thus leading to the over-predictions on runoff and soil loss.

In addition, the significances of the paired sample t-test for runoff and soil loss rate were 0.615 and 0.102, respectively, indicating that there were no significant differences between the observed and simulated values at 95% confidence level. All these results show that the WEPP Hillslope model can well predict soil loss under litter cover conditions in China's Loess Plateau. However, it is still necessary to improve the application of the model, especially in the development of WEPP-recommended soil parameter equations.

4. Conclusions

Litter interception storage capacity increased with increasing litter mass and rainfall intensities, and broad-leaf litter could intercept and store more rainwater than needle-leaf litter. The modified Merriam interception model developed in this study, which considered litter cover and rainfall conditions, produced litter interception values that were very close to measured values.

Litter cover played an important role in reducing water and soil losses. The litter layer was more important in protecting the soil surface

Table 9
The WEPP Hillslope model performance using the calibrated values of the four soil parameters in two schemes.

Scheme	K_e ($mm\,h^{-1}$)	τ_c (Pa)	K_i ($kg\,s\,m^{-4}$)	K_r ($s\,m^{-1}$)	Runoff		Soil loss	
					NSE	R_e (%)	NSE	R_e (%)
A	13.6	3.8	10,412,000	0.0139	−2.859	42.9	−0.901	64.3
B	3.1	4.5	4,974,960	0.0015	0.781	18.2	0.814	27.0

Note: The parameters were computed using WEPP-recommended equations in scheme A and were calibrated using sensitivity analysis in scheme B; K_e, τ_c, K_i, K_r, NSE and R_e represent effective hydraulic conductivity, critical shear stress, interrill erodibility, rill erodibility, Nash-Sutcliffe efficiency coefficient and mean absolute relative error, respectively.

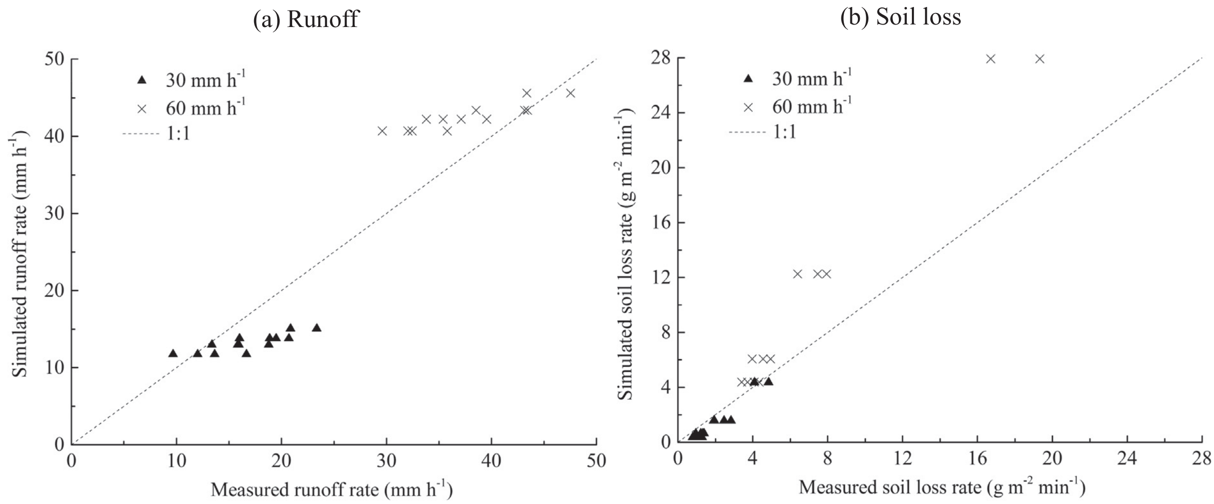

Fig. 5. Comparison of the simulated and measured runoff and soil loss rate under litter cover conditions.

against erosion than it was in reducing runoff. Soil loss was effectively controlled when litter mass levels reached a threshold value of $500\,g\,m^{-2}$. Therefore, particular attention should be given to the functions of the litter layer in practical soil conservation activities.

The WEPP Hillslope model could well predict runoff and soil loss under litter cover conditions in China's Loess Plateau, and the performance of the WEPP Hillslope model could be improved by reducing the effective hydraulic conductivity and soil erodibility computed by the WEPP-recommended equations. However, this model appeared to over-estimate runoff and soil loss for high rainfall events and under-estimate the two quantities for high rainfall events.

Overall, this research enhances understanding of the effects of litter cover on hydrological processes, and has implications for soil and water conservation as well as soil erosion modeling. Furthermore, this study mainly investigated the effects of undecomposed and half-decomposed litter on enhancing the soil's resistance to scouring, further studies performed under natural forested surface conditions are thus needed.

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