

Study on the runoff sediment transport rate of two planting modes under the influence of rainfall

Dongdong wang (✉ 1534849533@qq.com)

Dezhou University

Article

Keywords: Ecological planting pattern, Erosion process, Soil improvement, Earthworms, Erosion mechanism

Posted Date: July 21st, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1838423/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

In order to explore the impact of ecological planting pattern on runoff sediment transport rate(T_2), this study in two planting modes with a single planting of *Prunella vulgaris* (A) and *P. vulgaris* and earthworms (B) were investigated through simulated rainfall experiments in the field. The results showed that: 1) T_2 decreased first and then stabilized with the rainfall duration, which is dominated by the composition of soil particle size and runoff depth; 2) T_2 under gentle slope and steep slope conditions is greatly affected by rainfall intensity and slope, respectively; 3) T_2 , which has a good correlation with runoff separation rate (D_2), needs to be explained in conjunction with soil properties or raindrop kinetic energy. The main controlling factors of T_2 in bare slope, B, A are raindrop kinetic energy, D_2 , and organic matter, which explain 93.10%, 95.76%, and 98.65%. Compared with B, A has obvious economic and ecological value.

1 Introduction

Erosion process research is the key to preventing and controlling soil erosion. Runoff dominates erosion, runoff sediment transport rate directly reflects the intensity of erosion (Wang et al. 2015; Wang et al. 2016; Bing et al. 2019; Wang et al. 2021). However, it should be noted that the splashing of raindrops under rainfall conditions complicates the law of soil separation and transportation and makes related research difficult.

Various studies suggest that the runoff sediment transport rate can increase with an increase in slope discharge, flow discharge, or rain intensity (Zhang et al. 2008; Xiao 2017; Lei et al. 2006; Qingwei et al. 2018). These can be described by linear or power functions; the power function of the slope and flow discharge is applied in the ANSWERS model (Beasley et al. 1980). Because erosion during rainfall is limited by soil transport or separation, the response of runoff sediment transport to hydraulic parameters must be described in sections. While the sediment transport capacity in the limited soil transport stage can be described by the power function of the above hydraulic parameters, it is better described by the power function of the simulation effect of stream power combined with rainfall energy (Qingwei et al. 2018). Stream power, raindrop kinetic energy, and runoff sediment transport rate under open slope conditions have a significant negative correlation with runoff detachment rate, with contribution rates of 65.69%, 18.41%, and 6.5%, respectively (Bing et al. 2018). Further, the runoff sediment transport rate has a significant negative correlation with the raindrop detachment rate, hydrodynamic parameters, silt content, and biological characteristics (Wang et al. 2014). However, numerous disputes still remain over various aspects, such degree of influence of slope, flow discharge, rain intensity on runoff sediment transport rate, which may be caused by differences in experimental design.

In China, *Prunella vulgaris* is an important medicinal herb used in the National Medical Industry Information Standard Promotion Project. It has a wide range of cultivation, simple and easy planting techniques, a short life cycle, as well as considerable economic benefits (Lejoly et al., 2021). Under the requirements of high-quality agricultural development, two methods are used to cultivate traditional

Chinese medicine plants. The traditional, single planting of *P. vulgaris*, and the ecological planting method, where planting is combined with introduction of earthworms. This study set three simulated farmland treatments: no crops, single planting of *P. vulgaris*, and *P. vulgaris* combined with earthworms. First, determining of the variation characteristics of runoff sediment transport rates during rainfall in two planting models; secondly, analysis of the response of mean runoff sediment transport rate to rainfall intensity and slope in two planting models; finally, comparing the variation mechanisms of runoff sediment transport rate in two planting models.

2. Test Materials And Research Methods

2.1 Test location and materials

Field tests and soil sample determination were conducted in the Guangdong Wuhua Soil and Water Conservation Science and Technology Demonstration Park, and the Guangdong Provincial Environmental Science and Technology Public Laboratory. The equipment used included portable rainfall equipment, a laser rain spectrometer, and a digital video camera. The materials included *P. vulgaris* L (plant spacing of 15 cm × row spacing of 20 cm) and *Eisenia foetida* (5 g/piece, 400 g/m²). The soil in South China is latosolic red soil and the soil properties of the sample plot are listed in Table 1.

Table 1
Soil physical and chemical properties of sample plots

Test items	pH	OM	SD	CD	WS	BD	MC
unit of measure	Dimensionless	g/kg	g/cm ³	ds/m	g/kg	g/cm ³	mg/kg
-	5.84	7.80	2.60	0.13	0.9	1.12	66.8
Note: The significance level of the equation in the table is 0.05. BD is soil bulk density, PH is soil pH, OM is organic matter, SD is soil density, CD is electrical conductivity, WS is water-soluble salt content, and MC is microbial carbon.							

2.2 Sample plot layout and test sites

To design the field test plan, the slope length of the sample plot was set to 120 cm, and a four-directional splash collector (5 cm × 5 cm × 20 cm) was designed to collect sputter erosion in four directions, which was arranged along the contour line (Fig. 1). The length and width of the simulated rainfall test plot were 1.2 and 1.0 m, respectively. The plots were ploughed and transplanted with *P. vulgaris* and earthworms. The test treatments are listed in Table 2.

Table 2
Field simulation rainfall test design and times

Treatment	O	B	A
Level	Conduct 18 fields with earthworm treatment and bare plots at a slope of 10° at 0.7, 1.2, 1.6, 2.2, 2.7mm/min or at a slope of 2°, 5°, 15°, 20° at a rain intensity of 1.6mm/min;		According to the rain intensity of 1.6, 2.2 and 2.7mm/min at a slope of 10° or 1.6mm/min rain at a slope of 15° and 20°
Repetition	1		1
total	44		
Note: O is Bare slope; B is Prunella vulgaris combined with earthworm planting slope;A is Single planting prunella vulgaris slope			

2.3 Test process and observation content

Before the test, the bulk density, soil particle density, organic matter, microbial carbon, electrical conductivity, total water-soluble salt, mechanical composition, pH, and other indicators were determined according to conventional methods. Two months after planting *P. vulgaris*, simulated rainfall was carried out in the field. Before the simulation, the rain intensity was adjusted according to the test plan, and a sample was collected every 3 min, until the end of the simulation. simulated rainfall test was run for 40 min. The sputter erosion and flow production in four directions were collected in a graduated cylinder to measure the volume, and then sampled. Following this, the volume of the muddy water was measured with a graduated cylinder, and then clarify, skim off the water, dry, and weigh heavy. Before sampling, the flow velocity in the velocity measurement area (2 cm at the lower end of the erosion monitoring area and 2 cm at the edge of the velocity measurement area) was measured using the dye method. The distance was set at 50 cm. During the test, a thermometer was used to measure the temperature of the muddy water, and the laser rain spectrometer was used to measure the size of the raindrops and the end speed of the raindrops.

2.4 Index calculation

The soil migration index was calculated according to the principles of sediment transport, erosion balance, soil detachment, and sediment transport balance. The raindrop detachment capability (rate) is calculated as the total amount of splash erosion of raindrops in four directions (up, down, left, and right) per unit time within the projected splash collection area (Eq. 1); raindrop sediment transport capability (rate) is the difference between splashes in two directions up and down per unit time within the projected eclipse collection area of the upper and lower sides (Eq. 2). The runoff sediment transport rate (runoff sediment transport capacity) is equal to the ratio of the difference between the erosion rate and the raindrop sediment transport capacity (rate) (Eq. 3); The runoff detachment rate is the difference between the erosion rate and the raindrop detachment capacity (Eq. 4); Specified equations are below:

$$D_1 = (S_1 + S_2 + S_3 + S_4) / A_S \times t \quad (1)$$

$$T_1 = (S_2 - S_1) / A_o \times t \quad (2)$$

$$T_2 = SE - SC_o \quad (3)$$

$$D_2 = SE - SC \quad (4)$$

where D_1 , T_1 , SE , T_2 , and D_2 are the raindrop detachment capacity (rate), raindrop sediment transport capacity (rate), erosion rate, runoff sediment transport rate, and runoff detachment rate, respectively, in $\text{kg m}^{-2} \text{s}^{-1}$. S_1 , S_2 , S_3 , and S_4 are the amounts of splash erosion in the upper, lower, left, and right directions, respectively, in kg. A_s is the projected area of the splash collection area and A_o is the projected area of the splash collection area in the upper and lower directions, both are expressed with the unit is m^2 . Lastly, t is the rainfall time (s).

2.5 Data processing

SPSS19.0 and EXCEL2003 software were used for data analysis and chart making. Following this, the optimal multivariate equation was established with multiple factors. We then obtained the multivariate regression square, and calculated the contribution rate of the factors to the detachment or sediment transport of raindrops and runoff using the equation:

$$O_i = \frac{R^2}{\sum_{i=1}^n \beta_i^2} \times \beta_i^2 \times 100\%$$

5
,

$$\beta_i^2 = b_i \frac{\sigma_i}{\sigma_y}, \quad b_i$$

where O_i is the contribution rate of the i th factor, R^2 is the complex regression square, b_i is the regression coefficient of the i th factor, σ_i is the mean square error of the i th factor, and σ_y is the mean square error of the dependent variable.

3. Results

3.1 Variation characteristics of runoff sediment transport rates on slopes with different treatments during rainfall

The runoff sediment transport rate of the three treatment slopes under different rain intensities or slopes decrease then become stable with increasing duration of rainfall. The fluctuations are very large between 0–6 min. The runoff sediment transport rate of the bare slope, slope with *P. vulgaris*, and slope with *P. vulgaris* and earthworms became stable at 37 min with the stability values of $5 \times 10^{-5} \sim 6 \times 10^{-5} \text{ kg / (m}^2 \cdot \text{s)}$, $1 \times 10^{-5} \sim 5 \times 10^{-5} \text{ kg / (m}^2 \cdot \text{s)}$, and $0.5 \times 10^{-5} \sim 5 \times 10^{-5} \text{ kg / (m}^2 \cdot \text{s)}$, as shown in Figs. 2–4. The

results suggest that planting crops can reduce the fluctuation and intensity of runoff sediment transport rate but does not change the trend. Moreover, the time period 30 min before rainfall is the key to preventing and controlling runoff sediment transport rate.

The runoff sediment transport rate of the three treatment slopes between different rain intensities or slopes were consistent during the rainfall process. The difference in runoff sediment transport rate among the three treatment slopes decreased with rainfall time, while the difference between rain intensity was greater than the difference between slope gradients. When compared with bare slope, the reduction rate of the runoff sediment transport rate on the two planted slopes during the rainfall process became smaller. Among them, the effect of the slope planted with *P. vulgaris* and earthworms was the most obvious.

3.2 Variation characteristics of runoff sediment transport rate for different planting methods across a single rainfall

With an increase in rain intensity or slope gradient over single rainfall period, the mean runoff sediment transport rate of all three slopes increased slowly (Fig. 5). This can be described by a binary function equation with a correlation coefficient of greater than 0.6 (Table 3). Although the slope of 2°–20° and rain intensity of 0.7–2.6 mm/min did not increase rapidly throughout the process, gentle slopes (2° or 5°) and steep slopes (15° or 20°), light rain (0.7 or 1.2 mm/min) and heavy rain (2.2 or 2.6 mm/min) are significantly different (Table 4). Results showed that rain intensity dominates the runoff sediment transport rate on different slopes, but the impact of slope gradient under steep slopes or heavy rain conditions will increase significantly over the impact of rain intensity. The results of this experiment agree with previous studies (Bing et al. 2019).

Table 3
The relationship between the runoff sediment transport rate and the slope or rain intensity

Equation	
O	$T_2 = 9.54 \times 10^{-6} + 1.79 \times 10^{-6} S + 2.83 \times 10^{-5} I, R^2 = 0.9473, \text{Sig} < 0.05$
B	$T_2 = -2.3 \times 10^{-5} + 2.44 \times 10^{-6} S + 2.93 \times 10^{-5} I, R^2 = 0.9804, \text{Sig} < 0.05$
A	$T_2 = -9.8 \times 10^{-5} + 5.06 \times 10^{-5} \ln(S) + 6.39 \times 10^{-5} \ln(I), R^2 = 0.9942, \text{Sig} < 0.05$

Table 4
Compared with runoff sediment transport rates between three treatment slopes

Index	S(°)		Three treatment		
kg/(m ² s)	/l(mm/min)		O	B	A
T ₂ (10 ⁻⁵)	10	0.6	4.37a	1.99a	
		1.2	5.61ab	3.50b	
		1.6	7.81b	4.60b	4.74a
		2.2	8.80b	6.07c	7.01ab
		2.6	9.67b	7.81d	7.82b
	1.6	2	6.40a	3.11a	
		5	6.33a	3.87ab	
		10	7.81ab	4.60b	4.74a
		15	8.16ab	5.93c	6.91b
		20	9.48b	7.64d	8.30b
Note: D ₁ , T ₁ , D ₂ , T ₂ are raindrop detachment rate, raindrop sediment transport rate, runoff detachment rate, runoff sediment transport rate, respectively, S is Slope (o),I is Rainfall intensity(mm/min); a, b, c, d are the difference comparison of LSD, and the significance level is 0.05.					

3.3 Optimizing the sediment transport rate equation

It can be seen from Table 5 and Table 6, under naked soil conditions, Soil bulk density, organic matter, stream power, raindrop kinetic energy, runoff separation rate and runoff sediment transport rate have high correlation coefficient, and their relationship can be described in multi-power equation, which can be explained to 2.76%, 4.09%, 0.04%, 93.10% ,0.01%,total 99.99%, of which the effect of raindrop kinetic energy is the largest; Under the planting mode of *Prunella vulgaris* combined with earthworms, microbial carbon, > 2 soil particle content, stream power, raindrop kinetic energy, runoff separation rate and runoff sediment transport rate have high correlation coefficients, which can be described by multivariate linear equations, with a total explanation of 99.99%, of which the runoff separation rate is the main controlling factor, and the explained 95.76%; Under the single planting mode of *Prunella vulgaris*,the correlation coefficient of organic matter, shear stress, raindrop separation rate and runoff sediment transport rate is relatively high, which can be described by a ternary logarithmic equation, explaining a total of 99.99%, of which organic matter is the main controlling factor, explaining 98.65%.

Table 5
Correlation analysis of runoff sediment transport rates of three treatment slopes

Treatment	O	B	A
BD	-0.46	-0.61	-0.51
pH	0.38	-0.22	0.25
OM	-0.47	-0.57	-0.54
SD	0.24	0.61	-0.02
CD	0.29	0.28	0.38
WS	0.32	-0.04	0.47
MC	-0.45	-0.59	-0.50
P ₁	0.46	0.62	0.52
P ₂	-0.21	-0.50	0.33
τ	-0.43	0.01	-0.87
ω	0.72	0.85	0.63
U	0.70	0.72	0.63
E	0.66	-0.22	0.69
RD	-0.14	-0.54	-0.11
RE	0.53	0.76	0.37
D ₁	0.73	0.79	0.74
T ₁	0.89	0.81	0.50
D ₂	0.89	1.00	1.00
Note: The significance level of the equation in the table is 0.05. BD is soil bulk density, PH is soil pH, OM is organic matter, SD is soil particle density, CD is electrical conductivity, WS is water-soluble salt content, MC is microbial carbon, P1 is > 2 soil particle content, P2 is < 0.002 soil Particle content, τ is shear stress, ω is stream power, U is unit stream power, E is unit energy, RD is raindrop diameter, RE is raindrop kinetic energy, D₁ is raindrop separation rate, T₁ is raindrop sediment transport rate, D₂ is runoff separation rate, T₂ is runoff sediment transport rate.			

Table 6

The contribution rate of the main influencing factors to the runoff sediment transport rate of the three treatments

Treatment	Equation	Contribute(%)
O	$T_2 = 0.94 \times BD^{-0.24} \times OM^{0.004} \times \omega^{-0.01} \times RE^{0.002} \times D_2^{1.01}$	BD:2.76%, OM:4.09%, ω :0.04%, RE:93.10%, D_2 :0.01%
B	$T_2 = 2.76 \times 10^{-6} - 2.1 \times 10^{-9} MC - 6.8 \times 10^{-8} P_1 - 1.1 \times 10^{-6} \omega - 1.6 \times 10^{-9} RE + 1.02 D_2$	MC:0.44%, P_1 :1.00%, ω :0.50%, RE:1.16%, D_2 :97.35%
A	$T_2 = 1.27 \times 10^{-6} - 2.4 \times 10^{-8} OM - 4.9 \times 10^{-7} \tau + 0.99 D_2$	OM: 98.65%, τ : 1.34%, D_1 :0.01%

4. Discussion

4.1 Soil particle size composition and runoff depth determine the change trend of runoff sediment transport rate

The red soil of South China evolved from sedimentary rock; hence, it has coarser grains and less clay. In the early stages of rainfall, the raindrops splashing on the slope and the soil roughness were large (Feng et al. 2019); additionally, the fluctuations in the early stage of runoff sediment transport rate were particularly large. As rainfall progresses, increasing amounts of sand and gravel make that runoff require more energy to transport sediments. The runoff sediment transport rate gradually stabilised within a certain range. This meant that, before stabilising, the runoff sediment transport rate fluctuated and decreased, then stabilised with the increase in rainfall duration. In other words, the change trend of runoff sediment transport rate on the slope surface during the rainfall process of the three treatments was determined by the composition of soil particle size and runoff depth. This is why it is different from the variation characteristics of runoff sediment transport rate on loess slopes (Su et al. 2014; Wang et al., 2014, 2015; Bing et al. 2019).

4.2 Rainfall intensity has a significant import on runoff sediment transport rate

The greater the rain intensity, the greater the splashing kinetic energy of the raindrops, and the greater the runoff formed on the surface. It also leads to greater runoff sediment transport rate. Although the slope gradient cannot provide erosion energy, the larger the slope, the smaller the erosion energy in a specific area, and the greater the erosion energy conversion rate. On the other hand, the planting pattern cannot change the erosion energy, but only increased the soil erodibility (Lei et al., 2006; Zhang et al. 2020). Therefore, under these combined influences, although the effect of rain intensity is more than 10 times that of slope gradient, but sometimes the effect of slope is greater than that of rain intensity..

4.3 The planting mode of *P. vulgaris* and earthworms significantly reduces runoff sediment transport rate

Under the condition of bare soil, runoff and sediment transport are directly affected by raindrops, but the single planting of *P. vulgaris* shields the rainfall, which did not significantly improve the soil properties in the short term, and the main indicators affecting soil migration did not change. This suggests that farmlands cannot be improved under the current planting mode. Instead, using the ecological method of planting *P. vulgaris* and introducing earthworms to the soil can significantly improve soil properties in a short period of time, causing the main indicators affecting runoff sediment transport rate to change, and in turn, improving agricultural land (Borken et al. 2000; Xiao et al. 2017; Dongdong et al. 2018; Bing et al. 2019; Wang et al. 2020; Ma et al. 2021). Therefore, the runoff sediment transport rate in the rainfall process or single rainfall follow the pattern: exposed slope surface > single planting *P. vulgaris* slope surface > *P. vulgaris* and earthworms slope surface. In conclusion, the main controlling factors of runoff sediment transport rate in bare soil, *Prunella vulgaris* combined with earthworm, single planting *Prunella vulgaris* planting modes are raindrop kinetic energy, runoff separation rate, and organic matter, which explain 93.10%, 95.76%, and 98.65%.

5. Conclusion

(1). As rainfall progresses, When the amount of easy-to-migrate soil decreases gradually to steady, the runoff sediment transport rate also decreased gradually to a steady state. These results suggest that the clay content and runoff depth determine the overall change trend of runoff sediment transport rate.

(2). The study showed a slow increase in the runoff sediment transport rate with an increase in rain intensity or slope, which can be described by a binary function. Rain provides erosion kinetic energy, but the effect of steep slopes on runoff sediment transport rate is greater than rainfall intensity. Compared with single planting of *Prunella vulgaris*, *Prunella vulgaris* combined with earthworm planting mode has obvious economic and ecological value.

Declarations

Acknowledgments

The National Key Research and Development Program of China (2017YFC0505404); Guangdong Provincial Science and Technology Project 2018B030324001 ; Key-Area Research and Development Program of Guangdong Province (2019B110205003); GDAS' Project of Science and Technology Development (2019GDASYL-0503003; 2019GDASYL-0401003; 2019GDASYL-0502004; 2019GDASYL-0102002; 2019 GDASYL-0301002); Guangzhou Science and Technology Plan Project 202002020026 ; The high-level leading talent introduction program of GDAS (2016GDASRC-0103); The Innovation-driven Development Capability Construction Program of GDAS (2018GDASCX-1301); School-level research projects (30101451; 30101937; 320114; SYJS18009; SYJS18015; ZZYQ20004).

Author contributions

Dongdong Wang conceived and designed the research themes, and wrote the paper.

Competing Interests Statement

The author(s) declare no competing interests.

Data availability statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

References

1. Beasley D B, Huggins L F, Monke E J. 1980.ANSWERS: a model for watershed planning[J]. Transactions of the ASAE - American Society of Agricultural Engineers, 23(4): 938 ~ 944. DOI:10.13031/2013.34692
2. Bing Wu. 2018.Experimental study on dynamic process of sheet erosion on Loess hillslope[D].University of Chinese Academy of Sciences.
3. Bing Wu, Zhanli Wang, Qingwei Zhang, Nan Shen, Jun'e Liu.2018.Distinguishing transport-limited and detachment-limited processes of interrill erosion on steep slopes in the Chinese loessial region[J]. Soil and Tillage Research. 177:88–96.DOI:10.1016/j.still.2017.12.005
4. Bing,W.,Zhan-Li, W., Qing-Wei, Z., Nan, S., June, L.. 2019.Response of soil detachment rate by raindrop-affected sediment-laden sheet flow to sediment load and hydraulic parameters within a detachment-limited sheet erosion system on steep slopes on loess plateau, china[J]. Soil and Tillage Research,185, 9–16.DOI:10.1016/j.still.2018.08.012
5. Borken W, Gründel S, Beese F. 2000.Potential contribution of *Lumbricus terrestris* L.to carbon dioxide, methane and nitrous oxide fluxes from a forest soil [J]. Biology and Fertility of Soils, 32(2): 142–148. DOI: 10.1007/s003740000228
6. Dongdong, W., Zhanli, W., Qingwei, Z., Qilin, Z., Naling, T., & Jun'E, L.. 2018. Sheet erosion rates and erosion control on steep rangelands in loess regions: sheet erosion rates and erosion control on steep rangelands. Earth Surface Processes and Landforms, 43.DOI:10.1002/esp.4460.
7. Feng, Y., Wang, J., Bai, Z., Reading, L.2019. Effects of surface coal mining and land reclamation on soil properties: A review. Earth-Science Reviews, 191, 12–25.DOI: 10.1016/j.earscirev.2019.02.015.
8. Qingwei, Z., Zhanli, W., Bing, W., Nan, S., Jun'e L .2018. Identifying sediment transport capacity of raindrop-impacted overland flow within transport-limited system of interrill erosion processes on steep loess hillslopes of china[J]. Soil and Tillage Research,184, 109–117.DOI: 10.1016/j.still.2018.07.007.

9. Qingwei, Z., Zhanli, W., Qi G., Naling T., Nan, S., Bing W., Jun'e L. 2019. Plot-based experimental study of raindrop detachment, interrill wash and erosion-limiting degree on a clayey loessal soil[J]. *Journal of Hydrology*, 575: 1280–1287. DOI: 10.1016/j.jhydrol.2019.124535.
10. Lei T W, Zhang Q W, Zhao J, Nearing M A. 2006. Tracing sediment dynamics and sources in eroding rills with rare earth elements. *European Journal of Soil Science*, 57(3): 287 ~ 294. DOI:10.1111/j.1365-2389.2005.00737.x.
11. Lejoly Justine, Quideau Sylvie, Laganière Jérôme. 2021. Invasive earthworms affect soil morphological features and carbon stocks in boreal forests[J]. *Geoderma*, 404. DOI:10.1016/j.geoderma.2021.115262.
12. Su Z L, Zhang G H, Yi T, Liu, F. 2014. Soil Detachment Capacity by Overland Flow for Soils of the Beijing Region. *Soil Science*, 179(9): 446 ~ 453. DOI:10.1097/SS.0000000000000089.
13. Ma Li, Shao Ming'an, Fan Jun, Wang Jiao, Li Yanpei. 2021. Effects of earthworm (*Metaphire guillelmi*) density on soil macropore and soil water content in typical Anthrosol soil[J]. *Agriculture, Ecosystems and Environment*, 311. DOI:10.1016/j.agee.2021.107338.
14. Wang J G, Li Z X, Cai C F, Ma R M. 2014. Particle size and shape variation of Ultisol aggregates affected by abrasion under different transport distances in overland flow[J]. *Catena*, 123: 153 ~ 162. DOI:10.1016/j.catena.2014.07.020.
15. Wang Z L, Yang X, Liu J, et al. 2015. Sediment transport capacity and its response to hydraulic parameters in experimental rill flow on steep slope[J]. *Journal of Soil & Water Conservation*, 70: 36 ~ 44. DOI:10.2489/jswc.70.1.3.
16. Wang Dongdong, Yuan Zaijian, Cai Yitong, Jing Dawei, Liu Fen, Tang Yan, Song Ningning, Li Yangyang, Zhao Chunyu, Fu Xiuyong. 2021. Characterisation of soil erosion and overland flow on vegetation-growing slopes in fragile ecological regions: A review [J]. *Journal of environmental management*, 285. DOI: 10.1016/j.jenvman.2021.112165.
17. Wang, Xuejia Gu, Jingrui Chen, Jianqiang Zhu. 2020. Raindrop-induced ejection at soil-water interface contributes substantially to nutrient runoff losses from rice paddies[J]. *Agriculture, Ecosystems and Environment*, 304. DOI:10.1016/j.agee.2020.107135..
18. Xiao H, Liu G, Liu P L, Zheng F L, Zhang J Q, Hu F N. 2017. Response of soil detachment rate to the hydraulic parameters of concentrated flow on steep loessial slopes on the Loess Plateau of China[J]. *Hydrological Processes*, 31(14): 2613 ~ 2621. DOI:10.1002/hyp.11210.
19. Zhang K L, Shu A P, Xu X L, Yang Q K, Yu B. 2008. Soil erodibility and its estimation for agricultural soils in China. *Journal of Arid Environments*, 72(6): 1002 ~ 1011. DOI:10.1016/j.jaridenv.2007.11.018.

Figures

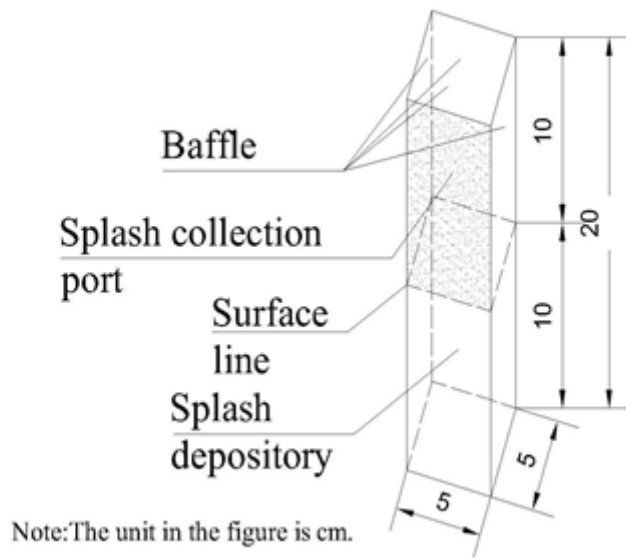


Figure 1

Splash collector

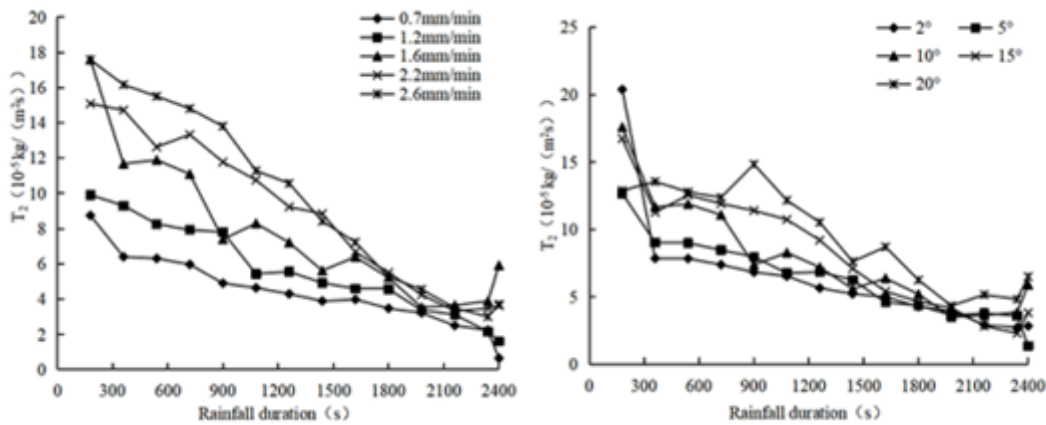


Figure 2

Variation in mean runoff sediment transport rates of exposed slopes over a period of rain

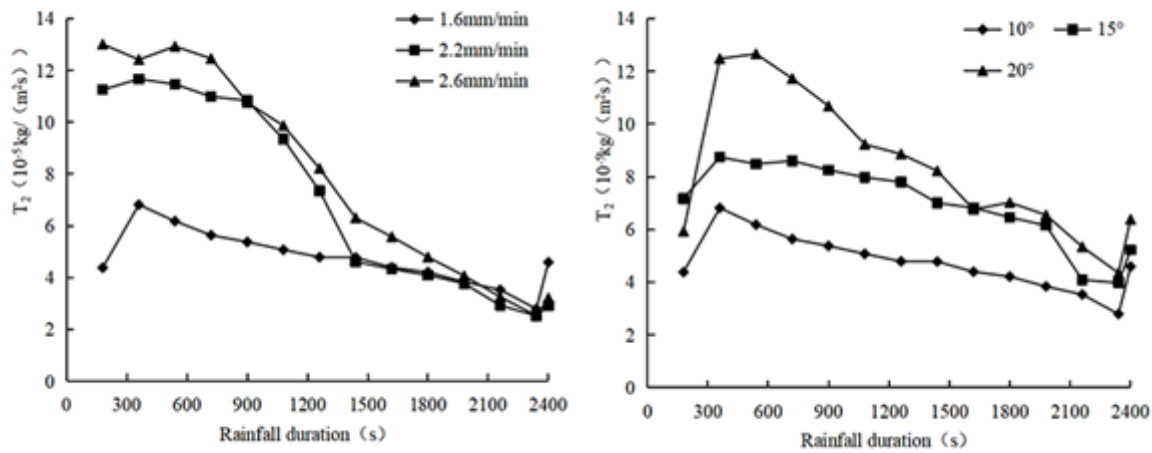


Figure 3

Variation of mean runoff sediment transport rates of slopes with *Prunella vulgaris* over a period of rain

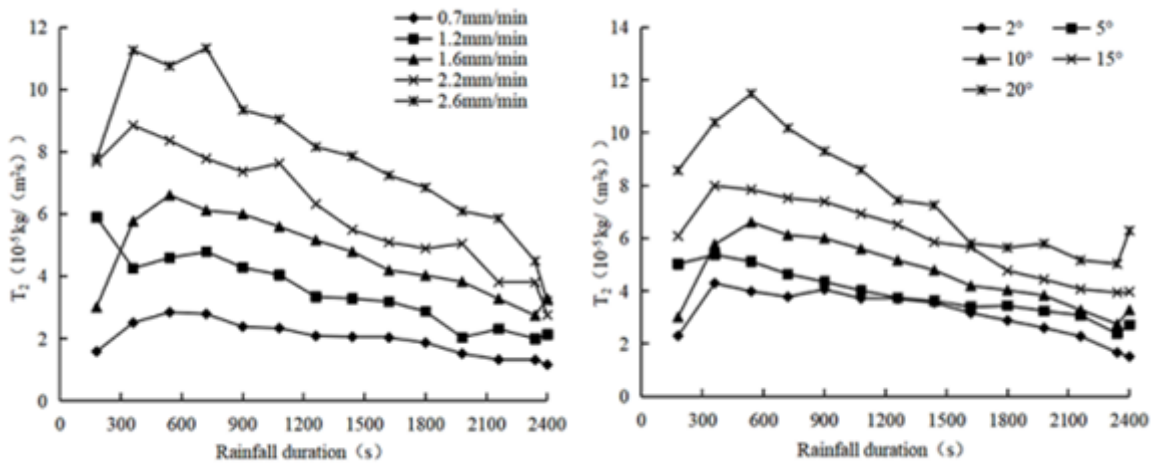


Figure 4

Variation of mean runoff sediment transport rates on slope surface with *Prunella vulgaris* combined with earthworms over a period of rain

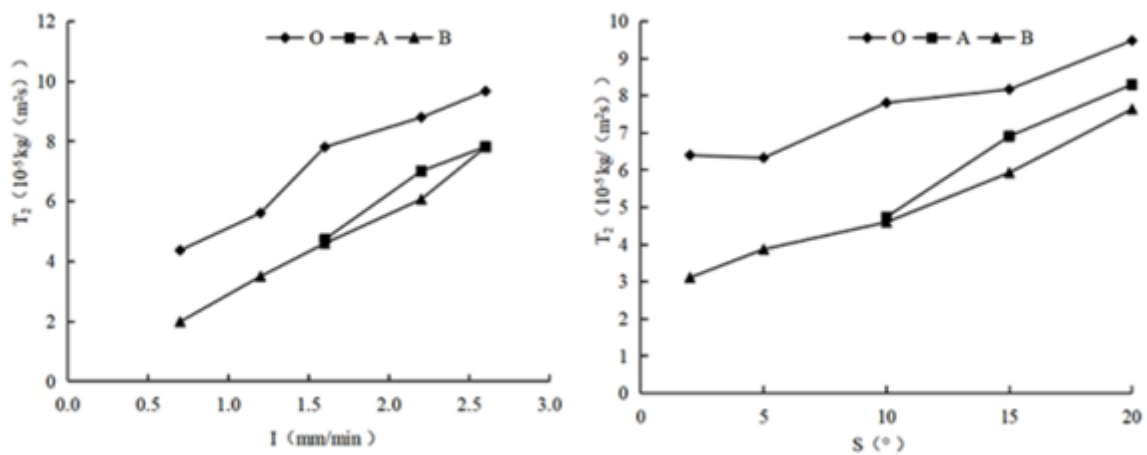


Figure 5

Changes of mean runoff sediment transport rates of three treatment slopes with rain intensity or slope gradient