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Runoff hydraulic characteristics and sediment generation in sloped grassplots under simulated rainfall conditions

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Summary Evaluation of grass influence on soil erosion process can provide important information in soil and water conservation. The laboratory experiment was conducted to study runoff and sediment producing processes and runoff hydraulics in the grassplots with different covers (35%, 45%, 65% and 90%) and bare soil plot (control) at a slope of 15°. The results showed that grass significantly reduced runoff and sediment. Compared with bare soil plot, the grassplots had a 14–25% less runoff and an 81–95% less sediment, and played a more important role in reducing sediment at the final stage of rainfall. There was a significantly negative logarithmic relationship between sediment yield rate (SDR) and cover (C): SDR = 1.077–2.911 ln(C) ($R^2 = 0.999^{**}$). Sediment yield rate of grassplots decreased with rainfall duration, and decreased linearly as runoff rate increased. Overland flow velocities deceased with increase in grass cover, and the cover had greater effect on lower slope velocity than upper one. Froude numbers decreased with increase in cover, and flow regimes of all treatments were laminar and tranquil. Darcy–Weisbach and Manning friction coefficients of grassplots increased as ground cover increased. Therefore, increase in grass coverage can efficiently reduce soil loss and improve ecological environments.

Introduction

Soil erosion is one of the most serious eco-environmental problems in the world. Vegetation has long been recognized as an efficient way to prevent soil erosion, and is widely

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used as an important measure of soil and water conservation (Morgan and Rickson, 1995). Grasses have an important effect on slope runoff and sediment. Based on field experiments in which grass stems and leaves were cut close to ground surface, Prosser et al. (1995) concluded that flow resistance and critical shear stress of concentrated overland flow in sediment translocation decreased compared to those of a complete grass cover. Chatterjea (1998) studied runoff and sediment generation on bare and grassplots under natural rainstorm, and concluded that the responses of the bare surfaces to incoming rainfall were more instantaneous and more significant than those of grassplots. Based on comparison experiments under laboratory-simulated rainfall, Pan et al. (2006) showed that grasses and moss significantly reduced sediment yield, and that moss had a negative effect on soil infiltration.

Although numerous studies have mentioned vegetation cover impacts on soil erosion (Thornes, 1987; Trimble, 1990; Stocking, 1994; Morgan and Rickson, 1995; Braud et al., 2001), relatively less information on erosion process in grassplots was provided. Moreover, the differences in soil properties, slope surface conditions, vegetation types, etc. in field experiments tend to have negative effects on the findings. Such emphasis is based more on common sense than on the results of scientific investigations and little is known about runoff and sediment yielding process.

Hydraulic characteristics of overland flow, such as flow velocity, flow depth and friction coefficients, etc., and their relationships have been studied widely on overland flow (Foster et al., 1984; Gilley et al., 1990; Govers, 1992; Abrahams et al., 1996; Nearing et al., 1997). However, few studies have examined interrill flow in vegetation-covered plots under rainfall conditions. Some investigations have demonstrated that vegetation modifies the hydrology of overland flow and this modification has implications for the transfer and deposition of sediment (Evans, 1980; Kang et al., 2001; Neave and Abrahams, 2002). However, it is difficult to understand the erosion process and mechanics on vegetation-covered plots due to lack of sufficient reliable data. Meanwhile, it is a focus on ecological research to illustrate terrestrial eco-hydrology processes at present (Baird and Wilby, 1999).

The objectives of this study are to better understand the influence of grasses on runoff hydraulic characteristics and sediment producing process, and to further clarify the differences among grassplots with different covers. The findings can offer basic data for the building of erosion mechanics model on vegetation-covered slopes, and present a theoretical guidance for the construction of soil and water conservation.

Materials and methods

Experimental conditions

The experiment was conducted in a laboratory under simulated rainfalls, at the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Yangling, China. A side-sprinkle precipitation set-up system, in which rainfall intensities can be precisely adjusted through nozzle sizes and water pressure, was used in the experiments. The height of rainfall simulator is up to 16 m and simulated storm with uniformity of above 85% is similar to natural rainfall in raindrop distribution and size. Calibrations of rainfall intensities were conducted prior to the experiments.

Each of experimental steel plots was 2.0 m in length, 0.55 m in width, and 0.35 m in depth. A metal runoff collector was set at the bottom of the plot to direct runoff into a container. Apertures were formed at the bottom of plot to allow soil moisture to freely infiltrate. Experimental plot slope was adjusted at 15°, which is the threshold gradient for transforming farmland to forestland or grassland in the experimental region. Soils used in the study were a loessial loam collected from Fuxian county in the north of the Loess Plateau, which is susceptible to soil erodibility. The soil texture information is listed in Table 1.

Experimental treatments and measurements

Soil was gently crushed before passing through a 10 mm sieve, and the sieved soil was thoroughly mixed to minimize the difference among treatments. The 30 cm thick soil was packed in each plot in three 10-cm layers to achieve a 1.2 g cm^{-3} bulk density. Additionally, each soil layer was raked lightly before the next layer was packed to diminish the discontinuity. Perennial black rye grass (*Lolium perenne* L.), a commonly seen grazing grass, was used for vegetation cover.

The treatments included: four grassplots with plant space × row space of 15 cm × 15 cm, 5 cm × 20 cm, 10 cm × 10 cm and 5 cm × 10 cm, respectively, and a control of bare soil plot (Fig. 1). All treatments had two replicates. One day before experiment, a specialized soil auger with a diameter of 1 cm was used to determine soil water content of the different treatments. According to the measured values, different amount of water was sprayed with a commonly used household sprayer to minimize the differences in antecedent soil water content among treatments. Soil water content was adjusted to 15% (gravimetrically) for all the treatment plots at the beginning of rain simulation experiments.

The simulated rainfall at an intensity of about 100 mm h^{-1} was employed for about 70 min. For each treatment, runoff-initiating time was recorded; all runoff and

Table 1 Physical properties of the soil used in this experiment

Soil type	Particle size distribution % (μm)						Soil texture
	1000–250	250–50	50–10	10–5	5–1	< 1	
Loessial soil	0.01	2.91	54.61	13.03	12.09	17.35	Sandy loam soil

Figure 1 Contrast of a bare soil plot and a grassplot before simulated rainfall.

sediment samples were collected in a pail; and flow velocity was measured at 3-min intervals during rainfall. Sediment was deposited, separated from the water, dried in an air forced oven to constant weight at 105 °C, and weighed. Sediment concentration was determined as the ratio of dry sediment mass to runoff volume, while sediment yield rate was defined as dividing sediment yield per unit area by the period of time. Infiltration rates were determined by subtracting the measured runoff rates from the rainfall application rate. Thus, evaporation, interception and surface storage components were considered as infiltration. Steady runoff and sediment rates were the average values during the final 15 min of the rainfall.

Surface flow velocities (V_s) on upper and lower slope were measured by the means of $KMnO_4$ coloration. The upper slope was from top to middle (0–1 m) and the lower slope from middle to outlet (1–2 m). Time tracer traveling across a marked distance (1 m) is determined according to the color-front propagation using a stop-match. Values of V_s are used to estimate profile mean velocities (V) by the relation of $V = kV_s$, where k is a coefficient. Assuming the vertical velocity distribution in laminar flow of depth followed by a quadratic equation and the theoretical value k is 0.67 (Li et al., 1996).

Grass cover was measured by ERDAS Imagine (8.4) processing digital photo. The general approach is as following: first, to take pictures of the 50 cm × 50 cm grass area in each grassplot with a digital camera under the same conditions (e.g., the same distance from lens to object); then to process the pictures by ERDAS Imagine by dividing them into 12 colors, and to make sure which colors stand for grass cover. Thus, the percentage covered by grass stands for grass cover. Meanwhile, it was modified through the assessment by naked eyes.

Data analysis

Soil instantaneous infiltration rate (f_i) was calculated by formula:

$$f_i = I\cos\theta - \frac{10R_i}{S \cdot t} \qquad (1)$$

where I is rainfall intensity (mm min^{-1}), θ is slope (°), t is interval time to collect runoff samples (min), R_i is the ith runoff volume collected (ml), S is area of the plot (cm^2), and 10 is adjusting coefficient.

Flow depth is an important factor of surface flow. But it is very difficult to be measured because of erosion process on plot surface. Assuming slope flow is uniform, mean flow depth can be calculated from:

$$h = \frac{q}{U} = \frac{Q}{U \cdot Bt} \qquad (2)$$

where h is flow depth (cm), q is unit discharge (cm^2 s^{-1}), Q is runoff volume during t time (ml), U is mean flow velocity (cm s^{-1}), and B is width of water-crossing section (cm).

Flow Reynolds number (Re) and Froude number (Fr) were calculated from Eqs. (3) and (4), respectively:

$$Re = \frac{Uh}{\upsilon} \qquad (3)$$

$$Fr = \frac{U}{\sqrt{gh}} \qquad (4)$$

where υ is kinematical viscosity (cm^2 s^{-1}) and g is acceleration of gravity (cm s^{-2}).

Darcy–Weisbach (f) and Manning friction coefficients (n) were used to characterize retardation of flow and can be calculated by Eqs. (5) and (6), respectively:

$$f = \frac{8ghJ}{U^2} \qquad (5)$$

$$n = \frac{h^{2/3}J^{1/2}}{U} \qquad (6)$$

where J is surface slope (m m^{-1}).

The relationship between sediment and runoff was regressed by the following linear equation:

$$q_s = aq_w + b \qquad (7)$$

where q_s is sediment yield rate (g m^{-2} min^{-1}), q_w is runoff rate (mm min^{-1}), a is a regression coefficient (g m^{-2} mm^{-1}) describing soil erodibility, and b is also a regression coefficient (g m^{-2} min^{-1}).

Paired t test and least significant difference (LSD) multiple-comparison test were used to identify statistically difference among treatments. ANOVA methods were used to analyze the relationship between runoff and sediment. The SPSS 11.0 were performed for all these analyses.

Results and discussion

Runoff

Runoff rates in the grassplots ranged from 0.85 to 0.97 mm min^{-1}. Grass cover reduced runoff rate by about 14–25% compared to bare soil plot (Table 2). Our result is consistent with other studies (Lal, 1997; Chatterjea, 1998; Johansen et al., 2001; Benito et al., 2003) in vegetation cover reducing runoff, but our study had lower cover importance. This may be associated with the greater storm intensity with long duration, higher soil bulk density and lower aggregate stability in our study compared to those observed from filed plots.

Table 2 Average runoff rate, sediment concentration, and sediment yield rate of the different grass cover plots and reductions in these parameters as compared with bare soil plot

Cover (%)	Runoff rate (mm min^{-1})	Sediment concentration (kg m^{-3})	Sediment yield rate (g m^{-2} min^{-1})	Reduction (%)		
				Runoff rate	Sediment concentration	Sediment yield rate
0	1.13 a	17.00 a	21.20 a	—	—	—
35	0.97 b	3.92 b	3.98 b	14.2	76.9	81.2
45	0.85 bc	3.64 b	3.22 b	24.8	78.6	84.8
65	0.95 b	2.50 c	2.81 b	15.9	85.3	86.7
90	0.89 b	1.21 d	1.22 bc	21.2	92.9	94.3

Means within a column followed by the same letter are not significantly different at $\alpha = 0.05$ level using the least significant difference (LSD) method.

The difference in runoff was only detected between the 45% and 65% grass cover treatments. Average runoff rate in the 45% cover grassplot was lower than those in the others (Table 2). This may be associated with the pre-disposal of the experiment. Additional water had been spayed on the different cover plots with exception of the 45% cover due to its highest soil water content (15%, gravimetrically) measured prior to the experiment, which resulted in its surface layer infiltration capacity larger than those of the other grassplots.

Steady runoff rate of grassplots was reduced 7.5—16% compared to that of bare soil plot. Grassplots had greater steady runoff rates than bare soil plot, and there was no significant difference among grassplots except for the 65% cover (Table 3). Runoff rate on bare soil plot increased more abrupt than on the grassplots at initiation of rainfall (Fig. 2). In bare soil plot, runoff occurred at the first 1 min, and the initial and steady runoff rates were about 0.88 and 1.2 mm min^{-1}, respectively, which were greater than those of the grassplots (Fig. 2). This may be due to the facts that grass cover reduces the kinetic energy of raindrop so as to prevent surface soil sealing, grassplots surface roughness impedes overland flow and increases infiltrating time, and grass root improves the soil infiltration capacity (Bajracharya and Lal, 1998; Li et al., 1991).

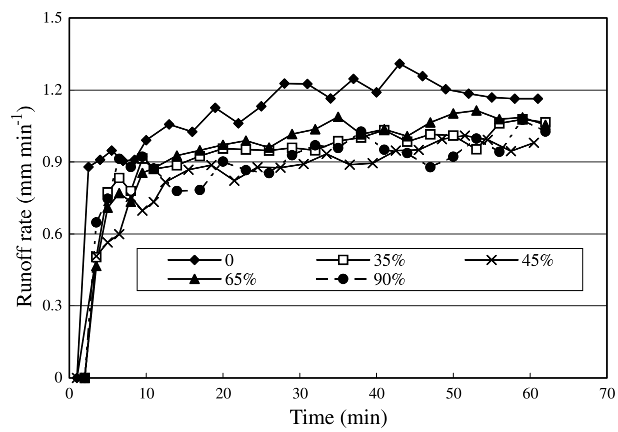

Figure 2 Runoff rate as a function of time on different cover plots.

Sediment

Grass covers reduced sediment yield by 81.2—94.3% compared to bare soil plot (Table 2). This result accords with Benito et al. (2003) who found vegetation cover could reduce by 96% in erosion. This behavior has also been found under different vegetation types and climates (Abrahams et al., 1988; Cerdà, 1998; Ziegler and Giambelluca, 1998; Edeso et al., 1999; Casermeiro et al., 2004) in vegetation cover controlling erosion rate. This result may be mainly due to: (1) an increase in the interception of raindrops may reduce raindrops energy approaching to soil surface, prevent soil crusting and reduce runoff; (2) an increase in hydraulic roughness due to plant stems can reduce flow velocity; (3) an increase in plant roots, which bind the soil, improves soil

Table 3 Steady runoff and sediment yield at the final time of runoff for the different grass cover plots and their reductions as compared with bare soil plot

Cover (%)	Runoff rate (mm min^{-1})	Sediment concentration (kg m^{-3})	Sediment yield rate (g m^{-2} min^{-1})	Reduction (%)		
				Runoff rate	Sediment concentration	Sediment yield rate
0	1.18 a	20.97 a	24.67 a	—	—	—
35	1.03 b	1.51 b	1.56 b	12.2	92.8	93.7
45	0.98 b	1.73 bc	1.72 bc	7.6	91.7	93.0
65	1.09 c	1.28 b	1.50 b	16.3	93.9	93.9
90	0.99 b	0.58 b	0.57 b	15.6	97.3	97.7

Means within a column followed by the same letter are not significantly different at $\alpha = 0.05$ level using the least significant difference (LSD) method.

structure to reduce its erodibility and increase its infiltration capacity. There was a relatively small difference in average sediment yield among the grassplots (Table 2).

Furthermore, sediment concentration (SC), sediment yield rate (SYR) were found to be a negative logarithmic function of cover (C) expressed in the equations: $SC = 1.458-2.258\ln(C)$ ($R^2 = 0.998^{**}$) and $SDR = 1.077-2.911\ln(C)$ ($R^2 = 0.999^{**}$), respectively. The equation has been also used to describe the relationship between average sediment yield and vegetation cover under field conditions in the Loess plateau (Dong et al., 1998). Steady sediment concentrations and sediment yield rates of the grassplots were 92–98% less than those of the bare soil plot. The grassplot with 90% cover had much less steady sediment yield than the other grassplots (Table 3).

Sediment-yielding processes were significantly different between the grassplots and bare soil plot (Fig. 3). Sediment yield rate in the bare soil plot decreased at first, then increased in the first 45 min of the rainfall, and thereafter became almost constant. For the grassplots, sediment yield rate decreased with rainfall duration. This pattern is in disagreement with Parsons et al. (1996) and Wainwright et al. (2000) who found erosion rates in the grassland continuously increased with time. The difference in erosion process may be attributed to the coarse-loamy soils with gravelly or rock fragments which act as enough detached materials and the larger plot size in their field experiments.

Fig. 4 shows percentage reductions of the grassplots in sediment yield rate compared with the bare soil plot over time. All of the grassplots mirrored each other in terms of relative effectiveness regardless of absolute difference in sediment yield rate, and each grassplot behaved similarly. The percent reductions decreased firstly with the minimum value ranging from 17% to 63% for different grassplots at initial 6–10 min, then increased, and finally kept relatively steady (Fig. 4).

Runoff hydraulics

Flow velocity deceased with increasing cover and the grassplots had a decrease of about 50% in flow velocity compared to the bare soil plot (Fig. 5). There was no statistical difference in flow velocity of upper slope among the grassplots

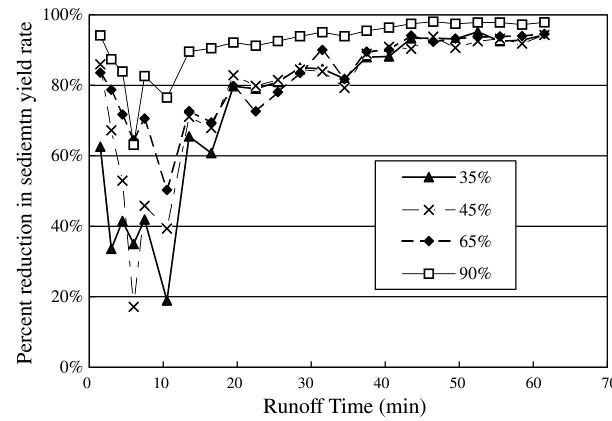

Figure 4 Percentage reduction grassplots compared with bare soil plots in sediment yield rate over runoff time.

with the average of 1.7 ± 0.1 cm s^{-1}. However, for lower slope, flow velocity deceased with increasing cover, ranging from 2.5 to 3.5 cm s^{-1}. These results indicated that grass cover had more important effect on lower slope velocity than upper slope one. For the same cover plot, there were significant differences among the velocities of upper slope, lower slope, and the mean velocity. The velocity ratio of lower slope to upper slope decreased with increase in grass cover and varied from 1.4 to 2.7.

Froude numbers decreased with increasing cover. Grassplots reduced it by 56–72% compared with bare soil plot ($Fr = 0.77$, Table 4). However, there was a little difference in Reynolds numbers among different covers, ranging from 30 to 40. According to the criterion of open channel flow, all overland flows are tranquil and laminar. Our results differ from the findings observed in numerous rill experiments (Gilley et al., 1990; Zhang, 1999; Zhang, 2002) in which both Fr and Re values were much greater than those of our study. The differences may be explained by the concentrated runoff with greater velocity and flow depth.

Darcy–Weisbach (f) and Manning (n) friction coefficients increased with the increscent grass cover (Table 4). Similarly, Abrahams et al. (1994) found cover mainly attributed to surface roughness. The f values of the grassplots, ranging

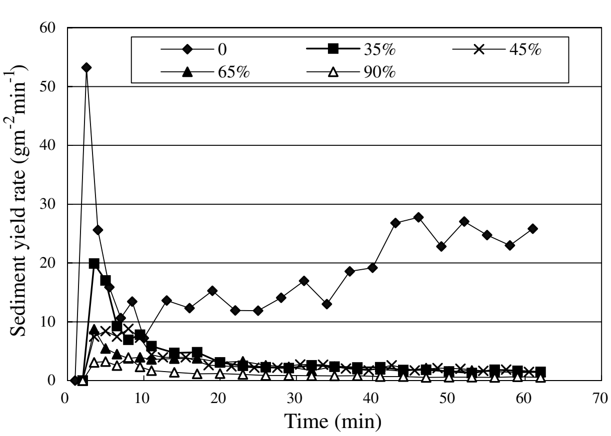

Figure 3 Sediment yield rate as a function of time in different cover plots.

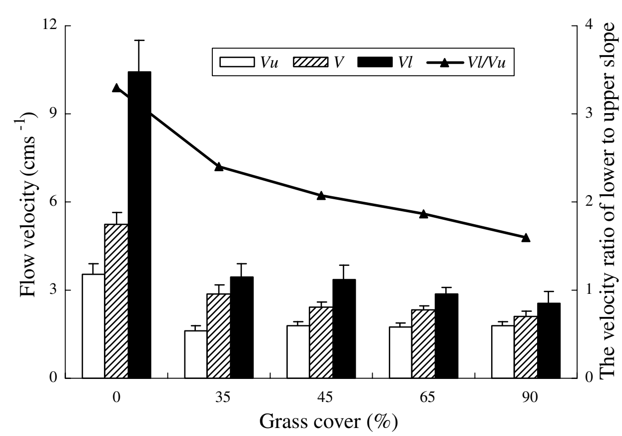

Figure 5 Flow velocities of different slope positions in different cover plots (V_u, V_l and V refer to the velocities of upper slope, lower slope and mean velocity, respectively) .

Table 4 Flow hydrodynamic characteristics of the different grass cover plots

Cover (%)	Unit flux q ($cm^2\ s^{-1}$)	Mean flow velocity U ($cm\ s^{-1}$)	Mean flow depth h (mm)	Reynolds number (Re)	Froude number (Fr)	Darcy–Weisbach f	Manning n ($\times 10^{-2}$)
0	0.40	5.22	0.77	40.42	0.60	5.84	1.76
35	0.34	2.85	1.19	34.15	0.26	30.30	4.32
45	0.32	2.43	1.33	32.55	0.21	46.62	5.45
65	0.33	2.34	1.41	33.32	0.20	53.29	5.89
90	0.32	2.09	1.55	32.57	0.17	73.61	7.03

from 30.3 to 73.6, were as 5–13 times as that of bare soil plot, and the n values of the grassplots were as 2.5–4 times as that of bare soil plot. The f values of the grassplots in our experiment were greater than those reported by Abrahams et al. (1994) who found that f ranged from 0.5 to 18.8, with a median of 8.3 in the grassplots with 0.5 m (width) by 1.5 m (length) by simulated overland flow from trough. This may result from the difference of the methods of application of water to the plot (Parsons et al., 1994). However, the f values of our study were less than results of Weltz et al. (1992) who estimated an f of 114.2 for the grassland plots by optimization of the kinematics wave equations with 3.05 m (width) by 10.70 m (length) under 65 mm h^{-1} simulated rainfall. The greater f values observed by Weltz et al. (1992) may be attached with lower simulated rainfall intensity and greater micro-hypsography in native rangeland areas. In contrast, the f values for the grassplots in our study were much greater than those measured in rill experiments (Foster et al., 1984; Gilley et al., 1990; Abrahams et al., 1996; Zhang, 1999) in which most f values were less than 3.0.

Relationships between runoff and sediment

The relationship between sediment yield rate and runoff rate as an indicator of soil erodibility has commonly been regarded as a linear function under net detachment conditions or a quadratic regression under depositional conditions (Huang and Bradford, 1993).

Sediment yield rate (q_s) was a function of runoff rate (q_w) for each treatment and their relationship could be well described by the linear equation (7) (Fig. 6). From Fig. 6a, q_s were negatively correlated with q_w in grassplots. This pattern differs from those observed in field bare plots in which runoff had a significantly positive correlation with soil loss (Huang and Bradford, 1993; Flanagan et al., 2002; Benik et al., 2003). However, our results are similar to those observed on vegetation slopeland (Abrahams et al., 1988; Cerdà, 1998). Abrahams et al. (1988) showed that sediment concentrations generally had negative correlation with flow discharge on shrub land and suggested that the exhaustion of available materials by raindrop detachment and weathering be an important control on interrill transfer. Cerdà (1998) found runoff coefficient was negatively related to sediment concentration 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.

The slopes of the regression lines among different cover treatments in the grassplots were significantly different (Table 5). The absolute values of the slopes, namely soil erodibility decreased as grass cover increased, and ranged from 35.57 g m^{-2} mm^{-1} for the 35% cover to 5.99 g m^{-2} mm^{-1} for the 90% cover (Table 5). This decreasing value with increasing cover may be attributed to an increase in soil aggregate stability due to grass root and a decrease in effective kinetic raindrop energy and flow velocity with increasing cover. For the bare soil plot, the relationships between q_s and q_w could be divided into two distinct linear regions: a lower region with less runoff rate where q_w is negatively correlated with q_s with a negative erodibility (a value), and an upper region where q_s increases with q_w, which results in a positive relationship.

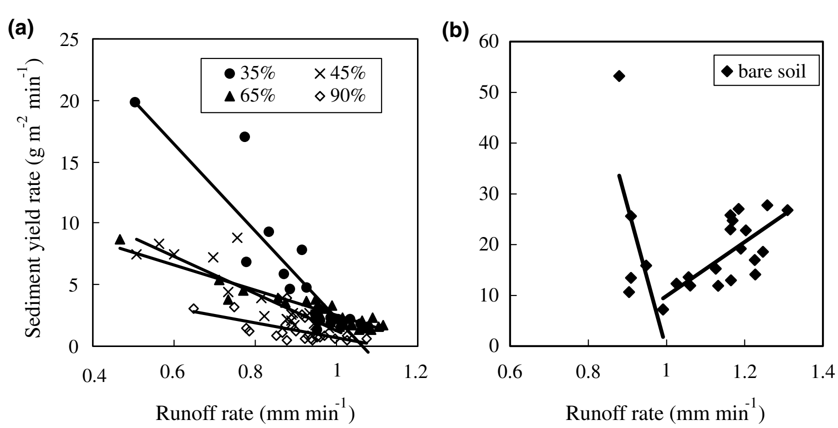

Figure 6 Sediment yield rate (q_s) as a function of the runoff rate (q_w) in grass-covered plots and bare soil plot (for bare soil plot, there is a negative relationship between q_s and q_w for relatively less q_w, and a positive relationship for greater q_w).

Table 5 The slope (a), intercept (b) and coefficient of determination (R^2) of linear regression of sediment yield rate (q_s) and runoff rate (q_w) ($q_s = aq_w + b$) for each treatment

Cover (%)	a	95% Confidence interval of a		b	n	R^2
		Lower limits	Upper limits			
0[a]	−284.65	−727.62	158.31	283.85	6	0.443
	53.22	24.53	81.92	−43.35	18	0.491**
35	−35.57	−43.23	−27.90	37.80	23	0.816**
45	−15.15	−18.81	−11.49	16.44	23	0.779**
65	−10.22	−11.79	−8.64	12.68	23	0.897**
90	−5.99	−9.75	−2.23	6.74	23	0.344**

The sample size (n) and the 95% confidence interval of a are also presented.
[a] The first row indicates the results when q_w is relatively less, and the second row represents them when q_w is greater than 1 mm min^{-1}.
** Significant $\alpha = 0.01$.

Conclusions

Under simulated rainfall at an intensity of 100 mm h^{-1} for about 70 min, the processes of runoff and sediment generation in the grassplots with different covers (35%, 45%, 65% and 90%) and bare soil plot (control) at a slope of 15° were studied. The conclusions can provide a theoretical guidance to the vegetation construction aiming at soil and water conservation. The following results can be drawn regarding grass coverage effects on plot runoff and sediment generation and hydraulic characteristics:

There were significant differences in runoff and sediment yield between bare soil plot and grassplots. Compared with bare soil plot, grassplots decreased average runoff rate by 14—25% and final runoff rate by 7.5—16%, respectively. Grasses had a more important role in reducing sediment than runoff. Grassplots had a 81.2—94.3% less sediment yield than bare soil plot, and achieved better benefit at the final stage of rainfall. There was a negative logarithmic relationship ($SC(SYR) = a - b\ln(C)$) between sediment concentration (SC), sediment yield rate (SYR) and grass cover (C). Grassplots had a similar sediment yielding process and sediment yield rate decreased with rainfall duration. For grass plots, sediment yield rate decreased as a linear function of runoff rate, and the decreasing slope decreased with the increase in cover.

Overland flow velocity deceased with the increasing grass cover, and grass coverage had more important effect on flow velocity in lower slope than in upper slope. Froude numbers decreased with increase in cover, and flow regimes of all treatments were laminar and tranquil. Darcy—Weisbach and Manning friction coefficients of the grassplots increased with the increasing cover, which were, respectively, 5—13 times and 2.5—4 times as much as those of bare soil plot.

Acknowledgments

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