Environ Earth Sci (2016) 75:477
DOI 10.1007/s12665-016-5329-7

ORIGINAL ARTICLE

Effects of grass coverage and distribution patterns on erosion and overland flow hydraulic characteristics

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Received: 15 May 2015 / Accepted: 30 November 2015 / Published online: 10 March 2016

Abstract Grass coverage and its spatial distribution patterns have crucial influences on erosion. The laboratory scouring experiments were conducted to research the influence of grass cover on runoff, erosion rates, and overland flow hydraulic characteristics in the plots with differing grass coverage rates (30, 50, 70, and 90 %), grass distribution patterns (where US, MS, and DS stand for the grass laid on up-slope, middle-slope and down-slope, respectively) and with a bare soil plot (CK) at a slope gradient of 20. The results illustrate that the grassplots had a 2.06–10.94 % runoff reduction and 28.57–75.4 % sediment decreases, respectively, as compared with CK plot. There was no significant difference in the runoff rate among the three grass distribution patterns for the same grass coverage, while DS had the lowest sediment yield rate and greatest sediment yield reduction in comparison with US and MS. The sediment yield rates were found to have a significantly negative exponential relationship with the grass coverage ($p < 0.01$), while the sediment concentration had a significantly negative linear relationship with the grass coverage ($p < 0.01$). The overland flow velocity (V) increased with increasing inflow discharges and deceased with increasing grass cover, and it was negatively correlated with the grass coverage following a linear trend ($p < 0.01$). The mean Froude number (Fr) holds to a similar variation law with the changes in the V. There was no significant relationship found to exist between the grass coverage and Reynolds number (Re). The average Darcy–Weisbach resistance coefficient (f) of the whole slope for grass plots was 2.2–25.6 times of that for CK plot, and f was found to be an exponent correlated with the coverage rate ($p < 0.01$). In addition, f was negatively correlated with the erosion rate following a power function ($p < 0.01$); however V, Fr, and Re were positively correlated with the erosion rate ($p < 0.01$). The sediment yield rate itself was a function of the runoff rate for each treatment, and their relationships could be well described by the linear equation ($p < 0.01$). These results indicate that both grass coverage rates and distribution patterns have significant effects on hydrological characteristics of overland flow.

Keywords Grass coverage · Spatial distribution patterns · Erosion rate · Overland flow hydraulic characteristics

Introduction

Many research results in the past several decades indicate that vegetation is a very important efficient way to prevent soil erosion, and the relationship of vegetative coverage and erosion has been reported in a variety of literature (Boer and Puigdefábregas 2005; Cerda 1997; Gyssels et al. 2002; Rogers and Schumm 1991; Zhou and Shangguan 2007). Numerous researchers have demonstrated that in a wide range of environments both runoff and sediment loss will decrease exponentially with an increase in the vegetation coverage (Dunne et al. 1978; Snelder and Bryan 1995). Due to the positive role of vegetation for reducing soil erosion, the protective effects of plant covers are used extensively in soil conservation practices on agricultural fields all over the world (Gyssels et al. 2005). From a hydrological point of view, it is generally accepted that the vegetation used in controlling soil erosion operates mainly by intercepting

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raindrops, enhancing infiltration, providing additional surface roughness, reducing soil water transpiring, and trapping some of the eroded sediment (Bochet et al. 2000; Gyssels et al. 2005; Pan and Shangguan 2010; Pravat et al. 2012).

In recent years, numerous studies regarding the impact of vegetation, especially grass cover, on the hydraulic characteristics of overland flow have been widely conducted, and results have demonstrated that vegetation cover could change overland flow hydrology characteristics, which has implications for erosion sediment transfer and deposition (Cerda 1998; Zhang et al. 2012). Pan and Shangguan (2006) studied runoff and sediment producing processes and runoff hydraulics properties in different covers grassplots under stimulated rainfall experiments, and concluded that grass covers significantly reduced sediment yield, runoff hydraulic parameters on slope were obviously affected by grass coverages. Based on laboratory simulated rainfall experiments, Zhang et al. (2012) showed that a patchy distribution of *Artemisia capillaris* has a significant effectiveness in retarding overland flow velocity and commented that the flow velocity increased with rainfall intensity; moreover, the contributions of grass shoots and roots in relation to the varied reductions in flow velocity under different rainfall intensities differed. Liu et al. (2010) and Wu et al. (2011) similarly concluded that vegetation cover has important effects on both the erosion process and hydrological process via their simulated experiments.

Although above mentioned studies have proved that vegetation cover has an impact on both soil erosion and surface runoff hydraulic characteristics, these researchers were dealing with the case of vegetation that was uniformly distributed on whole slopes, a situation which differs substantially from that of vegetation which is spatially distributed (Wu et al. 2011; Zhang et al. 2014). Moreover, previous research proved that the sediment reduction benefits of grass cover varied widely, ranging from 30 to 95 %. Sediment reduction efficiency depends heavily on inflow characteristics, sediment characteristics, grass distribution patterns, slope gradients, and other factors. In fact, although many researchers have demonstrated the fact that the patterns of vegetation are spatially distributed along the slopes is regarded as an important factor for decreasing the sediment runoff in many parts of the world (Cerda 1997; Duran Zuazo and Rodriguez Pleguezuelo 2008; Li et al. 2009), relatively less information on erosion processes and surface runoff hydraulic characteristics in different vegetation coverage and distribution patterns grassplots has been actually provided. However, when one considers the soil erosion mechanism itself, it can be seen that erosion is a dynamic process occurring between the interactions of the overland flow and underlying soil surface, leading to a great number of factors which can substantially affect the hydraulic characteristics of overland flow that result in different patterns of erosion. Therefore, the objectives of present research are: (1) to evaluate the effect of differing degrees of grass coverage and spatial distributions on both runoff and sediment yield of the hillslope; (2) to better understand the influence of grasses on runoff hydraulic characteristics and the sediment producing processes; and (3) to further clarify the differences among grassplots with different covers and different spatial distribution patterns. These findings can hopefully deepen insights on the sediment reduction mechanism of vegetation cover and distribution patterns.

Materials and methods

Soil sample collection

The soil used in this study was sandy loam (with 61.04 % sand, 28.16 % silt, and 10.8 % clay), which is derived from Loessic and classified as Alfisol according to the US Soil Taxonomy (USDA 1999). It was taken from north of Zhengzhou (113°39′36″E, 34°45′36″N), in the Henan province of China, which is susceptible to soil erodibility. The climate is semi-humid in the warm temperate zone with a mean annual rainfall of 620 mm and a mean temperature of 14 °C. The pH value of soil is 7.2. The natural consolidated soil has a bulk density about 1.3 g cm^{-3} and with an organic matter content of 2.0 %. The soil texture information is listed in Table 1 and Fig. 1. From the Fig. 1, soil particle size distribution curves of undisturbed soil and experimental soil present the similarity regularity. The soil was sampled from a cultivated land, up to 0.3 m deep, along the shoulder area of a hill. A sufficient amount of soil was transported back to the laboratory for the experiments.

Experimental design

The experiments were conducted at the key lab of Yellow River sediment research of the Ministry of Water Resources, Yellow River institute of hydraulic research. A scouring experiment was used in this study. A constant flow rate along the flume was maintained during the tests, by keeping water in the supply reservoir at a constant level. The fixed water level controlled the inflow discharges in the experiments. Before each experiment, inflow discharges were calibrated at the outlet of the soil box using of a flowmeter. The two water inflow rates of 3.2 and 5.2 L min^{-1} were used in these present experiments. The chosen inflow discharges corresponds to the cropland overland runoff generated under the typically occurring local storms with rainfall intensities of 100 and 150 mm h^{-1}.

Table 1 Basic information of the soil studied in this work

Soil type	Soil texture	Soil particle-size distribution (g kg^{-1})			pH (H_2O)	OM (%)
		Sand	Silt	Clay		
Loessic soil	Sandy loam	61.04 ± 7.14	28.16 ± 4.20	10.80 ± 3.90	7.2 ± 0.26	1.93 ± 1.23

Values represent mean ± SD (standard deviation)

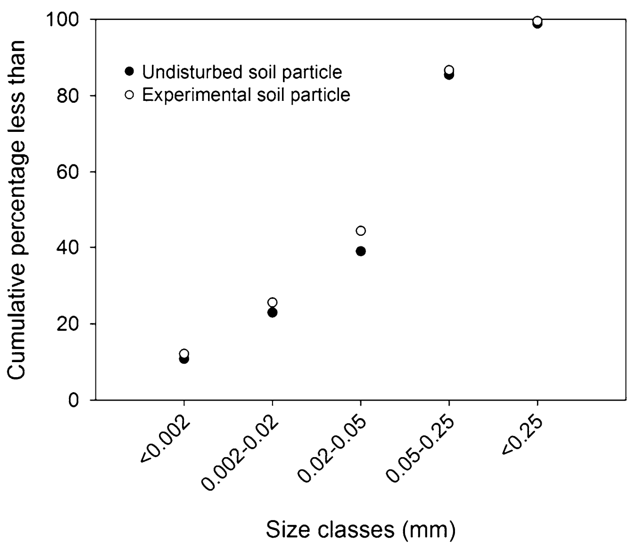

Fig. 1 Soil particle size distribution of the undisturbed and experimental soil used in study

Soil box preparation and experimental procedure

Runoff plots were manufactured with brick and concrete, measuring 4.0 m long, 2.0 m wide, and 0.5 m deep. The slope gradient was set at 20°, which is a general gradient for cultivated land on the study area (Because the 25° slope is the slope gradient for prohibit farming according to the Chinese Soil and Water Conservation Law, 20° is almost the maximum slope gradient for cultivation.). The runoff plot was divided into four experimental portions through use of a PVC board, and each plot had a metal runoff collector which was set at the bottom of the plot to direct runoff into a container. As a result, a control plot without any grass cover (CK) and three additional plots were constructed to represent the differing vegetation spatial distribution patterns on the slope, which were then considered as the Up-slope (US), Middle-slope (MS), and Down-slope (DS), respectively (Fig. 2a–c).

The soil was air-dried, gently crushed, and passed through a 10 mm sieve to remove both the gravel as well as the animal and plant residues to insure homogeneity.

Before packing, a 10 cm layer of fine sand was put into the bottom of each plot to allow for better drainage. Then 30 cm thick soil was packed in three 10 cm layers at a bulk density of 1.30 g cm^{-3}. Wild buffalo grass (*Buchloe dactyloides*), a commonly seen indigenous plant, was employed as the target species. The grass seed was sowed into the plot surface, to best ensure a uniform grass cover in each of the soil surface areas; a similar seeding density was used in each experimental plot. The coverage degree was then calculated by determining that amount of grass area which accounts for the total hillslope surface area. The present research involved four grass coverage degrees, which were 30, 50, 70 and 90 %, respectively. The reason for selecting above four grass coverage degrees is that it is widely considered that the threshold coverage for vegetation influencing soil erosion is about 50 % (Zhang et al. 2012). To get the significant differential of erosion, 20 % percent grass coverage interval was chosen. Therefore, experimental treatments that designed based on above rules but different distribution patterns were designed in this study. For each grass coverage degree, except for the 90 % coverage, there were three spatial distributions patterns, as mentioned above. The soil surface within the plot was pre-wetted uniformly by spraying water to ensure adequate surface saturation without any runoff yield. In this manner, the initial conditions of every experiment were maintained as consistently as was possible. Soil water content was adjusted to about 15 % for all of the treatment plots at the beginning of these scouring experiments. The runoff plot was repacked with new soil for each experiment, and two replicates were used for each experimental condition.

During these experiments, the flow velocities, flow discharges, and sediment concentrations at the outlet of the plot were measured. The sediment samples at the outlet of the flume were collected every minute using a 10 L bucket, and the flow velocities were measured by employing dye tracing techniques every minute. The time for the tracer to travel across a marked distance (1.0 m) was determined according to the color-front propagation through use of a stopwatch. The measured values of runoff velocity multiplied by theoretical value 0.67 were used to estimate profile mean velocities (Li et al. 1996). From the upslope to the downslope for each runoff plot, there were a total of three different cross-sections selected to determine runoff velocities, except in the case of the 90 % grass coverage (only one cross-section was selected to determine runoff velocity). The section partitioning is illustrated in Fig. 2a.

Each experiment lasted for approximately 20 min. After the scouring experiment, all of the buckets were weighed, and the sediment-laden water was allowed to stand until

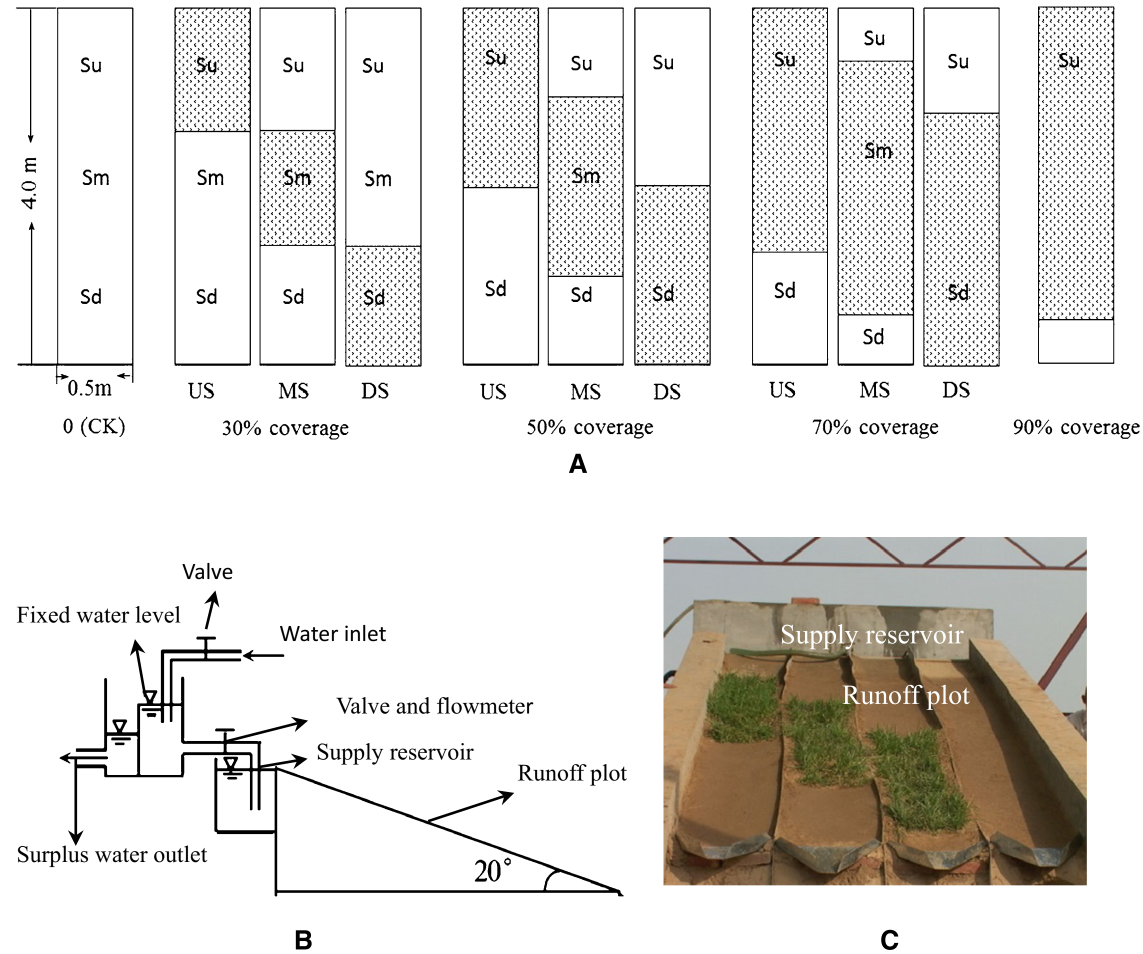

Fig. 2 Sketch map of the different grass coverage and different grass spatial distribution patterns on the experimental soil box (**a**); Sketch map and photograph of laboratory system (**b**, **c**). *US* grass cover on up-slope, *MS* grass cover on middle-slope coverage, *DS* grass cover on down-slope coverage, *Su* up-slope section, *Sm* middle-slope section, *Sd* down-slope section

suspended sediments settled within the buckets. Clear water was then siphoned off, and the sediments were transferred into iron basins and oven-dried at 105 °C for 24 h and again weighed. The sediment concentration was defined as the ratio of the dry sediment mass to runoff volume, while the sediment yield rate was defined by dividing the sediment yield per unit area by the period of time.

Data calculation and analysis

The sediment reduction rate due to grass coverage (%) can be calculated using the following equation (Zhou and Shangguan 2007):

$$E_s = \frac{S_{ck} - S_g}{S_{ck}} \times 100\,\% \quad (1)$$

where S_{ck} is the sediment yield in CK plot (kg) and S_g is the sediment yield in the grass cover plot (kg).

For runoff reduction due to grass coverage (%) calculations, the equation is:

$$E_r = \frac{R_{ck} - R_g}{R_{ck}} \times 100\,\% \quad (2)$$

where R_{ck} is the runoff generation in CK plot (L) and R_g is the runoff generation in the grass cover plot (L).

The Reynolds number (*Re*) is the ratio of inertia forces to viscous forces of the overland flow. According to the theory of open-channel flow dynamics, $Re = 500$ is the critical value determining the flow pattern. If $Re < 500$, the flow is laminar, where if $Re > 500$, the flow is turbulent. It was calculated using following equation:

$$Re = \frac{Uh}{v} \quad (3)$$

where υ is kinematical viscosity (cm^2 s^{-1}), U is the average flow velocity (cm s^{-1}), and h is the mean overland flow depth (cm).

Because slope overland flow depth is very thin and the erosion is a dynamic process, it is difficult to measure it, in actual calculation flow depth, assuming slope flow is uniform and the flow depth can be calculated using following formula:

$$h = \frac{Q}{UBt} \quad (4)$$

where h is flow depth (cm), Q is the runoff volume during t time (ml), U is the mean flow velocity (cm s^{-1}), B is width of water-crossing section (cm), and t is unit time (s).

The Froude number (Fr) is the ratio of the inertial forces to the gravitational forces, and $Fr = 1$ is the critical value. If $Fr < 1$, the flow is tranquil sub-critical, while if $Fr > 1$, the flow is rapid super-critical. The Froude number (Fr) was calculated from following equation:

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

where U is the average flow velocity (cm s^{-1}), h is the mean overland flow depth (cm), and g is the acceleration of gravity (cm s^{-2}).

The Darcy–Weisbach (f) was used to characterize the retardation of flow and can be calculated using the following equation:

$$f = \frac{8gRJ}{U^2} \quad (6)$$

where U is the average flow velocity (cm s^{-1}), g is the acceleration of gravity (cm s^{-2}), R is the wetted perimeter (cm) (it is often occurred with flow depth when then overland flow was wide and shallow), and J is the surface slope (m m^{-1}).

Data analyses included regression and ANOVA testing. Analysis of regression was used to detect the relationship between the study factors (grass coverage, inflow discharge, and grass distribution patterns) and the dependent variables (runoff and soil loss). Significant differences between treatments for runoff rate and soil loss rate were determined using the PLSD (Protected Least Significant Difference) procedure for a multiple range test at the 0.05 significance level. All tests were performed using the statistical program SPSS 11.0.

Results and discussion

Runoff and sediment

Both the runoff rate and sediment yield rate for the CK plot and grass cover plots with different vegetation treatments have been summarized in Table 2.

As can be observed in Table 2, for the inflow discharge 3.2 L min^{-1} condition, the runoff rate ranged from 2.85 to 3.20 L min^{-1}, and the runoff rate reduced by approximately 2.06–10.94 % as compared to the CK plot. Meanwhile, the same trends of runoff rate variation with vegetation coverage decreasing from 90 % to 0 also occurred under the flow discharge of 5.2 L min^{-1}, where the runoff rate ranged from 4.61 to 5.16 L min^{-1} and the runoff rate reduced by approximately 8.53–10.66 % as compared to the CK plot.

From Table 2, results also can be found that there is no significant difference in the runoff rate among the three grass distribution patterns for the same grass coverage, and there also was no significant differences in runoff rates between the CK plot and the 30 % grass coverage for inflow discharge 3.2 L min^{-1}. Furthermore, there is no significant differences in the runoff rate between the CK plot and the 30 % grass coverage and the 50 % grass coverage with an inflow discharge 5.2 L min^{-1}, but there exists a significant difference between the CK plot and 70 % grass coverage and 90 % grass coverage for both inflow discharges.

These present results are found to be consistent with other studies (Benito et al. 2003; Lal 1997; Li et al. 2009; Pan and Shangguan 2006; Zhang et al. 2014) with regard to the effects of vegetation coverage reducing runoff, although our study indicated there has decreased importance in grassplot which had lower grass coverage. These may be associated with different grass coverage, different grass distribution patterns on slope, steeper slope gradient, or the higher soil bulk density in our study as compared to those observed from the indoor simulated runoff plots. Previous studies were always done on <15° slope, but our experiments slope gradient was 20°, which steeper than previous researches. The steeper the slope, the less runoff infiltrates into the soil and the greater runoff volume is. The same grass coverage rates on slope would have the less benefits of runoff reduction. Other possible explanation is that experiment method adopted in this study was the scouring method and the previous studies mentioned above were based on simulated rainfall experiments. Under the simulated rainfall experiments condition, a part of rainfall will be intercepted by grass and goes down into the soil. The inflow discharges in present study correspond to the cropland runoff generated under the typically occurring local storms with rainfall intensities of 100 and 150 mm h^{-1}, respectively. These are greater than the rainfall intensities adopted by previous experiments. So, the above differences results existed and these indicated that both slope condition and experiments method have much effect on runoff generation.

For sediment yield rates, there appeared to be a different trend as compared with the runoff rate variation (Table 2). Both the grass coverage and grass distribution patterns do have a significant influence on sediment yield rates. Grass cover reduced the sediment yield rate by 36.17–75.41 % for

Table 2 Mean runoff rate, sediment yield rate, and sediment concentration of the different grass coverage and different distribution patterns plots and reduction in these parameters compared with bared plot

IR L min^{-1}	GC %	GDP	RR L min^{-1}	SYR kg min^{-1}	SC kg m^{-3}	Reduction (%)		
						RR	SYR	SC
3.22	0	–	3.20a	1.22a	381.25a	–	–	–
3.22	30	Up	3.17a	1.03b	324.92b	0.94	15.57	14.51
3.215	30	Middle	3.18a	0.78c	245.28d	0.63	36.07	35.46
3.16	30	Down	3.15a	0.69de	219.05e	1.56	43.44	42.36
3.21	50	Up	3.08ab	0.84c	279.22c	3.75	31.15	26.53
3.19	50	Middle	2.99b	0.61de	204.01ef	6.56	50.00	46.32
3.15	50	Down	2.98b	0.59de	197.99ef	6.88	51.64	47.91
3.155	70	Up	2.99b	0.75cd	250.84d	6.56	38.52	34.00
3.165	70	Middle	2.94bc	0.57de	193.88f	8.13	53.28	48.99
3.17	70	Down	2.91bc	0.47e	161.51g	9.06	61.48	57.50
3.25	90	–	2.85c	0.30f	105.26h	10.94	75.41	72.30
5.18	0	–	5.16a	2.12a	410.66a	–	–	–
5.185	30	Up	5.12a	1.76b	354.24b	0.78	16.98	13.74
5.19	30	Middle	5.13a	1.45c	282.94d	0.58	31.60	31.10
5.21	30	Down	5.14a	1.22d	236.38e	0.39	42.45	42.44
5.18	50	Up	5.10ab	1.56c	311.27c	1.16	26.42	24.20
5.175	50	Middle	5.09ab	1.28d	250.69e	1.36	39.62	38.95
5.2	50	Down	5.11ab	1.19d	232.78e	0.97	43.87	43.32
5.215	70	Up	5.08ab	1.46c	287.80d	1.55	31.13	29.92
5.2	70	Middle	5.04b	1.24d	245.34e	2.33	41.51	40.26
5.23	70	Down	5.04b	1.05e	209.13f	2.33	50.47	49.07
5.17	90	–	4.61c	0.75f	163.45g	10.66	64.62	60.20

IR, GC, GDP, RR, SYR and SC refer to inflow rate, grass coverage, grass distribution pattern, runoff rate, sediment yield rate, and sediment concentration, respectively

Least significant difference (LSD) multiple-comparison tests were used to identify the differences of RR, SYR and SC among the same inflow rate, different grass coverages and distribution patterns treatments. Values of RR, SYR and SC with the same letter are not significantly different at the $\alpha = 0.05$ level using the LSD method

an inflow discharge 3.2 L min^{-1}, and by 28.57–64.62 % for an inflow discharge 5.2 L min^{-1}, respectively. The grass cover had a greater effectiveness in reducing erosion as compared to a decreasing runoff.

These results are consistent with the findings of other researchers who similarly found that vegetative coverage significantly reduced runoff and sediment losses (Benito et al. 2003; Castillo et al. 1997; Gyssels et al. 2002). However, the present research results indicated that the role of vegetation on controlling erosion was smaller than that founded in some previous study, such as obtained by Benito et al. (2003), who observed vegetation coverage could decrease 96 % of erosion as compared with a similarly bare slope. Our research was also inconsistent with results founded by Pan and Shangguan (2006), who obtained grass coverage reduced erosion by 81.2–94.3 %. These results also have been proven by a few researchers under dissimilar vegetation types in others regions of the world (Cerda 1998; Shit et al. 2012). The main reason for these differences between the present study and the previous researches may be associated with the different runoff plot area, grass distribution patterns on slope and the slope gradient in our study as compared to those observed from indoor simulated runoff plots, which could result in the sediment concentration larger than those founded in previous research. For example, under the condition of inflow discharge 5.2 L min^{-1} and vegetation coverage 0 and 30 %, the sediment concentration reached 530.22 kg m^{-3}, which belongs to a hyperconcentrated flow. Xu (1999) pointed out that hyperconcentrated flow has significantly different characteristics as compared with common sediment concentration flow, for it illustrates both greater detachment and transport capacity than common sediment concentration flow. Zhou et al. (2013) evaluated the sediment trapping from a hyperconcentrated flow as affected by grass filter strips, results demonstrated that the deposition efficiency decreased with increasing sediment concentration, and the trapping efficiency was 55.5 and 15.7 % for the 147 and 429 kg m^{-3} sediment treatments. Our research results were consistent with the consequences illustrated by Zhou et al (2013).

By comparing the sediment yield reduction rates according to the differing vegetation distribution patterns on the slopes, one can observe that the DS had the lowest sediment yield rate and the greatest sediment yield reduction in comparison with both US and MS. In essence, these results indicate that the DS is more effective than either the US or MS in both soil and water conversion under these established experimental conditions. The results are consistent with Neibling and Alberts's (1979) results, which indicated that 90 % of the incoming sediment load could be trapped in the first 0.6 m width of the buffer grass strip, for all of the grass strips had a width over 1 m in our experiments. So, when the grass cover is distributed on the low-slope, it can definitely retain more sediment than is possible along other sloping positions.

Furthermore, our regression analysis indicated that both the sediment yield rates (SYR) and the sediment concentrations (SC) were found to have a significantly negative exponential relationship with the grass coverage (GC) (Fig. 3), which can be expressed as: SYR = 2.026 exp (−0.009 GC) ($R^2 = 0.641$, $n = 11$, $p < 0.01$) for inflow discharge 3.2 L min^{-1}, and SYR = 1.259 exp (−0.013 GC) ($R^2 = 0.725$, $n = 11$, $p < 0.01$) for inflow discharge 5.2 L min^{-1}; SC = 386.87 exp (−0.008 GC) ($R^2 = 0.618$, $n = 11$, $p < 0.01$) for inflow discharge 3.2 L min^{-1}, and SC = 383.92 exp (−0.011GC) ($R^2 = 0.675$, $n = 11$, $p < 0.01$) for inflow discharge 5.2 L min^{-1}. The above exponential relationship between SYR, SC, and grass coverage were also observed by Liu et al. (2010), and Rogers and Schumm (1991), but were inconsistent with results observed by Adekalu et al. (2007), who reported that a polynomial relationship exists between SYR, SC, and grass coverage. Pan and Shangguan (2006) also demonstrated that SYR and SC were found to be a negative logarithmic function of grass coverage. This may be associated with the different grass distribution patterns on slopes and the different experimental method employed in our study as compared to those observed from indoor simulated runoff plots.

Sediment concentration

Due to the similar variation processes of sediment concentration for each treatment under different inflow discharge, the present work took 3.2 L min^{-1} as an example to analyze the temporal variations of sediment concentration. Figure 4 shows the sediment concentration variations for all of the different grass coverage and different grass distribution patterns on the slopes as compared with the CK plots. Characteristically, for different grass coverages, the sediment concentration processes were obviously different between the grassplots and CK plot (Fig. 4b). The mean sediment concentrations from the CK plots were 13–72 %

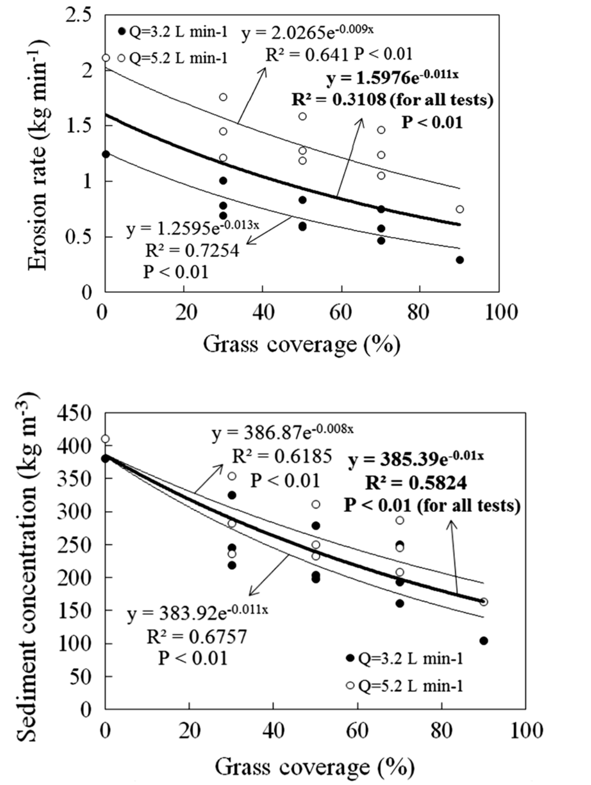

Fig. 3 Relationship between erosion rate, sediment concentration, and grass coverage

higher than those observed from the grassed plots. Sediment concentration processes in CK plot showed a trend of increasing to a peak value and then fluctuating while decreasing. For the grass cover plots, the sediment concentration continuously fluctuates and decreases over the experimental duration. For the different grass distribution patterns on a slope, at the initial stage of these experiments, the sediment concentration of the three different treatments have no obvious differences, then present the following order, CK > US > MS > DS (Fig. 4a). These results are consistent with previous research which indicated that the sediment concentration in grassplots decreased with rainfall duration (Pan and Shangguan 2006). However, this variation is in disagreement with Parsons et al. (1996) and Wainwright et al. (2000), who found that sediment concentrations in the grassland continuously increased with time. The different erosion processes may be attributed to the different soil properties which are in contrast with their research. A reasonable explanation for this discrepancy might be that the trapping sediment capacity of the grass coverage section on the slope was limited, at the initial stage of experiment, especially for the initial experiment to the 14th min (Fig. 4a), where the inflow discharge has the maximum detachment and transport ability, soil erosion increases dramatically, and higher sediment concentrations

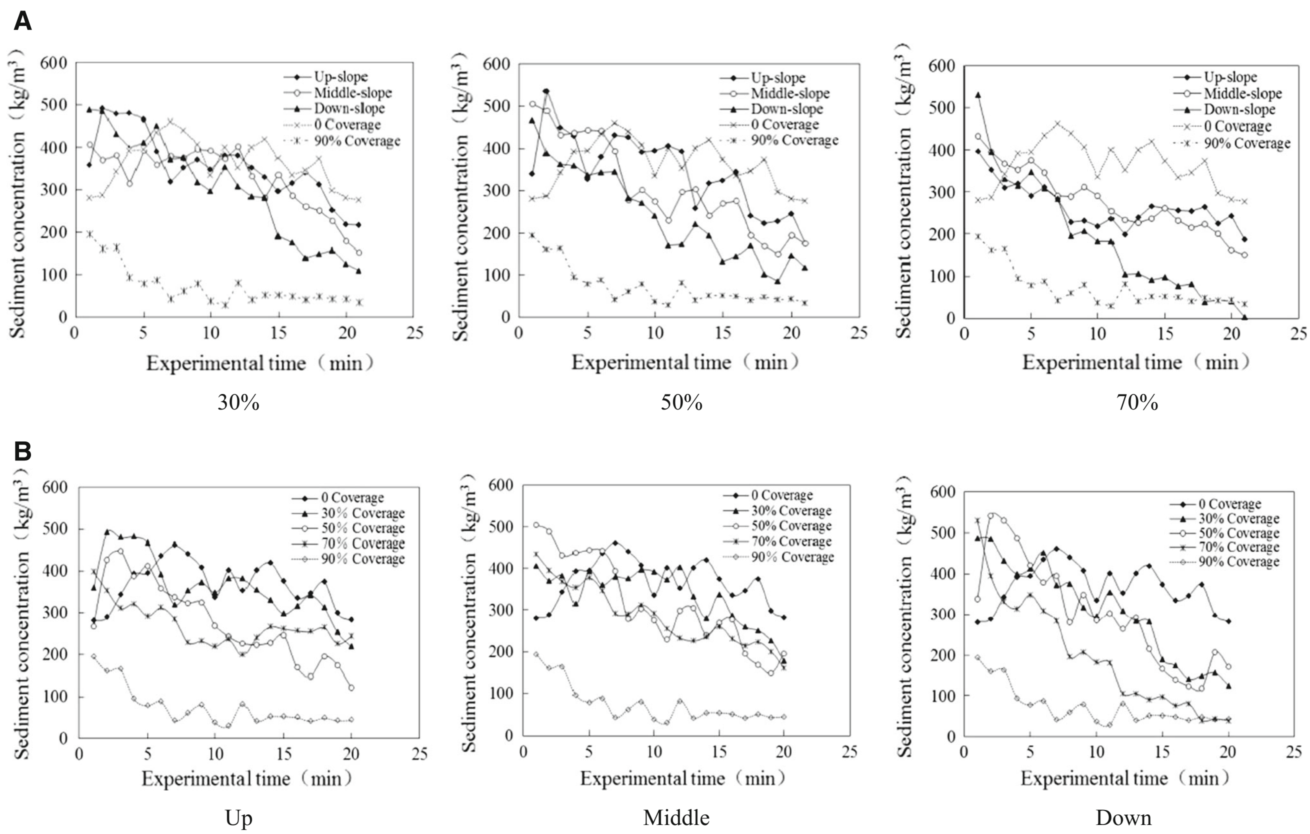

Fig. 4 Sediment concentration temporal variation in different grass coverage *plots* (**a**) and different distribution patterns plots (**b**)

flow rapidly to reach the maximum capacity, thus making the grass cover section lose the sediment trapping ability. Therefore, these three different grass coverage patterns have no significant differences of sediment trapping and sediment concentration. However, with the increases in runoff time, the erosion tends to be stable and sediment concentration decreases, for when compared to the higher sediment concentrations, the grass coverage section can trap a greater percentage of sediment, particularly when the grass is distributed on the lower and middle slope positions, where it can trap more sediment coming from the upslope and middle-slope. So, these three different grass distribution patterns may illustrate an obvious discrepancy in sediment concentration patterns.

Runoff hydraulic parameters characteristics

Four hydraulic parameters, which are the runoff velocity (*V*), Reynolds number (*Re*), Froude number (*Fr*), and Darcy–Weisbach resistance coefficient (*f*), were calculated using the methods related to river dynamics (Eqs. 3–6) as shown in Table 3.

From Table 3, it can be seen that the runoff velocity of the different sections increased with increasing inflow discharges, being 0.26–0.56 m s^{-1} for CK plots and 0.06–0.12 m s^{-1} for grass plots. The mean velocity of the whole plot decreased with an increasing grass cover and the grassplots had a decrease of about 34–80 % when compared to a CK plot. For any given grass coverage rate, the runoff velocity of the grass coverage section followed the order $V_{US} < V_{MS} < V_{DS}$, as there was no statistical difference in the runoff velocity of other the two sections.

For the same slope position, the runoff velocity decreased with increasing grass coverage rate. Runoff velocity was negatively correlated with the grass coverage (GC) following a linear trend ($p < 0.01$), with the regression analyses of $V = -0.0027$ GC $+ 0.3195$ ($R^2 = 0.797$, $n = 22$). This result was consistent with the report observed in many experiments (Liu et al. 2010; Pan and Shangguan 2006; Zhang et al. 2012).

Froude numbers (*Fr*) work with the similar variation law when the overland flow velocities are changing; the mean *Fr* values of the whole plot typically decreased with increasing coverage, and the grassplots had a decrease of about 30–87% as compared to a CK plot. However, there was a little difference in the Reynolds numbers (*Re*) among the different covers, for the *Re* values of the different sections increased with increasing inflow discharges, with these values standing at 707.99–1546.33 for CK plots, 949.69–1630.16 for 30 % grass coverage plots,

Table 3 Mean flow hydraulic characteristics of the different grass coverage and different grass distribution patterns on slope

Inflow rate L min^{-1}	Grass coverage %	GDP	Flow velocity (V) m s^{-1}				Reynolds number (Re)				Froude number (Fr)				Darcy–Weisbach (f)			
			S1	S2	S3	Average	S1	S2	S3	Average	S1	S2	S3	Average	S1	S2	S3	Average
3.22	0	–	0.26	0.30	0.37	0.31	1027.10	902.50	433.70	787.77	1.42	1.91	2.09	1.81	2.57	1.89	0.77	1.74
3.22	30	Up	0.09	0.24	0.28	0.20	400.40	1388.10	1387.90	1058.80	0.42	1.11	1.41	0.98	14.66	2.65	2.50	6.60
3.215	30	Middle	0.25	0.11	0.22	0.19	1368.90	521.60	498.40	796.30	1.36	0.47	1.14	0.99	3.53	12.50	0.22	5.42
3.16	30	Down	0.26	0.29	0.13	0.22	1249.10	1123.30	609.50	993.97	1.40	1.79	0.57	1.25	2.84	1.67	10.12	4.88
3.21	50	Up	0.08	0.23	–	0.15	339.50	1026.20		682.85	0.38	1.21		0.80	18.39	3.07		10.73
3.19	50	Middle	0.19	0.10	0.22	0.17	1159.00	312.70	807.70	759.80	1.30	0.53	1.15	1.00	3.91	14.11	1.01	6.34
3.15	50	Down	0.24	–	0.11	0.17	1063.40		291.50	677.45	1.25		0.65	0.95	2.31		12.99	7.65
3.155	70	Up	0.07	0.21	–	0.14	333.90	1060.40		697.15	0.29	1.08		0.68	32.77	3.94		18.35
3.165	70	Middle	0.19	0.08	0.21	0.16	1086.50	639.60	1247.20	991.10	1.15	0.34	2.42	1.31	3.78	19.73	0.56	8.02
3.17	70	Down	0.21	–	0.09	0.15	1112.20		268.30	690.25	1.11		0.44	0.78	3.80		16.90	10.35
3.25	90	–	0.06			0.06	328.50			328.50	0.23			0.23	44.63			44.63
5.18	0	–	0.31	0.39	0.56	0.42	2237.60	1513.00	888.40	1546.33	1.73	1.91	2.28	1.97	2.42	4.45	0.90	2.59
5.185	30	Up	0.10	0.24	0.25	0.19	649.40	2424.70	2035.40	1703.17	0.56	1.80	1.99	1.45	13.74	3.02	2.73	6.50
5.19	30	Middle	0.24	0.12	0.34	0.23	2189.50	906.80	1434.00	1510.10	1.54	0.41	1.86	1.27	5.47	11.09	1.57	6.05
5.21	30	Down	0.27	0.30	0.14	0.24	2101.70	2125.10	804.80	1677.20	1.65	1.98	0.55	1.39	2.05	3.61	8.94	4.87
5.18	50	Up	0.09	0.26	–	0.18	586.60	2180.20	1996.30	1587.70	0.50	1.98		1.24	15.14	2.64		8.89
5.175	50	Middle	0.24	0.11	0.11	0.15	2127.00	570.70	1448.10	1381.93	1.85	0.53	2.09	1.49	4.21	12.44	1.67	6.11
5.2	50	Down	0.26		0.12	0.19	2542.90		604.60	1573.75	1.24		0.57	0.91	2.95		9.26	6.11
5.215	70	Up	0.06	0.24		0.15	567.70	1731.90		1149.80	0.43	1.89		1.16	17.25	3.62		10.44
5.2	70	Middle	0.24	0.10	0.10	0.15	1088.50	590.50	2072.20	1250.40	1.27	0.49	1.65	1.14	3.35	15.99	2.38	7.24
5.23	70	Down	0.25		0.11	0.18	1563.80		531.20	1047.50	1.29		0.48	0.88	2.84		13.62	8.23
5.17	90	–	0.08			0.08	626.20			626.20	0.30			0.30	28.70			28.70

IR, GC, GDP refer to inflow rate, grass coverage, and grass distribution pattern, respectively. S1, S2, and S3 are the three cross-sections distributed on different slope positions. Numbers with underline represent the data on the grass cover section

706.70–1514.46 for 50 % grass coverage plots, 792.83–1149.23 for 70 % grass coverage plots, and 328.5–626.2 for 90 % grass coverage plots, respectively. For the same grass coverage rate, the *Re* values on a grass covered section was obviously less than that on a bared section. All of the average *Re* values were larger than 500 under the two inflow discharges conditions, except in the instance of the 90 % grass coverage under the inflow discharge of 3.2 L min^{-1}, which indicated that the runoff flow in our study was always defined as a "turbulent" flow according to the criteria of the open-channel flow. No significant relationship was seen to exist between the grass coverage and overland flow *Re* values; however, the *Fr* was found to be linearly correlated with the coverage rate (GC), as described by the correlation equation: $Fr = -0.0134$ GC + 1.7465, ($R^2 = 0.6373$, $n = 22$, $p < 0.01$). Therefore, our results differed from the consequence that were obtained by Pan and Shangguan (2006) and Liu et al (2010), for both their *Fr* and *Re* values were much lower than those found in our study. These discrepancies may be attributed, in part, to different experimental treatments, where our studied grass had differing distribution patterns and they employed a uniform distribution pattern. Another possible reason for the above differences may be ascribed to the different experimental method of the study itself, in which we employed the scouring experiment in our study and they chose to use simulated rainfall experiments in their studies. The overland flow was more easily concentrated under the scouring experiments, and both the flow velocity and depth were found to be more extensive than that experienced under the simulated rainfall experiments. The sediment concentration reached levels of up to and higher than 500 kg m^{-3}, where this sediment concentration was resultant of the hyperconcentrated flow, which was differed greatly from previous studies. Nevertheless, our results were similar with the findings observed in numerous rill experiments, which were also conducted by the use of the scouring experimental technique (Peng et al. 2015; Zhang 2002).

Grass coverage and distribution patterns both had a high effectiveness for the overland flow Darcy–Weisbach friction coefficients (*f*), where the grass plots had a higher *f* than did the CK plots, and the grass vegetated sections were similarly higher than the bare ones for any given grass coverage rate. The average *f* value of the whole slope for grass plots was in the range of 5.63–44.63 for the inflow discharge of 3.2 L min^{-1} and 5.80–28.70 for the inflow discharge of 5.2 L min^{-1}, which was 3.2–25.6 times and 2.2–11 times that for the CK plot. In addition, the mean *f* value of the whole slope was found to differ slightly among the US, MS, and DS treatments, where the *f* values of the US were evidently higher than that for the *MS* and DS. No statistical differences were detected between the MS and DS. These results indicated that the US treatments had performed more effectively than either the MS or DS in increasing the hydraulic roughness. The *f* was found to be exponent correlated with the coverage rate (GC), as described by the correlation equation: $f = 2.3059e^{0.0246GC}$ ($R^2 = 0.7752$, $n = 22$, $p < 0.01$). The *f* values of the grassplots in our experiment were greater than those reported by Abrahams et al. (1994), who revealed that their reported *f* values ranged from 0.5 to 18.8, with an average value of 8.3 in the grass cover plots (0.5 m width and 1.5 m length), as obtained by simulated overland flow experiments.

The present results are also greater than those reported by Liu et al (2010), where the *f* values of the grass coverage plots ranged from 0.52 to 1.22, which were 1.3–3.2 times the amount as that of the CK plot. Zhang et al. (2014) indicated that the mean *f* value of the whole grass coverage plots with different patterned treatments were in the range of 2.8–9.1, which were approximately 1.25–13.0 times those calculated for the CK plot. However, Pan and Shangguan (2006) found that the *f* values of the grass coverage plots ranging from 30.3 to 73.61, which were 5–12.6 times higher than those for the bare soil plot. Weltz et al. (1992) reported that the *f* values was about 114.2 for the grassland plots (3.05 m width and 10.70 m length) under the simulated rainfall intensity of 65 mm h^{-1}. Our research results were much lower than were their study results. These differences may be attributed to both the lower simulated rainfall intensities and the uniform grass coverage on slopes used in their experiments.

In the current study, both the relationship between *f* and *Re* and that between *f* and *Fr* could be well described by the following power functions: $f = a^* Re^{b}$ and $f = a^* Fr^{b}$ (Fig. 5). As can be seen from Fig. 5, the power parameters for a smaller inflow discharge are larger than those for a greater inflow discharge, with both of them being larger than 1. This indicates that *f* was more sensitive to *Re* and *Fr* for a smaller inflow discharge than for a greater inflow discharge, and that *f* decreased with *Re* much faster for a smaller inflow discharge than for a greater inflow discharge. The relationship between *Fr* and *Re* also could be well described by the power function: $f = a^* Re^{b}$ (Fig. 5). These power parameters have no obvious variation with the changes in the inflow discharges, and the power parameters for both of the two different inflow discharges are again smaller than 1. This indicates that the *Re* was not as sensitive to *Fr* variations for the two inflow discharges.

Our results agree with previous studies in the relationship between *f* and *Re* and *f* and *Fr*, but different in terms of the power parameters. Zhang et al. (2014) researched the relationship between the *f* and *Re* on bared plots, intact plant patterned plots, and root patterned plots, and found that a distinct power function between *f* and *Re* did exist;

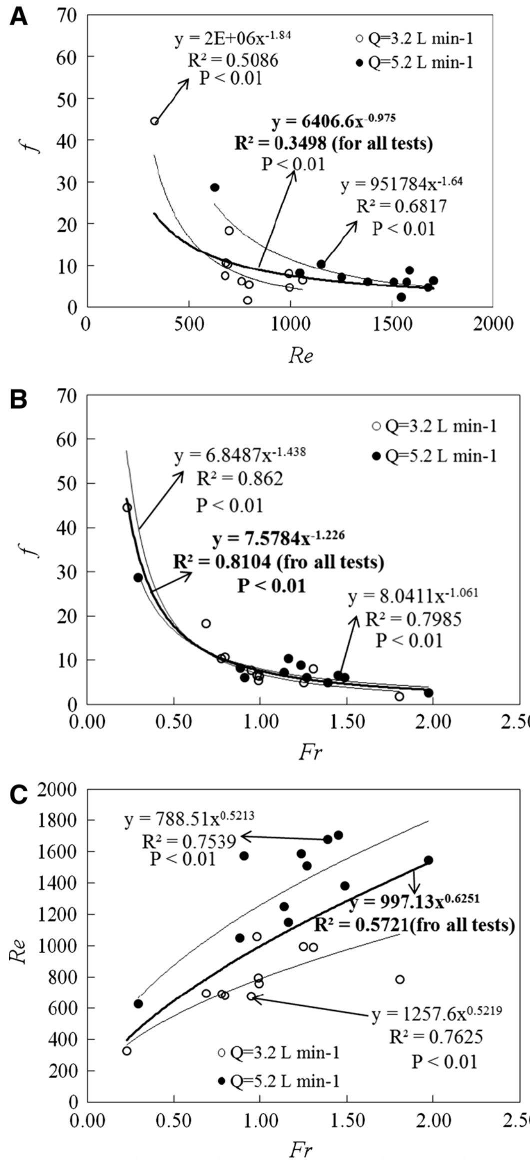

Fig. 5 Darcy–Weisbach friction coefficient (*f*) as a function of the Reynolds number (*Re*) (**a**), Froude number (Fr) (**b**), and Reynolds number (*Re*) as a function of the Froude number (Fr) (**c**)

the power parameter varied from −0.42 to −1.359 for root patterned plots to bared plots, amounts which are much smaller than those indicated in present research results. Abrahams et al. (1994) studied the *f* of non-vegetated soil in Arizona and found that the power parameter varied from −0.43 to −1.10. These differences may be attributed to rainfall, underlying surface, vegetation type, and other slope features (Zhang et al. 2014).

Relationship between runoff hydraulic parameters and erosion

The erosion process is the result of an interaction between erosive dynamics and an underlying surface friction force; therefor, overland flow hydraulic properties will have a profound influence on the erosion process. The relationship between the erosion rate and runoff hydraulic characteristics (V, *Re*, *Fr* and *f*) were further analyzed (Fig. 6). As shown in Fig. 6, *f* was negatively correlated with the erosion rate following a power function, with a regression analysis of $E_r = 2.1422f^{-0.402}$ ($R^2 = 0.3389$, $n = 22$, $p < 0.01$), while *V*, *Fr*, and *Re* were positively correlated with the erosion rate following a linear function, with a regression analysis of $E_r = 3.8217\ V + 0.3332$ ($R^2 = 0.4004$, $n = 22$, $p < 0.01$), $E_r = 0.786\ Fr + 0.1876$ ($R^2 = 0.5127$, $n = 22$, $p < 0.01$), and a power function, with a regression analysis of $E_r = 0.0011\ \mathrm{Re}^{0.979}$ ($R^2 = 0.7403$, $n = 22$, $p < 0.01$), respectively. The four above runoff hydraulic characteristics were significant correlation with erosion rate and coefficient of correlation following the order $Re > Fr > V > f$. The result demonstrated that *Re* was more sensitive to erosion rate than *Fr*, *V and f*, and *e*rosion rate decreased with *V* much faster than *Fr and f*. This is due to the flow velocity determines the rate at which water flow transports sediment (Liu et al. 2010), greater grass coverage would turbulent of overland flow and further reduce the runoff sediment carrying capacity, and hence the amount of sediment lost. Therefore, grass coverage changes the overland flow hydraulic characteristics is the main reason that sediment yielding decreasing compared with the bare soil slope. The various calculated results were consistent with Zhang et al. (2012), who observed the effect of grass patches on the erosion rate using a simulated rainfall experiment.

The sediment yield rate (SYR) was a function of the runoff rate (RR) for each treatment, and their relationship could be well described by the linear equation (Fig. 7). The relationship between SYR and RR under the different inflow discharges (3.2 and 5.2 L min^{-1}) are shown in Fig. 7a. From Fig. 7a, the SYR was positively correlated with the RR in grassplots. The slopes of the regression lines among the different grass coverage treatments of the grassplots were significantly different. The absolute values of the slopes, namely the soil erodibility, ranged from 0.264 for the 70 % grass coverage to 0.309 for the 30 % coverage. This increasing value with decreasing coverage could be ascribed to a decrease in soil erodibility. This pattern was similar to those observed in field bare plots in which runoff had a significantly positive correlation with soil loss (Pan and Shangguan 2006). The results were also consistent with those obtained by Shit et al. (2012), who observed the impact of vegetal cover on runoff and soil erosion on a lateritic environment in the field. However, our present results are contrary to those observed on vegetation plots (Cerda 1998; Pan and Shangguan 2006; Wu et al. 2010). Pan and Shangguan (2006) reported that sediment yield rate was negatively correlated with runoff rate in grassplots. Cerda

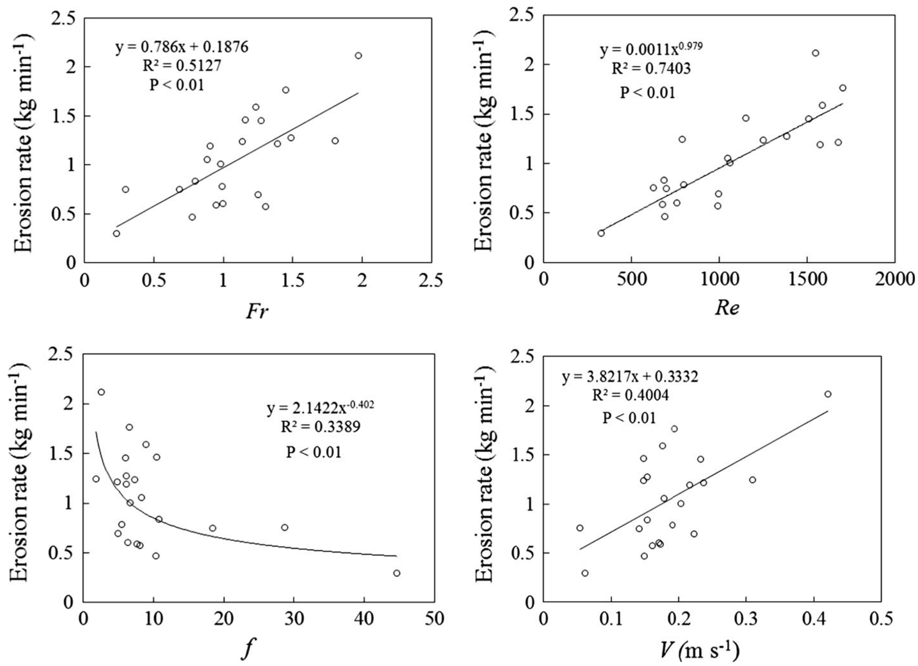

Fig. 6 Relationships betweent erosion rate and different overland flow hydraulic parameters

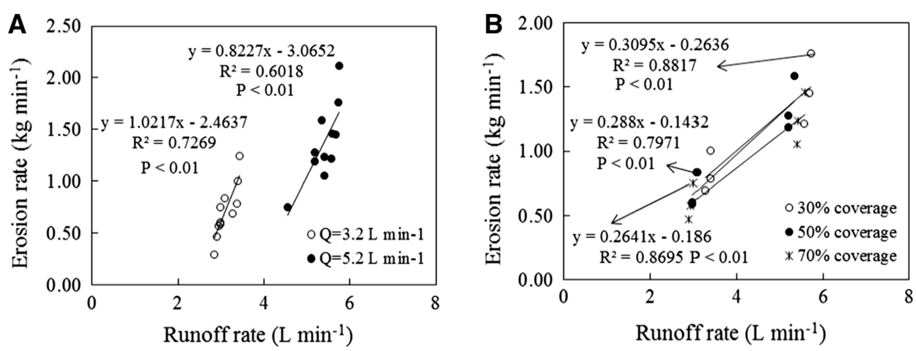

Fig. 7 Erosion rate as a function of the runoff rate for different inflow discharges and different grass coverage *plots*

(1998) observed that the runoff coefficient was negatively related to sediment concentrations on a Mediterranean hillslope with vegetation and attributed the negative trend to a result of the control exerted by sediment available for detachment and transport. Wu et al. (2010) observed the effects of grass hedges on the overland flow and soil erosion using simulated rainfall experiments, where the results show that the relationship between soil loss and overland flow could be perfectly described by an exponential instead of a linear model.

The main reason for these differences between the present study and the calculations contained within Pan's and Cerda's research is that the present study was conducted through use of scouring experiments, while simulated rainfall experiments were used in both Pan's and Cerda's research. For the natural situation, when one considers that in rainfall experiments the runoff amount has increased with the downslope, then the detachment ability and erosion amounts from the downslope would be greater than those calculated by means of the above experimental method. Another reason for the differences between the present research and Pan's study is that the grass distribution patterns employed in the present research differ from Pan's study, for different grass coverage and different grass distribution patterns were adopted in our research, while uniform grass coverage was standard in Pan's study. This indicates that both grass coverage and distribution patterns have significant effects on erosion. However, further studies employing the rainfall experiments would be required to most accurately determine the effects of grass coverage and distribution patterns on erosion.

Conclusions

Using scouring experiments for different water inflow discharges on different grass covered plots (30, 50, 70 and 90 %), different grass distribution patterns (US, MS and

DS) and the bared plot (CK) at a slope gradient 20°, the runoff and sediment generation, overland flow hydraulic characteristics, and relationship between runoff and erosion rate were studied. The following conclusions can be drawn.

There were significant differences in runoff generation and sediment yield between bared soil plot and grassplots. Compared with bare soil plot, grassplots runoff rates were reduced by approximately 2.06–10.94 and 8.53–10.66 % for 3.2 and 5.2 L min^{-1} water inflow discharges respectively. There was no significant difference in the runoff rate among the three grass distribution patterns for the same grass coverage. Grass cover had a more important role in reducing sediment than decreasing runoff. Grassplots had 36.17–75.4 and 28.57–64.62 % less sediment yield than bared soil plot for inflow discharge of 3.2 and 5.2 L min^{-1}, respectively. In addition, DS had the lowest sediment yield rate and greatest sediment yield reduction in comparison with US and MS. These results indicate that the DS is more effective than either the US or MS in both soil and water conversion under these established experimental conditions. In practices of soil erosion control, increase of grass coverage rate can obviously reduce the runoff and sediment yield, but under the condition of could not further increasing the grass coverage rate, DS can get the greater benefit than MS and US. This study also demonstrated that, when planted or recovered grass on a Loessic soil slope, drainage system should still be established during the construction of grass on slope.

Both grass coverage rates and distribution patterns have significant effects on hydrological characteristics of overland flow. With grass cover increased, the mean velocity of the whole plot decreased and Darcy–Weisbach friction increased, which result in overland flow carrying capacity was reduced and a negative power function existed between f and erosion rate. This result indicates that although the reduction in runoff was notably lower than that of the eroded sediments. However, grass cover can significantly decrease the overland flow velocity, increase underlying surface roughness, and reduce the overland flow Fr value. As a result, both the carrying capacity of the overland flow and runoff detachment capacity were reduced, leading to an exponentially lower erosion rate as grass coverage increased.

The sediment yield rate was found to be a function of the runoff rate for each treatment, and their relationships could be well described by the linear equation. Essentially, the varied SYRs were positively correlated with the RR in grassplots. The slopes of the regression lines among different grass coverage treatments of the grassplots were significantly different.

The results of this study provide erosion researchers with significant information, which was helpful for understanding the effects of grass coverage and grass distribution pattern on controlling of soil erosion at different inflow discharges. In addition, the relationship between sediment yields and grass coverage as well as the relationship between sediment yields and overland flow hydraulic characteristics can be considered in erosion prediction models. The results may also be useful in framing policies for the transformation of cultivated land to forests and grassland in China.

Acknowledgments This work was supported by the National Natural Science Foundation of China (41271303), the National Key Technology R&D Program (2012BAK10B04, 2008BAD98B02), the Changjiang River Scientific Research Institute of Sciences Innovation Team Project (CKSF2012052/TB), and the Changjiang River Scientific Research Institute of Sciences Foundation (CKSF2013013/TB).

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