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RESEARCH ARTICLE

Effects of alfalfa coverage on runoff, erosion and hydraulic characteristics of overland flow on loess slope plots

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Abstract An evaluation of the interactions between vegetation, overland and soil erosion can provide valuable insight for the conservation of soil and water. An experiment was conducted to study water infiltration, runoff generation process, rate of sediment erosion, and hydrodynamic characteristics of overland flow from a sloping hillside with different draw-off discharges from alfalfa and control plots with 20° slope. The effect of alfalfa on runoff and sediment transport reduction was quantitatively analyzed. Alfalfa was discussed for its ability to reduce the overland flow scouring force or change the runoff movement. Compared to the bare-soil plots, alfalfa plots generated a 1.77 times increase in infiltration rate. Furthermore, the down-slope water infiltration rate for the bare soil plots was higher than in the up-slope, while the opposite was found in the alfalfa plots. In addition, alfalfa had a significant effect on runoff and sediment yield. In comparison to the control, the runoff coefficient and sediment transportation rate decreased by 28.3% and 78.4% in the grass slope, respectively. The runoff generated from the alfalfa and bare-soil plots had similar trends with an initial increase and subsequent leveling to a steady-state rate. The transport of sediment reduced with time as a consequence of the depletion of loose surface materials. The maximum sediment concentration was recorded within the first few minutes of each event. The alfalfa plots had subcritical flow while the bare-soil plots had supercritical flow, which indicate that the capability of the alfalfa slope for resisting soil erosion and sediment movement was greater than for bare soil plots. Moreover, the flow resistance coefficient and roughness coefficient for the alfalfa plots were both higher than for the bare-soil plots, which indicate that overland flow in alfalfa plots had retarded and was blocked, and the flow energy along the runoff path had gradually dissipated. Finally, the ability to erode and transport sediment had decreased.

Keywords alfalfa, soil erosion, runoff and sedimentation, soil water infiltration, overland flow, hydrodynamic characteristics

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1 Introduction

Soil erosion is one of the most problematic eco-environmental issues in the world. It involves the detachment and transport of soil particles, water storage and runoff, and soil water infiltration [1,2]. The relative magnitude and importance of these processes depend on a host of factors, including climate, soil, topography, cropping and land management practices, control practices, antecedent conditions, and the amount of area under consideration [3]. The Loess Plateau in Northern China is famous for its deep loess soil. Due to the special geographic landscape, soil and climatic conditions, and history (over 5000 years) of human activity, there has been prolonged intensive soil erosions that have significantly impacted the environment and the social and economic development in the region [4,5]. Many studies have shown that the runoff is the main factor contributing to soil and water loss in the hillside area [6]. Vegetation is the most important measurement to control soil and water losses in the Loess Plateau Region, therefore, tree planting and grass cultivation must be constantly developed to improve the ecological environment in this region [7,8].

Based on field experiments in which grass stems and leaves were cut close to the ground surface, Prosser et al.

concluded that both the flow resistance and critical shear stress of concentrated overland flow in the sediment translocation decreased compared to a complete grass cover [9]. Chatterjea, Braud, and Pan have studied the influence of vegetation on runoff and sediment generation. Their results show that grasses significantly reduce sediment yield, and that the presence of moss results in a decrease of soil infiltration [10–12]. Cerda and Casermeiro studied the influence of vegetation cover on the erosion and hydrological processes [13,14]

Although numerous studies were conducted on the effect of grass on decreasing slope runoff and sediment, the present research focuses primarily on the runoff and soil erosion processes. To date, there are few reports on the effect of alfalfa on decreasing runoff, erosion yield, and regulating hydraulic characteristics of overland flow. Soil erosion is known to involve a complex physical process involving interactions between both overland flow and soil properties, in which the scouring force due to overland flow becomes the major factor affecting soil erosion and the transfer and deposition of sediment and runoff movement [15,16]. Some studies have demonstrated that the mechanism on overland flow scouring surface soil can be explained and clarified by quantitative research on the hydraulic characteristics of overland flow, such as flow velocity, flow depth, friction coefficients, and their relationships [17–21]. However, few studies have examined the inter-rill flow in the vegetation-covered plots under rainfall conditions. The objectives of this study are to improve the understanding of the influence of alfalfa on soil infiltration and runoff and sediment-producing processes, and to verify the mechanism of alfalfa on cutting down the overland flow scouring force and changing the runoff movement through the analyses of its hydraulic characteristics. The results have deepened our understanding of the effect of this type of vegetation on erosion and provide the basis for the development of a model for vegetation-regulated soil erosion.

2 Materials and methods

2.1 Environmental conditions and treatments

The experiments were conducted at the soil erosion and dryland farming field experiment station on the Loess Plateau in Yangling. The location was in an arid-semiarid region of China. The soil was loamy-clayey of loess origin, with a particle-size distribution of: 0.10%, 1.00–0.25 mm particles; 2.30%, 0.25–0.05 mm; 36.70%, 0.05–0.1 mm; 14.60%, 0.01–0.005 mm; 13.30%, 0.005–0.001 mm; and 32.90%, $<$ 0.001 mm. The content for water-stable aggregates ($<$ 0.01 mm particles) was 61.60%.

The experimental station has a total of 24 field standard runoff plots situated on two types of slopes (10-degree and 20-degree angles). The functions of research sites were: to long-term monitoring the runoff, sediment yield and the soil moisture in different treatment measurements, to analyze the soil erosion situation, and to develop a reasonable scheme of soil and water conservation. Six experimental plots were constructed in the research area. Design of the experimental plots, alfalfa field plot and bare-soil plot are shown in Fig. 1, each with a length of 20 m and a width of 1.66 m which a width of 5 m was divided into three equimultiple. Three plots were performed on a two-year old alfalfa field with a height of about 14.77 cm and a vegetative covering of about 60.4% (measurement method shown in Section 2.2). The other three plots were performed on a bare-soil control. Layout figure of alfalfa plots and bare-soil field control plots are shown in Fig. 2

Runoff experiments were carried out to measure scouring on the plots with a 20° ground slope. Periphery height of plot is 30-cm high as shown grey shaded part of in Fig. 2, and cement-block borders were installed around each plot to limit the catchment areas and to improve the accuracy of runoff and scouring measurements.

Based on the climate, topography and maximum possible runoff in this region, the flow rates were specified

(a) (b) (c)

Fig. 1 Design of the experimental plots (a), alfalfa field plot (b) and bare-soil plot (c) at 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 $m^3 \cdot h^{-1}$ by use of a flowmeter, equivalent to 0.70, 1.06, 1.42, 1.78, 2.14, and 2.50 $mm \cdot min^{-1}$ of the average application intensity.

2.2 Index measurements

1) Coverage measurement

Coverage refers to the ratio of projected area of the plant branches and the leaves vertical to the surface of the whole sample area. Thus, the coverage was calculated by the following by Eq.(1):

$$\text{Coverage(C)} = \frac{\text{Projected area(P)}}{\text{Sample area(S)}} \times 100\%. \quad (1)$$

Vegetative coverage was determined using the projective geometry method. The calculation procedures were (i) to obtain digital images (a) through the camera and import them onto a computer, (ii) to process the image using Photoshop 6.0 software to obtain the gray image (b), (iii) to use "colors range" in order to select the coverage of the green area, and to fill the green areas with white and the rest with black, and finally, a black and white image (c) generated (Fig. 3), (iv) by selecting the "Histogram" order in the Photoshop 6.0 software, the number of green leaf pixels and all sample land pixels were obtained. (v) The coverage was consequently calculated using the ratio of the number of green leaf pixels to sample land pixels.

2) Soil water content

The soil water content was determined using a Time-Domain-Reflectometry instrument (TRIME/TDR, MIKO, Germany) on the up-slope, mid-slope, and down-slope sections of each plot, before and after each scouring experiment with different draw-off discharges. The soil water content was measured at 10-cm intervals, at a maximum depth of 150 cm, and infiltration rates were determined by subtracting the measured runoff rates from the up-slope water application rate. The evaporation and surface storage components were implemented along with infiltration to ensure mass balance. The average values of the runoff and sediment rates were stable during the final 15 min of each simulated experiment.

3) Runoff and sediment collection

Discharge was adjusted and monitored by regulating the flow meter at the upper section of the experimental plots. The runoff and sediment yield in each plot was collected by a three-level runoff tank at the lower part of each plot. Each instance of runoff was recorded, and the collection of runoff and sediment occurred every two minutes. The sediment was separated from the water, then dried in an air-forced oven at 105°C, and then weighed. The sediment concentration was determined by the ratio of dry sediment mass to runoff volume. The sediment yield rate was defined by dividing the sediment yield per unit area by the period of time.

4) Surface flow velocity

Surface flow velocities (Vs) along the slope were measured using a $KMnO_4$ chemical tracer. The time elapsed for the tracer to travel a distance of 1 m was determined according to the color-front propagation, using a stopwatch. Values of Vs were used to estimate the profile mean velocities (V) by the relation of $V = k$ Vs. Assuming a quadratic vertical velocity distribution with respect to the water depth in laminar flow, the value of the coefficient k is 0.67.

5) Water infiltration

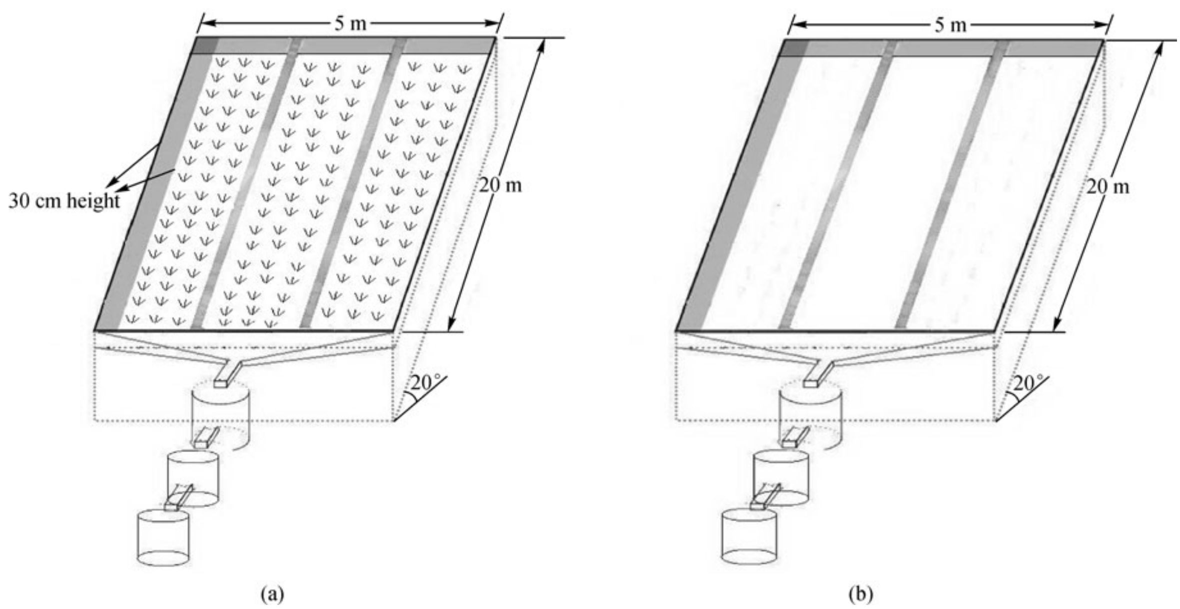

Fig. 2 Layout of alfalfa plots (a) and bare-soil field control plots (b)

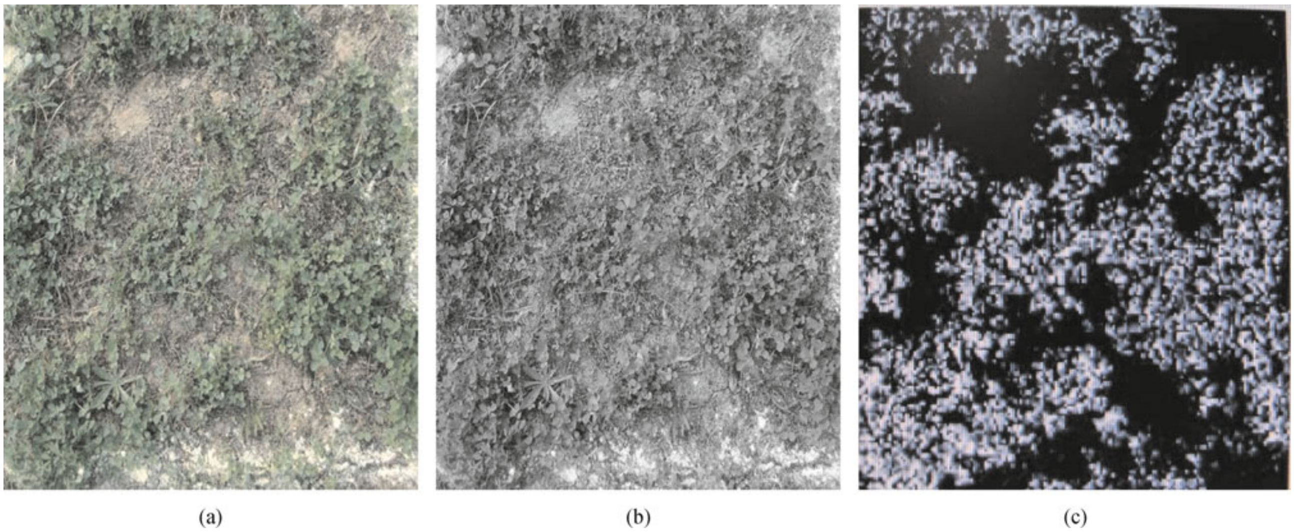

Fig. 3 Sample image (a), gray image (b) and black and white image (c) obtained in the experimental plots

The experimental study was based on the simulation of the surface runoff with various discharges at the alfalfa plots. Vegetative interception was ignored because the experiment used surface runoff rather than artificial rain. Therefore, the infiltration on the slope was calculated from the D-value of rainfall volume and the runoff yield was calculated according to a water mass balance. Thus, the water infiltration rate (i_j) ($mm \cdot min^{-1}$) was calculated through Eq. (2):

$$i_j = I\cos\theta - \frac{10R_j}{S \times t}, \quad (2)$$

where I is the application intensity ($mm \cdot min^{-1}$), θ is the ground slope (°), t is the time interval for the collection of runoff samples (min), R_j is the jth measured runoff volume (mL), and S is the surface area (m^2).

6) Hydraulic parameters

Water depth is an important factor for surface flow, yet difficult to measure because of the erosion processes on the plot surfaces. Assuming a uniform overland flow, the mean flow depth can be calculated through Eq. (3):

$$h = \frac{q}{U} = \frac{Q}{tUB}, \quad (3)$$

where h is the water depth (m), q is the discharge ($m^2 \cdot s^{-1}$) per unit width, Q is the total runoff volume (m^3) during time t (s), U is the mean flow velocity ($m \cdot s^{-1}$), and B is the cross-sectional width (m).

The Reynolds number is the ratio of inertia to viscous forces, and indicates the water flow (laminar or turbulent). As the Reynolds number increases, and the probability of turbulent flow also increases, with a critical value separating laminar and turbulent flow of about 500 for the experimental conditions. The Froude number (Fr) is the ratio of inertia to gravitational forces. Subcritical flow occurs when $Fr < 1$, and supercritical flow occurs when $Fr > 1$. The Reynolds (Re) and Froude (Fr) numbers were calculated according to Eqs. (4) and (5) respectively:

$$Re = \frac{Uh}{v}, \quad (4)$$

$$Fr = \frac{U}{\sqrt{gh}}, \quad (5)$$

where v is kinematic viscosity ($m^2 \cdot s^{-1}$), which is equal to 1.0 (10) $^{-6}$ $m^2 \cdot s^{-1}$ for the measured water temperature of 20°C, U is as defined above, and g is the ratio of weight to mass (9.81 $m \cdot s^{-2}$).

The Darcy-Weisbach resistance coefficient (f) is dependent on soil particle resistance, configuration, wave, and rainfall resistance, which reflects the resistance to overland flow exerted by the soil. Soil particle resistance (f_g) is the flow resistance generated by the adhesive strength between soil particles. Wave resistance is the water flow resistance generated by the land cover, vegetation, gravel, and other rough sources that produce a larger separation vortex and energy dissipation of secondary flow. f_g and wave resistance (f_w) numbers were calculated according to Eqs. (6) and (7) respectively:

$$f_g = 3.19Re^{-0.45}, \quad (6)$$

$$f_w = 2.8C, \quad (7)$$

where f_g is Soil particle resistance, f_w is wave resistance, and C is the coverage.

The Manning roughness coefficient (n) is related to the vegetation and terrain factors, and was used for quantifying the degree of surface roughness, which was calculated according to Eq. (8).

$$n = \frac{h^{2/3} J^{1/2}}{U}. \quad (8)$$

where J is the ground slope ($m \cdot m^{-1}$), which is equal to $\tan\theta$.

3 Results and discussion

3.1 Soil water

When the soil becomes saturated after the application of water, or when the application intensity exceeds the infiltration rate, the excess water becomes characterized by surface retention and runoff. Water infiltration on the slope was calculated according to the runoff yield and flow of discharged water. With the application of Eq. (2), the average infiltration rate was 0.220 $mm \cdot min^{-1}$ for the control plots, and 0.546 for the alfalfa plots. Accordingly, compared to the bare-soil plots, the alfalfa plots showed an increase of 1.77 times in infiltration rate (Table 1).

In Table 1, I_s, Sed, Rs refer to average of infiltration rate, sediment yield rate and runoff coefficient, respectively. Least significant difference (LSD) multiple-comparison test were used to identify significant difference of I_s, Sed, Rs among same discharge different the bare and alfalfa treatments. Value of I_s, Sed, Rs with same letter are not significantly different at the $\alpha = 0.05$ level using the LSD method.

The soil water content on the different parts of the slope was determined with a TRIME/TDR instrument and the measured water content variation before and after each experiment was indicative of the soil water storage. On the bare-soil plots, the measured soil water content variation on the down-slope section was 0.84 $cm^{-3} \cdot cm^{-3}$, which was greater than the up-slope section with a value of 0.61$cm^{-3} \cdot cm^{-3}$. However, on the alfalfa plots the value of soil water content variation on the up-slope section was 1.47 $cm^{-3} \cdot cm^{-3}$, which was greater than the down-slope section with a value of 0.64 $cm^{-3} \cdot cm^{-3}$. This phenomenon is closely related to the surface conditions. For the bare plot, water flow is mainly produced by the resistance of soil particles throughout the entire experiment, due to the no change of interception and terrain on the slope. When runoff was produced, the flow velocity in the up-slope was higher than that of the down-slope, which led to higher soil moisture content in the up-slope compared to that of the down-slope. For the alfalfa plot, due to the role of plant blocking runoff and root drinking water, slope runoff transport was slowed down, resulting in infiltration time and content in the up-slope greater than that of the down-slope.

3.2 Runoff and sediment yield

The effect of alfalfa on soil and water conservation was investigated in both the above- and below-ground parts of the slope. The surface roughness was increased so that the scouring force exerted on the surface by the runoff would decrease. In addition, the plant roots located in the underground section of the slope reinforced the soil structure to further enhance resistance to scouring.

The experimental study was based on the simulation of the surface runoff scouring process with various discharges

Table 1 Characteristics of runoff, sediment, and water infiltration on the alfalfa and bare-soil plots under different discharges

plots	draw-off discharge/($m^3 \cdot h^{-1}$)	I_s/($mm \cdot min^{-1}$)	Sed/($g \cdot m^{-2} \cdot min^{-1}$)	Rs	reduction with alfalfa		
					infiltration rate/%	sediment delivery rate/%	runoff coefficient/%
bare	1.0	0.374 b	21.7 b	0.466 a			
	1.5	0.206 c	77.9 b	0.733 b			
	2.0	0.125 b	80.3 b	0.757 a			
	2.5	0.169 bc	83.0 a	0.771 a			
	3.0	0.238 b	91.4 b	0.789 b			
	3.5	0.208 b	113.0 b	0.767 a			
alfalfa	1.0	0.425 b	2.6 b	0.197 a	–13.6	87.9	57.6
	1.5	0.319 a	28.7 c	0.587 b	–54.9	63.2	20.0
	2.0	0.464 b	12.7 a	0.598 b	–271.2	84.2	20.9
	2.5	0.633 b	16.5 b	0.596 b	–274.6	80.1	22.8
	3.0	0.703 a	22.9 b	0.586 c	–195.4	74.9	25.7
	3.5	0.734 c	27.6 b	0.593 b	–252.9	75.6	22.7

Notes: I_s, Sed, Rs refer to average of infiltration rate, sediment yield rate and runoff coefficient, respectively. Least significant difference (LSD) multiple-comparison test were used to identify significant difference of I_s, Sed, Rs among same discharge different the bare and alfalfa treatments. Value of I_s, Sed, Rs with same letter are not significantly different at the $\alpha = 0.05$ level using the LSD method on the alfalfa and bare soil plots. Again, the influence of direct rainfall on surface erosion was not measured in the experiment as there were only surface applications. Table 1 shows that the presence of alfalfa significantly decreased runoff and sediment yield. Compared with the control, the runoff coefficient and sediment yield rate decreased by 28.29% and 77.65%, respectively. The sediment delivery rate and runoff coefficient gradually decreased with an increase in draw-off discharge in the alfalfa and bare-soil plots; however the sediment delivery rate of the bare-soil plots was much higher than that of the alfalfa plots. This result is mainly due to (i) an increase in hydraulic roughness caused by the presence of alfalfa plant stems, reducing the flow velocity; and, (ii) the enhancement of the soil structure, which reduces its erosion and increases its infiltration capacity. There was a relatively small difference in the average sediment yield among the alfalfa plots (Table 1).

3.3 Processes of runoff and sediment production

The process of runoff production on the slope is strongly influenced by the effects of the underlying surface conditions. In the experiment, the condition of the underlying surface determined the soil infiltration, which further influenced the mean duration and velocity of runoff and the development of the runoff yield.

Figure 4 shows the sediment yield curve for a draw-off discharge of 1.5 $m^3 \cdot h^{-1}$. The variation in the sediment yield with increasing duration of up-slope water application on both the alfalfa and control slope showed an initial trend of an increased yield followed by a decrease until a steady condition was reached.

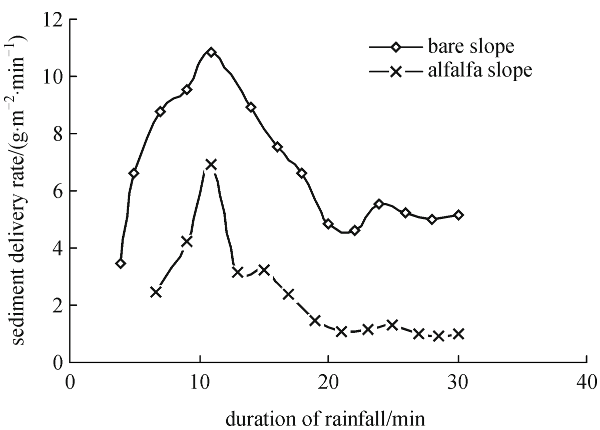

Fig. 4 Sediment yield curve for a draw-off discharge of 1.5 $m^3 \cdot h^{-1}$

For the higher application intensity, soil erosion was mostly caused by surface runoff. In Fig. 5, both runoffs followed the same pattern during the first 20 min of the experiment, in which an initial increase was followed by a decrease. However, after 20 min, a large difference occurred in sediment delivery between the two slope treatments. This was because the soil granules were loosened and destabilized before being subsequently removed and scoured by the initial runoff. Consequently, the sediment delivery rate had increased. However, with an increased time in water application, the bare soil plots continued to erode via rills and gully erosion, resulting in further soil dilapidation, destabilization, and transport, leading to an increase in sediment yield. On the other hand, the rills and rill erosion were not generated on the alfalfa plots, thus the sediment delivery yield gradually diminished and reached a steady state.

3.4 Overland flow hydraulic characteristics

Overland flow is a shallow layer of flow that spreads across the entire slope and flows slowly under gravity [22]. During the periods of excess discharge, the formation of rill flow close to the areas of open channels with shallow flow can be predicted [23,24]. The velocity and flow depth, *Re*, *Fr*, *f*, and *n* are indicators that reflect the hydrodynamic characteristics of the flow. The above hydraulic parameters were calculated using the methods related to river dynamics, along with the corresponding experimental formulas, as shown in Table 2.

Table 2 shows that velocity and water depth gradually increase with increasing discharge on both the alfalfa and bare-soil plots. The flow velocity on the bare-soil plots was much higher than that on the alfalfa plots, but a difference in flow depth between the two slopes was insignificant. Consequently, the alfalfa and bare-soil plots were predicted to have laminar flows for small discharges, and then transitioned to turbulent flow under high discharges.

The *Fr* reflects the interaction between flow depth and velocity, and is also an important flow parameter for a constant discharge. A higher *Fr* will increase the ability of runoff to carry sediment and increase the runoff shear strength. Furthermore, according to the criteria for open-channel flow, the *Fr* for the alfalfa plots was less than 1.0, indicating subcritical flow, while the *Fr* for the bare-soil plots was greater than 1.0, indicating supercritical flow. *f* is composed of two main resistances: f_g and f_w in the alfalfa plot, which is much larger than only f_g in the bare-soil plots. As the resistance coefficient increased, energy dissipation along the flow path increased, thus the ability to erode or transport the sediment decreased. *n* for the alfalfa slope was higher than those of the bare-soil plots, which demonstrated that the capability of resisting soil erosion and sediment movement on the alfalfa plots was higher than that of the bare-soil plots.

4 Conclusions

The effects of alfalfa coverage on slope runoff, soil erosion, and hydraulic characteristics of overland flow on the Loess Plots were studied under a simulated runoff

Table 2 Hydrodynamic characteristics of overland flow in the two slope plots

plot	discharge/($m^3 \cdot h^{-1}$)	velocity/($m \cdot min^{-1}$)	water depth/($h \cdot mm^{-1}$)	*Re* (flow regime)		*Fr* (flow regime)		*n*	f_g	f_w	f
bare	1.0	6.208 b	0.441	45.7	L	1.57	sub	0.055	0.375		0.375
	1.5	8.451 a	1.306	183.9	L	1.24	sub	0.083	0.293		0.293
	2.0	10.105 b	1.746	294.0	L	1.29	sub	0.084	0.240		0.240
	2.5	12.806 b	1.703	363.4	L	1.65	sub	0.065	0.213		0.213
	3.0	13.719 c	1.857	424.6	T	1.69	sub	0.064	0.197		0.197
	3.5	14.385 b	2.026	485.7	T	1.84	sub	0.065	0.184		0.184
alfalfa	1.0	3.088 b	0.642	7.3	L	1.49	super	0.052	0.294	1.960	2.254
	1.5	5.969 b	1.480	147.2	L	0.89	super	0.127	0.273	1.960	2.233
	2.0	6.749 a	1.635	183.9	L	0.89	super	0.120	0.242	1.960	2.202
	2.5	5.717 b	1.318	125.6	L	0.84	super	0.123	0.228	1.960	2.188
	3.0	8.160 c	2.072	281.8	L	0.95	sub	0.116	0.219	1.960	2.179
	3.5	9.711 b	2.144	347.1	L	0.86	sub	0.121	0.204	1.960	2.164

Notes: L and T refer to laminar flow and turbulent flow, respectively; super and sub refers to supercritical flow and subcritical flow, respectively. LSD multiple-comparison test were used to identify significant difference on the velocity (*U*) among same discharge different the bare and alfalfa treatments. Value of *U* with same letter are not significantly different at the $\alpha = 0.05$ level using the LSD method

scouring experiment for different discharges in the alfalfa and bare-soil (control) plots on a slope of 20°. The presence of alfalfa plant stems increased the hydraulic roughness of slope flow and reduced the velocity flow in order to decrease the slope runoff yield to 28.29% and increase the soil infiltration capacity by 1.77 times compared to the bare-soil plots. Furthermore, the stability of soil structure was enhanced by the function of the alfalfa roots reinforcing soil. Simultaneously, the overland flow scour force by the interactions together with wave resistance and soil particle resistance was cut down., which lead to the reduction of sediment transformation yield (77.65%), compared to the bare-soil plots.

By calculating the hydrodynamic parameters of the slope flow, including velocity and flow depth, Reynolds number, Froude number, resistance coefficient, and Manning roughness coefficient, the flow regime in the alfalfa and bare soil plots was found to be subcritical at low draw-off discharges, and supercritical flow at high draw-off discharges. This demonstrated a stronger capability of resisting soil erosion and sediment movement on alfalfa plots than that on bare soil plots. Furthermore, the flow resistance coefficient and roughness coefficient for the alfalfa plots were both higher than those for the bare-soil plots, which reflected that overland flow in alfalfa plots had retarded and was blocked, the energy along the flow path had gradually dissipated, and the ability to erode or transport sediment had decreased. By the analysis of overland flow hydraulic characteristics, this study clarified the mechanics of alfalfa coverage reduction on overland flow scouring force or changed runoff movement.

Soil erosion is a complex physical process involving the interaction between the overland flow and soil. Therefore, a more detailed study on the hydraulic characteristics of slope runoff will help further comprehend the process of runoff generation and sediment yield and reveal more clearly the mechanics of this process as regulated by vegetation.

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References

1. Benito E, Santiago J L, De Blas E, Varela M E. Deforestation of water-repellent soils in Galicia (NW Spain): effects on surface runoff and erosion under simulated rainfall. Earth Surface Processes and Landforms, 2003, 28(2): 145–155
2. Foster G R, Huggins L F, Meyer L D. A laboratory study of rill hydraulics: I velocity relationships. Transactions of the ASAE. American Society of Agricultural Engineers, 1984, 27: 790–796
3. Huang C H, Bradford J M. Analyses of slope and runoff factors based on the WEPP erosion model. Soil Science Society of America Journal, 1993, 57(5): 1176–1183
4. Li M, Yao W Y, Li Z B. Progress of the effect of grassland vegetation for conserving soil and water on loess plateau in China. Advance in earth science, 2005, 20(1): 74–80 (in Chinese)
5. Kang S Z, Zhang L, Song X Y, Zhang S H, Liu X Z, Liang Y L, Zheng S Q. Runoff and sediment loss responses to rainfall and land use in two agricultural catchments on the Loess Plateau of China. Hydrological Processes, 2001, 15(6): 977–988

6. Li M, Yao W Y, Ding W F, Yang J, Chen J. Effect of grass coverage on sediment yield in the hill-slope gully side erosion system. Journal of Geographical Sciences, 2009, 19(3): 321–330
7. Neave M, Abrahams A. Influences on water yields from grassland and shrubland ecosystems in the Chihuahuan Desert. Earth Surface Processes and Landforms, 2002, 27(9): 1011–1020
8. Wei X, Li Y G, Li Z B. Experiments on hydraulic characteristics of runoff in slope-gully systems in Loess Plateau. Transactions of the Chinese Society of Agricultural Engineering, 2009, 25(10): 19–25 (in Chinese)
9. Prosser I P, Dietrich W E, Stevenson J. Flow resistance and sediment transport by concentrated overland flow in a grassland valley. Geomorphology, 1995, 13(1–4): 71–86
10. Chatterjea K. The impact of tropical rainstorms on sediment and runoff generation from bare and grass-covered surfaces: a plot study from Singapore. Land Degradation and Development, 1998, 9(2): 143–157
11. Braud I, Vich A I J, Zuluaga J, Fornero L, Pedrani A. Vegetation influence on runoff and sediment yield in the Andes region: observation and modeling. ASCE J. Hydrology, 2001, 254(1–4): 124–144
12. Pan C Z, Shangguan Z P, Lei T W. Influences of grass and moss on runoff and sediment yield on sloped loess surfaces under simulated rainfall. Hydrological Processes, 2006, 331: 178–185
13. Cerda A. The influence of geomorphological position and vegetation cover on the erosional and hydrological processes on a Mediterranean hill slope. Hydrological Processes, 1998, 12(4): 661–671
14. Casermeiro M A, Molina J A, De la Cruz Caravaca M T, Hernando Costa J, Hernando Massanet M I, Moreno P S. Influence of scrubs on runoff and sediment loss in soils of Mediterranean climate. Catena, 2004, 57(1): 91–107
15. Luo R T, Zhang G H, Cao Y, Cao G H. Progress in the research of hydrodynamic characteristics of sediment-laden overland Flow. Progress in Geography, 2009, 28(4): 567–575 (in Chinese)
16. Li Z B, Qin B S, Kang W. Indoor experimental studies on hydrodynamic characteristics of runoff in rill erosion procession steep slope. Transactions of the Chinese Society of Agricultural Engineering, 2008, 24(6): 64–68 (in Chinese)
17. Leonard G R. Estimation of runoff critical shear stress for soil erosion from soil shear strength. Catena, 2004, 57 (3): 1–17
18. Gilley J E, Kottwite E R, Simanton J R. Hydraulic characteristics of rills. Transactions of the ASAE. American Society of Agricultural Engineers, 1990, 33(6): 900–1906
19. Govers G. Relationship between discharge, velocity, and flow area for rills eroding in loose, non-layered materials. Earth Surface Processes and Landforms, 1992, 17(5): 515–528
20. Abrahams A D, Li G, Parsons A J. Rill hydraulics on a semiarid hill slope in southern Arizona. Earth Surface Processes and Landforms, 1996, 21(1): 35–47
21. Weltz M A, Awadis A B, Lane L J. Hydraulic roughness coefficients for native rangelands. ASCE J. Irrig. and Drain. Engrg, 1992, 118 (5): 776–790
22. Zhang G H. Study on hydraulic properties of shallow flow. Advance in Water Science, 2002, 13(2): 159–165 (in Chinese)
23. Liu Q Q, Li J C, Chen L. Dynamics of overland flow and soil erosion (II) - soil erosion. Advances in mechanics, 2004, 34(3): 493–517 (in Chinese)
24. Zhang k L. Hydrodynamic characteristics of rill flow on loess slopes. Journal of Sedimentary Research, 1999, 1: 56–61 (in Chinese)