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The Role of Surface Microreliefs in Influencing Splash Erosion: A Laboratory Study

Jia WU[1,2], Longshan ZHAO[2,3,4], Faqi WU[2,3] and Zhanbin LI[1,3]

[1]Faculty of Water Resources and Hydro-electric Engineering, Xi'an University of Technology, Xi'an, P.R. China; [2]College of Natural Resources and Environment, Northwest A&F University, Yangling, Shaanxi, P.R. China; [3]State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling, P.R. China; [4]College of Forestry, Guizhou University, Guiyang, P.R. China

Abstract

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The detachment and transport of soil particles from soil mass are important effects of falling raindrops on soil erosion during rainfall. The objective of this study was to determine whether soil microrelief affects the detachability and transportability of soil particles by raindrop splash. Experimental microreliefs were manually simulated by two tillage practices: shallow hoeing, contour chisel plowing, and a smooth slope served as control treatment. The experiment included three simulated rainfall intensities (1.0, 1.5, and 2.0 mm/min). A splash board was used to collect sediment splashed upslope as well as that splashed downslope. Results show that microrelief has a positive effect on detachment rate (DR_t) and has a negative effect on net downslope movement rate (SP_{net}). With the exception of DR_t of which hoe treatment was less than smooth at the rainfall of 1.0 mm/min intensity, DR_t of hoe and chisel treatments were twice as high as that of smooth to other treatments. For all treatments, SP_{net} of hoe and chisel treatments were less than half of smooth. Regression analysis showed that DR_t change with increasing rainfall intensity could be described by a power function for all treatments. The change of SP_{net} could be described by a logarithmic function for hoe and chisel treatments, while the change of SP_{net} of the smooth treatment could not be described by a logarithmic function. Statistical results suggest that DR_t was significantly influenced by rainfall intensity, while SP_{net} was not. Conversely, SP_{net} was significantly influenced by soil microrelief, while DR_t was not.

Keywords: detachment rate; soil erosion; splash board; raindrop impact

Raindrop splash erosion is a major component of water erosion because it detaches soil clods and produces transport of soil particles from their mass (Ghadir & Payne 1977; Al Durrah & Bradford 1982). The detachability and transportability of sediment are parameters important for quantifying raindrop splash erosion (Poesen & Savat 1981; Savat & Poesen 1981). In the past, many studies have been done to explain the mechanism and characteristics of raindrop splash erosion and most of these studies showed that the detachability of soil particles by raindrop impact largely depends on rainfall characteristics (e.g. diameter, raindrop kinetic energy, and intensity), soil mass properties (e.g. soil type, soil shear strength, bulk density, cohesion, organic matter content, and surface water content), and vegetative cover (Meyer 1981; Park *et al.* 1983; Nearing & Bradford 1984; Bradford *et al.* 1987; Ghadir & Payne 1988; Morin & Van Winkel 1996; Miura *et al.* 2002; Legout *et al.* 2005). Furthermore, Torri and Poesen (1992) declared that soil slope gradient also has a positive effect on raindrop detachment.

Sediment transport is an important subprocess of raindrop splash erosion. Legout *et al.* (2005) and Leguedois *et al.* (2005) suggested that the transportability of splashed sediment was highly distance-

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dependent and was related to particle size. The mass of the splashed soil particles exponentially decreased with increasing transport distance (Savat & Poesen 1981; van Dijk *et al*. 2002). Moreover, the transport was also related to the splash direction. Wan *et al*. (1996) suggested that the soil mass of downslope splash transport increased as a power function with increasing the slope gradient.

From the above discussion it follows that many investigations, involving the splash mechanism and influencing factors, have been done in the past. However, almost all of these experiments were conducted on a uniform or flat surface in a soil box or small device. Little research has specifically measured the splash detachment and transportation on a rough surface. Therefore, the main objective of this experiment was to measure the effect of microrelief on splash detachment and transport under laboratory conditions. Likewise, the effects of changing rainfall intensities were also considered.

MATERIAL AND METHODS

Soil properties. Top soil (0–20 cm depth) was collected from farmlands at Yangling, Shaanxi Province, China (34°17'56''N, 108°04'07''E). The fields had been continuously cultivated for more than ten years. The soil was of Lou type according to the Chinese classification system and Udic Haplustalf according to the USDA system (Table 1).

Experimental design and methods. The objective of this study was to quantify the effect of soil microrelief on splash erosion. To achieve this purpose, we designed an experiment in which the mass of the splashed sediments from downslope and upslope directions was measured using a splash board. The experiments were conducted at the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau in China. Simulated rainfall intensities of 1.0, 1.5, and 2.0 mm/min were used. The soil surface microrelief was simulated manually at the upslope and downslope in soil box at a 10° incline.

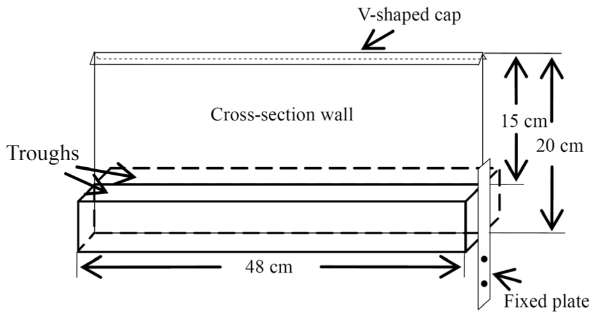

Figure 1. Scheme of splash board (microrelief)

Soil boxes and splash board. In this study, the soil box was 0.5 m wide, 0.5 m deep, and 0.3 m long. The splashed sediment was measured using a splash board (Figure 1). During rainfall, the splash board was fixed in the centre of the box using two fixed plates so the box was divided into two sections. The section close to the top of the box was defined as upslope and the section at the bottom half of the box was defined as downslope.

The splash board was made from a galvanized iron sheet. The framework of the splash board mainly consisted of a V-shaped cap, a cross-section wall, two troughs, and fixed plates. The cross-section wall was at a height of 30 cm and a width of 48 cm. It was by 2 cm shorter than the soil box (50 cm width) to ensure a proper installation of the splash board in the box. Two troughs were located at the bottom of both sides of the cross-section wall to collect the raindrop splash droplets from upslope and downslope. Each trough was 5 cm deep, 3 cm wide, and 48 cm long. A V-shaped cap at the top of the cross-section wall was used to protect samples in troughs from repeated raindrop impact.

Soil preparation of boxes. Air-dried soil was crushed and passed through a 5 mm sieve to ensure homogeneity. Then, soil boxes were filled with the sieved soil in successive layers of 10 cm thickness, with a total of five layers per box. The bulk density of each soil layer was around 1.30 g/cm^3. A wood block was then pulled along the box edges to level the soil surface over the box.

Table 1. Physicochemical properties of the studied soil (depth 0–20 cm)

Organic matter	Total N	Total P	CEC (mmol/100g)	Soil particle size (mm)					
				< 0.001	0.001–< 0.005	0.005–< 0.01	0.01–< 0.05	0.05–0.25	> 0.25
(g/kg)				(%)					
16.66	0.91	0.50	18.47	36.28	12.89	6.88	41.13	2.70	0.12

CEC – cation exchange capacity

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The surface microreliefs in boxes were then prepared manually, simulating the surfaces in agricultural fields of the Loess Plateau in China under different tillage practices: (1) shallow hoeing (Hoe) and (2) contour chisel plowing (Chisel) (Zhao *et al.* 2013, 2014).These two types of surface microreliefs are commonly observed in agricultural fields of the Loess Plateau in China (Fu *et al.* 2004; Wu *et al.* 2004). A smooth slope (Smooth) was used as a control treatment. After simulation of the surface microrelief, a 30 min rainfall of 0.167 mm/min intensity was applied to reestablish the cohesion of soil. This was done to reduce the effect of mechanical disturbances caused by the microrelief simulation. Each of the other boxes was also prepared using the same procedure and each run used freshly prepared soil.

Simulated rainfall. The study was conducted in a laboratory with a rainfall simulator equipped with 4 side-spray nozzles, positioned 15 m above the ground. The Maximum rainfall intensity can be up to 3 mm per min. This rainfall simulator has been used for rainfall related research scores of times over the past decades (Pan & Shangguan 2006).

Before each run, the rainfall intensities were calibrated with 5 rain gages to meet the desired intensity. The mean rainfall kinetic energy was 23.49, 26.21, and 28.42 J/m^2/mm for rainfall intensity of 1.0, 1.5, and 2.0 mm/min, respectively. During a rainfall event, the beginning and end time of rainfall were recorded and the sediment samples splashed by raindrops from downslope and upslope were collected using a splash board. The rainfall was stopped immediately if surface runoff initiated in any of the soil boxes. After the rainfall, the samples were dried at 110°C for about 8 h to eliminate water weight. The samples were cooled to room temperature and then weighed. Using these procedures the mass of upslope and downslope splashed sediment can be measured.

Data analysis. In this study, the detachment rate equation defined by Torri and Poesen (1992) was used for calculating detachment rate (gram per Joule of rainfall kinetic energy per square meter) on the surface with different microreliefs.

$$DR_t = DR_{down} + DR_{up} \quad (1)$$

where:

DR_t – detachment rate (g/J/m^2)

DR_{down}, DR_{up} – detachment rate on the downslope and upslope surface (g/J/m^2)

In addition, a percentage reflecting the net downslope sediment movement from upslope to downslope was calculated. The equation was:

$$SP_{net} = [(DR_{up} - DR_{down})/DR_t] \times 100 \quad (2)$$

where:

SP_{net} – net downslope movement rate (%)

The value ranges of SP_{net} allow the analysis of the transportability of raindrop splashed sediment. If SP_{net} value is positive, it indicates that the upslope splashed sediment was greater than the downslope splashed sediment. Inversely, if SP_{net} value is negative, it indicates that the downslope splashed sediment was greater than the upslope.

Statistical and regression analyses were done using MS Excel 10.0. Multi-variate analyses of variance (MANOVA) were done with SPSS 17.0 to test the significant difference of the effect of microrelief and rainfall intensiy on detachability and transportabilty of sediment by raindrop impact (i.e. DR_t and SP_{net}).

RESULTS

Rainfall duration. According to the experimental design, the rainfall event was stopped immediately once runoff was initiated from any of the slopes of the smooth, hoe, and chisel treatments. This was done in order to eliminate the effect of runoff on raindrop splash. In all cases, the first runoff appeared on the smooth slope, regardless of rainfall intensity (Table 2). This phenomenon affirms the common viewpoint that soil surface roughness can delay the initiation of surface runoff due to depression storage (Darboux & Huang 2005; Gómez & Nearing 2005).

The mean times to the initiation of runoff for smooth treatment were 1.95 min under the rainfall intensity of 2 mm/min, 4.42 min under the rainfall intensity of 1.5 mm/min, and 5.36 min under the rainfall intensity of 1 mm/min. Correspondingly, the standard deviation was 0.18, 0.45, and 0.91 min.

Table 2. Rainfall duration of different rainfall intensities

Rainfall intensities (mm/min)	First microrelief*	Mean	SD	CV (%)
		(min)		
1.0	smooth	5.36	0.91	17.01
1.5	smooth	4.42	0.45	10.18
2.0	smooth	1.95	0.18	8.99

*smooth surface was the first in treatments (shallow hoeing, contour chisel plowing and smooth surface) to generate surface runoff under the same rainfall condition; SD – standard deviation; CV – coefficient of variance

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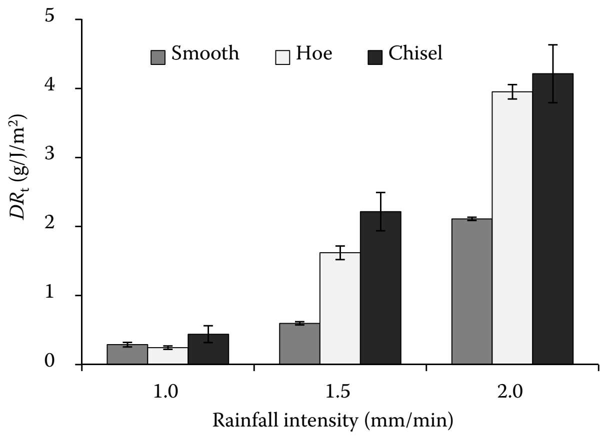

Figure 2. Detachment rate (DR_t) from various microreliefs during rainfall of different intensity; smooth – smooth slope; hoe – shallow hoeing; chisel – contour chisel plowing

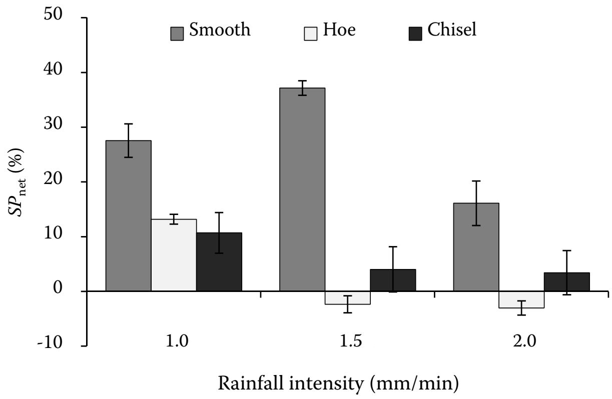

Figure 3. Changes in net downslope movement rate (SP_{net}) linked with rainfall intensity increase for various surface microreliefs; smooth – smooth slope; hoe – shallow hoeing; chisel – contour chisel plowing

Effect of microrelief on detachment rate. Figure 2 presents the detachment rate (DR_t) for each rainfall intensity and treatment. The DR_t was significantly different for all treatments. With the exception of smooth and hoe treatments at rainfall of 1.0 mm/min intensity, the overall DR_t of hoe and chisel treatments were larger than of the smooth treatment for all rainfall events. Under rainfall of 1.5 and 2.0 mm/min intensity, the DR_t of hoe and chisel treatments were approximately twice as high as that of smooth treatment.

For all treatments, the DR_t tended to increase with increasing the rainfall intensity. The best-fit regression analysis showed that the detachment rate (DR_t) and rainfall intensity (I) had a significant power function relation.

For smooth treatment, the equation was:

$$DR_t = 0.19\, I^{2.11}\ (R^2 > 0.81);$$

For hoe treatment, the equation was:

$$DR_t = 0.19\, I^{4.17}\ (R^2 > 0.99);$$

For chisel treatment, the equation was:

$$DR_t = 0.34\, I^{3.42}\ (R^2 > 0.99).$$

This nonlinear relationships between DR_t and I supports the detachment rate–rainfall intensity relationship mentioned in the literature (Foster 1982; Sharma *et al.* 1993). However, the power exponents of the regression equations in this study were significantly different from those in previous literature. The power exponent attained the value of 2 in the erosion model (Foster 1982). In the report by Sharma *et al.* (1993), the exponents ranged from 1.085 to 1.436 for two soil types and raindrop detachability. In this study, the power exponent was around 2 (approximately 2.11) only for the smooth treatment, while the power exponents for hoe and chisel treatment were greater than 3. This shows a strong dependence of detachment rate on rainfall intensity for hoe and chisel treatments.

Effect of microrelief on net downslope movement rate. The change of the net downslope movement rate (SP_{net}) with rainfall intensity for the different microreliefs is shown in Figure 3. Predictably, the SP_{net} of the smooth treatment was markedly greater than that of the hoe or chisel treatments, regardless of rainfall intensity. The SP_{net} was approximately 27.56% for the smooth treatment under the rainfall of 1.0 mm/min intensity. When the rainfall intensity was 1.5 mm/min, the SP_{net} showed a maximum value (approximately 38%) for the smooth treatment. Whereas for the hoe and chisel treatments, the greatest SP_{net} values were 13.18 and 10.70%, respectively, at the rainfall intensity of 1.0 mm/min. Beyond that, the SP_{net} decreased significantly with increasing rainfall intensity. This trend can be described by a logarithmic function.

For the hoe treatment, the equation was:

$$SP_{net} = -10.88 \ln(I) + 10.04\ (R^2 > 0.88)$$

For the chisel treatment, the equation was:

$$SP_{net} = -24.36 \ln(I) + 11.52\ (R^2 > 0.86).$$

However, no logarithmic relationship was found between SP_{net} and I for the smooth treatment.

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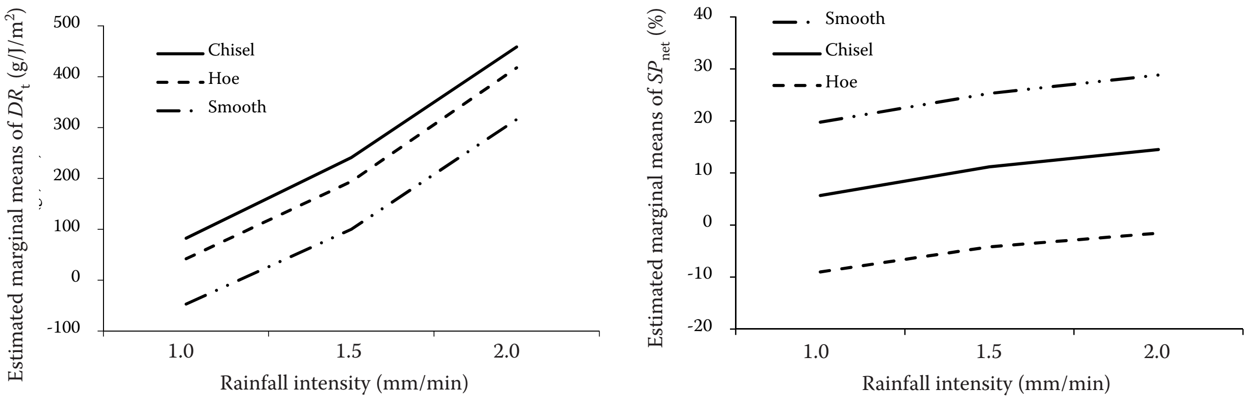

Figure 4. Detachment rate (DR_t) and net downslope movement rate (SP_{net}); any two lines crossed imply the existing interaction between microreliefs and rainfall intensities, and *vice versa;* smooth – smooth slope; hoe – shallow hoeing; chisel – contour chisel plowing

Furthermore, for the hoe treatment, the SP_{net} was negative when the rainfall intensity was 1.5 and 2.0 mm/min. This suggests that the mass of the splashed sediment from upslope was less than that of the downslope. In other words, a net upslope movement of splashed sediment appeared for the hoe treatment during rainfall.

Main effect analysis of microrelief and rainfall intensity on splash erosion. Figure 4 shows DR_t and SP_{net} tested based on the multi-variate analysis of variance (MANOVA). It can be seen clearly that three lines representing the smooth, hoe, and chisel treatments were parallel to each other, indicating that microrelief and rainfall intensity were independent of each other, i.e. no interaction effect existed on DR_t and SP_{net} from microrelief and rainfall intensity. The test results (Table 3) showed that the effect of microrelief on SP_{net} was significant at the 0.01 level, but the effect on DR_t was not (P = 0.109). Contrary to this, the effect of rainfall intensity on DR_t was significant at the 0.05 level, but the effect on SP_{net} was not (P = 0.278). It is apparent that the microrelief was the main factor leading to the difference in SP_{net} and rainfall intensity was the main factor leading to the difference in DR_t.

DISCUSSION

The differences in splash erosion between different surface treatments are likely related to the spatial structures of the surface microrelief. In this study, the surface microrelief structure of the smooth, hoe, and chisel treatments can be simple, as shown in Figure 5. For the smooth treatment, the surface microrelief was relatively smooth. In this case, the detachment rate was mainly determined by rainfall intensity and this characteristic agrees with those in the previous studies (Al Durrah & Bradford 1982; Wan *et al.* 1996). However, for the hoe and chisel treatments, special microrelief increased the local slope of surface and hence improved DR_t due to increased raindrop impact associated with the slope increase (Torri & Poesen 1992). Therefore, the DR_t of the hoe and chisel treatments were larger than

Table 3. Significance test of the effect of microrelief and rainfall intensity on the detachment rate (DR_t) and net downslope movement rate (SP_{net})

Factor	Type III sum of squares	df	Mean square	F-test	P
DR_t					
Rainfall intensity	201 635.286[a]	2	100 817.643	22.416	0.007
Microrelief	36 542.059[a]	2	18 271.030	4.062	0.109
SP_{net}					
Rainfall intensity	290.293[b]	2	145.146	1.359	0.278
Microrelief	4 034.609[b]	2	2 017.304	18.890	0.000

[a]R^2 = 0.930 (adjusted R^2 = 0.860); [b]R^2 = 0.648 (adjusted R^2 = 0.584); df – degrees of freedom

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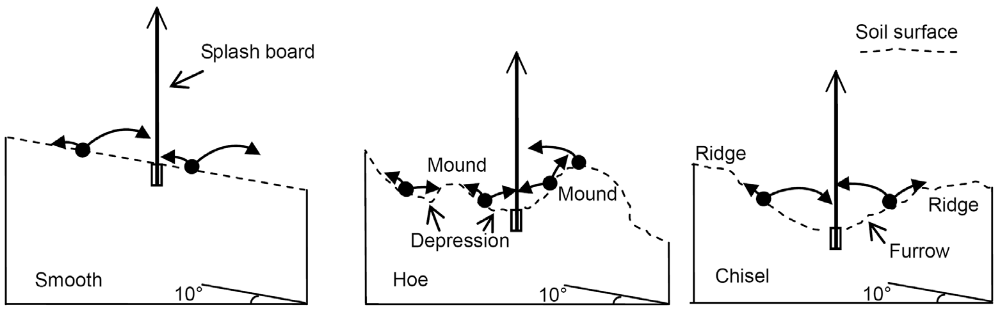

Figure 5. Schemes of the local profile showing the microrelief with a splash board; smooth – smooth slope; hoe – shallow hoeing; chisel – contour chisel plowing

that of the smooth treatment and showed a strong increasing trend with an exponent of 4.17 and 3.42 as rainfall intensity increased.

Our above given results indicate that the downslope detachment rate increased as the rainfall intensity increased while the upslope detachment rate decreased. This contradicts the common observations in the literature. Poesen and Savat (1981) measured a net downslope sediment movement and hereby built a splash model. Wan *et al.* (1996) found that the downslope splash transport was dominant when the slope was more than 10%. This may be related with the spatial structure of the microrelief. Bochet *et al.* (2000) and more recently Planchon and Mouche (2010) have suggested the effect of soil microrelief on the detachability and transportability of sediment. Their description was consistent with our results to a larger extent. At the chisel treatment, the microrelief structure with furrows and ridges represented a symmetric disposition on the soil surface. In this case, the mass of the splashed sediment from the downslope was closed to that from the upslope. Therefore, the value of SP_{net} was lower. At the hoe treatment, the microrelief consisted of intensive depressions and mounds, which represented random rather than symmetric disposition on the soil surface. This spatial characteristic of the microrelief was the so-called anisotropy and heterogeneity (Vidal Vázquez *et al.* 2005). As a result, the splashed sediment from downslope was larger than that from upslope, resulting in a negative SP_{net}. This suggests that the spatial structure of the surface microrelief has an important effect on the transportability of sediment.

CONCLUSIONS

Detachment and transport of soil particles are the main impacts of raindrops affecting soil erosion during rainfall. Generally, most studies have shown that the net downslope movement was the main process for soil sediment detaching by raindrop on the inclined surface. In this study, we found that detachment rates (DR_t) of the hoe and chisel treatments were larger than that of the smooth treatment, regardless of rainfall intensity. However, the net downslope movement rates (SP_{net}) of the hoe and chisel treatments were lower than that of the smooth treatment. This suggests that the microrelief structure can increase soil detachability but decrease transportability.

In addition, the detachment rate increased concurrently with increasing rainfall intensity for all treatments and the change can be described by a power function. Furthermore, the net downslope movement rate decreased with increasing rainfall intensity for the hoe and chisel treatments and the change can be described by a logarithmic function, while no logarithmic relationship was found for the smooth treatment.

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Corresponding author:

Dr. Longshan Zhao, Guizhou University, College of Forestry, Guiyang, 550025 Guizhou, P.R. China;
e-mail: zls@nwsuaf.edu.cn