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Influences of grass and moss on runoff and sediment yield on sloped loess surfaces under simulated rainfall

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Abstract:

It is important to evaluate the impacts of grasses on soil erosion process so as to use them effectively to control soil and water losses on the Loess Plateau. Laboratory-simulated rainfall experiments were conducted to investigate the runoff and sediment processes on sloped loess surfaces with and without the aboveground parts of grasses and moss (GAM: grass and moss; NGAM: no grass and moss) under slope gradients of 5°, 10°, 15°, 20°, 25° and 30°. The results show that runoff from GAM and NGAM plots increased up to a slope gradient of 10° and decreased thereafter, whereas the runoff coefficients increased with gradient. The average runoff rates and runoff coefficients of NGAM plots were less than those of GAM plots except for the 5° slope. This behaviour may be due to the reduction in water infiltration under moss. The difference between GAM and NGAM plots in average runoff rates varied from 1·4 to 8%. At the same gradients, NGAM plots yielded significantly ($\alpha = 0{\cdot}05$) more sediment than GAM plots. Average sediment deliveries for different slopes varied from 0·119 to 3·794 g m^{-2} min^{-1} from GAM plots, and from 0·765 to 16·128 g m^{-2} min^{-1} from NGAM plots. Sediment yields from GAM plots were reduced by 45 to 85%, compared with those from the NGAM plots. Plots at 30° yielded significantly higher sediments than at the other gradients. Total sediments S increased with slope gradients G in a linear form, i.e. $S = 9{\cdot}25G - 39{\cdot}6$ with $R^2 = 0{\cdot}77^*$, for the GAM plots, and in an exponential model, i.e. $S = 40{\cdot}4\exp(0{\cdot}1042G)$ with $R^2 = 0{\cdot}93^{**}$, for the NGAM plots. In all cases, sediment deliveries decreased with time, and reached a relative steady state at a rainfall duration of 14 min. Compared with NGAM plots, the final percentage reductions in sediment delivery from GAM plots were higher than those at the initial time of rainfall at all slopes. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS soil erosion; grassland; moss; gradient; runoff; sediment

INTRODUCTION

Soil erosion is one of the most severe eco-environmental problems in the world, particularly on the Loess Plateau of China. Grazing and traditional farming practices on steeply sloped lands have been the dominant land use in the region, which induce serious soil losses. To improve the eco-environments in the region, the Chinese Government proposed the project of transforming the cultivated land to forest or grasslands in 1999. Grasslands have spread rapidly as the project has been carried out, and an evaluation of the sediment delivery rates to streams and the Yellow River is now needed. Meanwhile, a ban on grazing has had a great influence on the incomes of local farmers, which in turn affects the enthusiasm of the farmers participating in the project. Restricted grazing or forage harvesting to feeding animals in feedlots was proposed to try to ease the opposition.

Soil erosion processes on hillslope are governed essentially by raindrop splashes and surface runoff processes (Flanagan and Nearing, 1995). Prior to runoff initiation, raindrop splashes play an important role in soil erosion,

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and the energy of raindrops reaching the soil surface is the critical factor inducing splash detachment to cause dislocations of soil particles (Wischmeier and Smith, 1978; Flanagan and Nearing, 1995). These dislocated soil particles could contribute to the increased sediment delivery rate at the initial runoff stage. Once the rainfall intensity surpasses water infiltration capacity, runoff occurs and overland sheet flow forms (Parsons *et al*., 1996). Raindrop detachment still plays an important role in soil erosion, because flow rate is initially still too low to transport the detached sediment. As the runoff increases due to the further decrease in infiltration rate, sufficient runoff is accumulated to create rills with concentrated flow that become the dominant pathways of soil erosion and sediment transportation.

Soil erosion increases with slope mainly due to increase in raindrop splashing and runoff scouring. Under the same rainfall condition, flow velocity increases and flow depth decreases as the slope gradient increases. Soil detachment by splash increases with decreased runoff depth (Evans, 1980; Moss and Green, 1983; Ferreira and Singer, 1985; Fox and Bryan, 1999). Increased flow velocity induces higher scouring capability and transport capability of the flowing water (Kloosterboer and Eppink, 1989). Another reason is a lower approach angle of raindrops to the soil surface for steeper slopes (Gerits *et al*., 1990). Kinnell and Cummings (1993) mentioned a possible indirect effect of slope on soil erosion related to the variability of aggregate stability and soil crusting, which are associated with topographic parameters.

Reports reveal another interesting phenomenon, whereby soil losses increase to a critical slope gradient and decrease thereafter (Singer and Blackard, 1982; Abrahams *et al*., 1988; Hu and Jing, 1999). Although numerous studies have been conducted, the effects of slope gradients on interrill erosion are not clearly established, and the interactions between erosive factors are not taken into account in laboratory experiments. The coupled physical processes of runoff and erosion under different slopes need further verification (Chaplot and Le Bissonnais, 2000).

The influence of vegetative cover on erosion takes place through the mechanism of reducing both the kinetic energy of raindrops and the hydrodynamic power of flowing water. Ground cover interception of precipitation reduces not only the runoff volume, but also protects surface soil from being detached and the detached soil particles being transported (Parsons *et al*., 1992; Wainwright *et al*., 1995, 1999; Lane *et al*., 1997; Bryan, 2000). Vegetative covers have the ability to reduce flow velocity, which reduces the erosive force (Evans, 1980; Pan and Shangguan, 2005). In addition, the soil structure under vegetative cover is improved, with a higher infiltration capability and plant roots reinforcing the soil body to resist higher erosive forces (Li *et al*., 1991; Ziegler and Giambelluca, 1998; Barthès and Roose, 2002). Therefore, it is expected that less splashing and scouring occur under vegetative cover than under bare conditions.

In general, vegetation reduces runoff due to canopy interception and higher infiltration rate associated with improved soil structure. Vegetation controls the erosion processes due to (i) canopy interception of raindrops to reduce the approach energy to the soil surface; (ii) lowered runoff scouring energy associated with increased infiltration and surface roughness; and (iii) reduced erodibility of soil associated with roots.

Numerous studies have been conducted on the soil erosion control by vegetation cover, concerning the aboveground biomass influences on soil losses (Moore *et al*., 1979; Thornes, 1987; Trimble, 1990; Stocking, 1994; Morgan, 1995) and roots (Reid and Goss, 1981; Li *et al*, 1991; Ghidey and Alberts, 1997; Mamo and Bubenzer, 2001a,b; Gyssels and Poesen, 2003). In the arid and semi-arid environments of the Loess Plateau of China, moss layers normally present at the soil surface beneath vegetation (Zhang *et al*., 2002). More attention has been paid to the aboveground biomass portion and the roots. But the effects of mosses on soil erosion tend to be neglected. It is reported that moss has positive impacts on preventing soil scouring (Zeng, 1995). The study of the combined influences of moss and aboveground biomass portion on soil erosion control is essential to understand the erosion mechanism.

Laboratory-simulated rainfall experiments have been used to investigate runoff and soil erosion (Renard, 1986; Abrahams *et al*., 1988; Johansen *et al*., 2001). The objectives of this study were to use simulated grazing by cutting the aboveground portion of grasses and moss (GAM) to investigate runoff and erosion processes with and without the aboveground parts of GAM for different slope gradients under simulated rainfall conditions.

MATERIALS AND METHODS

Experiment facilities

The experiments were conducted under simulated rainfall in a laboratory at the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau. Rainfall intensities were adjusted through nozzle sizes and water pressure. Calibrations of rainfall intensities were conducted prior to the experiments.

Experimental plots were constructed with metal sheets, with dimensions of 5 m (length) × 1 m (width) × 0·5 m (depth). The plots were placed on movable platforms for ease of moving around. A metal runoff collector was set at the bottom of the plot to direct runoff into a container. The plot was adjusted to a desired slope electrically between 0° and 30°. The soil used in the experiments was a loamy soil from Yangling of Shaanxi Province, China. The soil texture information is listed in Table I.

Methods

The soil was gently crushed though a 10 mm sieve. The experimental plots were planted with grasses and placed in the open for the plants to grow. A 20 cm layer of sands was put at the bottom of a plot for better drainage. The remaining 30 cm depth of the plot was packed with soil, in three 10 cm layers, to a bulk density of 1·20 g cm^{-3}. Each soil layer was raked lightly before the next soil layer was packed to diminish the discontinuity between each soil layer. A rye grass, a very commonly seen grazing grass of the locality, was used for the vegetative cover. The grass was seeded with a row spacing of 25 cm parallel to the end of the soil box so as to form a horizontal line across the slope when the box is set up to any given slope, with about 400 stands per square metre. The plots were moved into an indoor facility where simulated rainfall experiments were conducted about 3 months after the grass was seeded, when the grass was about 25 cm high and the coverage was about 35%. The plot soil surface was almost completely covered with naturally grown moss of less than 1 mm in height.

In the rain simulation experiments, the plots were adjusted to a desired slope of 30°, 25°, 20°, 15°, 10° or 5° before exposure to a given rain intensity. After the experiments with the above biomass and moss were completed, the grass was cut to ground level by sickle. The moss with the topsoil 1 mm soil layer was carefully and completely removed with a hatchet to simulate grazing or forage harvesting. The disturbed surfaces were exposed to consecutive rainfalls and allowed to recover for about 2 weeks before the experiments. The no GAM (NGAM) experiments were conducted under the same slope gradients. Antecedent precipitation with 85 mm h^{-1} for 20 min was carried out 24 h before each rainfall experiment, so as to keep soil conditions nearly same.

Simulated rainfall of 85 mm h^{-1} was applied to the plots for 16 min to test the effects of different treatments. An intensity of 85 mm h^{-1} was chosen in order to simulate the frequently occurring local storms, and a duration of 16 min was determined after an initial trial (at 30° slope) showed a steady decrease in sediment delivery during the first 14 min, after which the sediment rate remained relatively constant. Following initiation of runoff, all runoff was taken at 2 min intervals. Collected runoff samples were used to determine both runoff rate and sediment delivery in time, and runoff coefficient and sediment concentration were further calculated.

Table I. Particle size distribution of the experimental loam soil

Particle size (mm)	Distribution (%)
1–0·25	0·01
0·25–0·05	0·48
0·05–0·01	44·67
0·01–0·005	10·89
0·005–0·001	20·60
<0·001	23·35

Paired *t*-tests were conducted to analyse the differences in runoff rate and sediment delivery sampled every 2 min during the 16 min rainfall duration between GAM and NGAM plots for different slopes at $\alpha = 0{\cdot}05$ ($n = 8$). Regression analysis was undertaken to determine the relationship between sediment yield, runoff and gradient.

RESULTS AND DISCUSSION

Runoff

Under the simulated rainfall, average runoff rate for different slopes generally ranged from 1·10 to 1·26 mm min^{-1} on both GAM and NGAM slopes, and the runoff rates from NGAM plots were a little less than from GAM plots except for at 5° slope (Table II). However, under similar experimental conditions, Pan and Shangguan (2005) showed that grass coverage can decrease slope flow velocity and increase water infiltration on the 15° slope. The greater runoff of the GAM plots may be due to the moss, which reduces water infiltration and produces higher runoff. Therefore, the discrepancy in runoff between GAM and NGAM may be mainly determined by the comparison of the grass coverage and moss effects on runoff under specified experimental conditions. The difference in runoff between the GAM and NGAM slopes varied from 1·4% for a gradient of 20° to 8% for a gradient of 30°. Comparing GAM and NGAM slopes, there were significant differences ($\alpha = 0{\cdot}05$) in runoff rate except for at 5° and 20° by paired *t*-tests (Table II). The small difference between the GAM and NGAM plots at 20° indicates that the grass above portion has almost the same effect on water infiltration as the moss under the experimental conditions.

Slope gradient had a small influence on average runoff rate from each treatment (GAM and NGAM plots; Table I). The runoff rate from both the GAM and the NGAM plots increased up to a slope gradient of 10° and decreased thereafter (Table II), which might suggest that a critical gradient of about 10° exists for runoff. The reason for the decrease in runoff between the 10° and 30° plots could be due to the decrease in projected area of the plot to intercept rainfall. Nevertheless, runoff coefficients from both the GAM and the NGAM plots increased with gradient. This is due to higher gradients causing higher runoff velocity and lowered infiltration rate, and hence inducing increased runoff percentage. Figure 1 shows that the increasing slope of runoff coefficients at 5° to 30° from GAM plots is higher than that from the NGAM plots. The coefficient of variation of the runoff coefficients for different slopes is 0·052 for the GAM plots and 0·019 for the NGAM plots. These results indicate that gradient may have a more significant impact on runoff from GAM plots than from NGAM plots. One possible reason for the behaviour is that the grass rows slow down the water flow, which could cause backwater on the slope of the grass rows, and the increased ponding would increase surface retention and enhance water infiltration at a gentle slope, but such an effect would diminish as the

Table II. Average runoff rates and sediment deliveries from GAM and NGAM plots for different slopes[a]

Slope gradient (°)	Average runoff rate (mm min^{-1})			Average sediment yield (g m^{-2} min^{-1})		
	GAM	NGAM	GAM reduction cf. NGAM (%)	GAM	NGAM	GAM reduction cf. NGAM (%)
5	1·176 a	1·211 a	2·9	0·119 a	0·765 b	84·5
10	1·260 a	1·218 b	−3·5	1·040 a	1·896 b	45·2
15	1·245 a	1·197 b	−4·0	1·374 a	2·577 b	46·7
20	1·156 a	1·212 a	−1·4	1·087 a	3·279 b	66·8
25	1·210 a	1·144 b	−5·8	1·753 a	4·758 b	63·2
30	1·195 a	1·106 b	−8·0	3·794 a	16·128 b	76·5

[a] The same letter at the same slope indicates no significant difference at the $\alpha = 0{\cdot}05$ level (for runoff and for sediment) between GAM and NGAM plots by paired *t*-test ($n = 8$).

slope increases. The runoff coefficients of all treatments were higher than 0·82 due to the preliminary rainfall applied prior to the experimental rainfall. Figure 1 indicates that there were only small differences in runoff coefficient from the GAM plots at gradients of 10° to 20°, whereas notable impacts on runoff coefficients were seen at other gradients. Runoff coefficients from the NGAM plots increased evenly with the gradient and ranged from 0·85 to 0·90 under the experimental conditions. The differences in runoff coefficient between the GAM and NGAM plots at gradients of 25° and 30° were greater than those at the other gentle gradients (Figure 1).

The runoff processes of the GAM and NGAM plots at several typical gradients are presented in Figure 2. The runoff rate over time on the GAM and NGAM plots behaved similarly at the experimental gradients with the exception of the 5° plots. Compared with NGAM, the GAM plots increased runoff by less than 10% at each gradient (Figure 3).

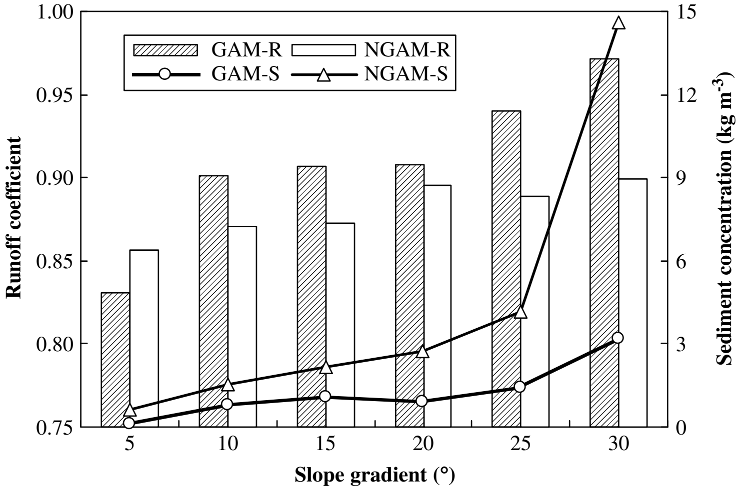

Figure 1. Runoff coefficients and average sediment concentrations from GAM and NGAM plots for different slopes (*R*: runoff coefficient; *S*: sediment concentration)

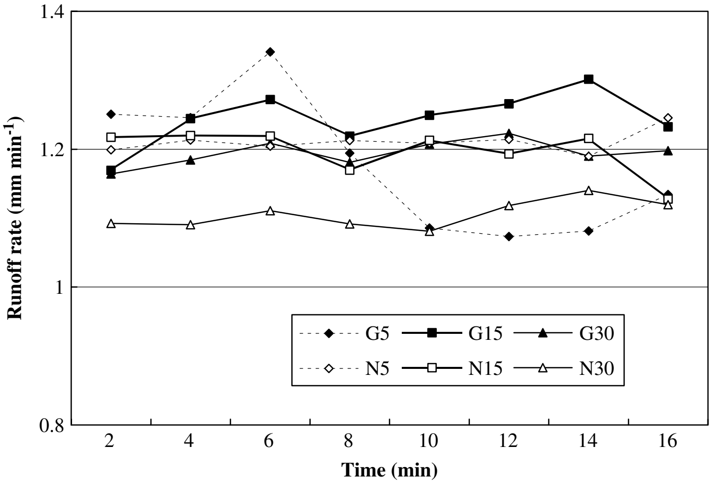

Figure 2. Runoff rates versus rainfall time on GAM and NGAM plots for different slopes (G and N refer to GAM and NGAM plot respectively, and 5, 15 and 30 are the plot gradients, e.g. G5 refers to sediment delivery at 5° on the GAM plot)

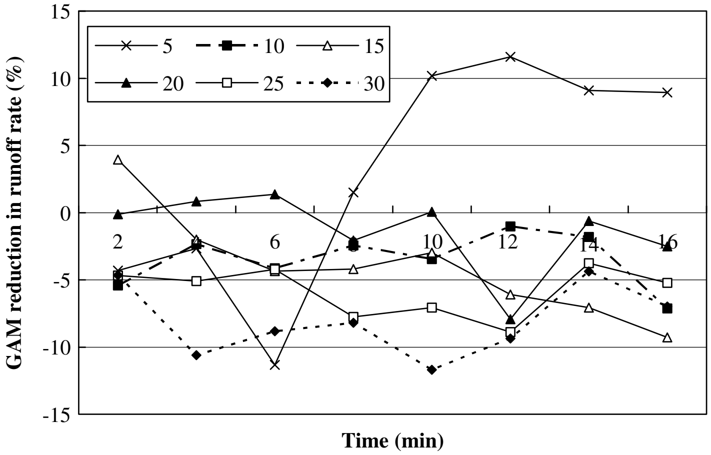

Figure 3. GAM percentage reductions in runoff rates compared with NGAM plots versus rainfall time for different slopes

The runoff rates from most treatments basically kept steady, except for those from the GAM plots at 5° (Figure 2). The runoff rates from the GAM 5° plots increased to the maximum values, 1·34 mm min^{-1}, 6 min after rainfall started and then gradually decreased to the steady rate of about 1·1 mm min^{-1}. This increase–decrease pattern might be associated with runoff depth. On the GAM 5° plots, the roughness from the grasses and the gentle gradient caused a decrease in velocity and an increase in interception area of precipitation, which increased runoff depth and accelerated the soil infiltration.

Sediment

The differences in sediment yield from the GAG and NGAM plots were much more significant than those in runoff. Under the experimental conditions, the average sediment deliveries for different slopes varied from 0·119 to 3·794 g m^{-2} min^{-1} from the GAM plots and from 0·765 to 16·128 g m^{-2} min^{-1} from the NGAM plots (Table II). The percentage reduction of sediments from the GAM plots, compared with the NGAM plots, ranged from 45·2% to 84·5% (Table II). Though the sediment deliveries from both the GAM and the NGAM plots at 5° were much less than those under the other gradients, the relative difference in sediment between the GAM and the NGAM plots at 5° was the greatest (Figures 4 and 5). The average sediment delivery from the NGAM plots was 5·4 times higher than that from the GAM plots at 5°. The percentage reduction in sediment from the GAM plots, compared with that from the NGAM plots, was the lowest at 10° and increased at higher slopes (Table II). This result may suggest that the influences of the aboveground grass portion and moss on sediment delivery at 10° were not as significant as those at other gradients. Paired t-tests indicated that there were statistically significant differences ($\alpha = 0{\cdot}05$) in sediment delivery between the GAM and NGAM plots at all slopes (Table II).

For both the GAM and NGAM plots, the total sediment yields S were significantly and positively correlated to gradient G. The sediment yield increased linearly with gradient, given by $S = 9{\cdot}25G - 39{\cdot}6$ ($R^2 = 0{\cdot}77^*$), for the GAM plots and exponentially with gradient, given by $S = 40{\cdot}4\ \exp(0{\cdot}1042G)$ ($R^2 = 0{\cdot}93^{**}$), for the NGAM plots.

Average sediment concentrations from both GAM and NGAM plots also increased with gradient (Figure 1), and the sediment concentrations had similar relationships as the total sediment yield with slope gradient. For different slopes, the sediment concentrations varied from 0·1 to 3·2 kg m^{-3} for the GAM plot and from 0·6 to 14·6 kg m^{-3} for the NGAM plot, and those from the NGAM plot were significantly greater than those from the GAM plot at a given slope by the paired t-test. Figure 1 shows that the difference in the sediment concentration between the GAM and NGAM plots increased with increscent gradient, ranging from 0·5 to

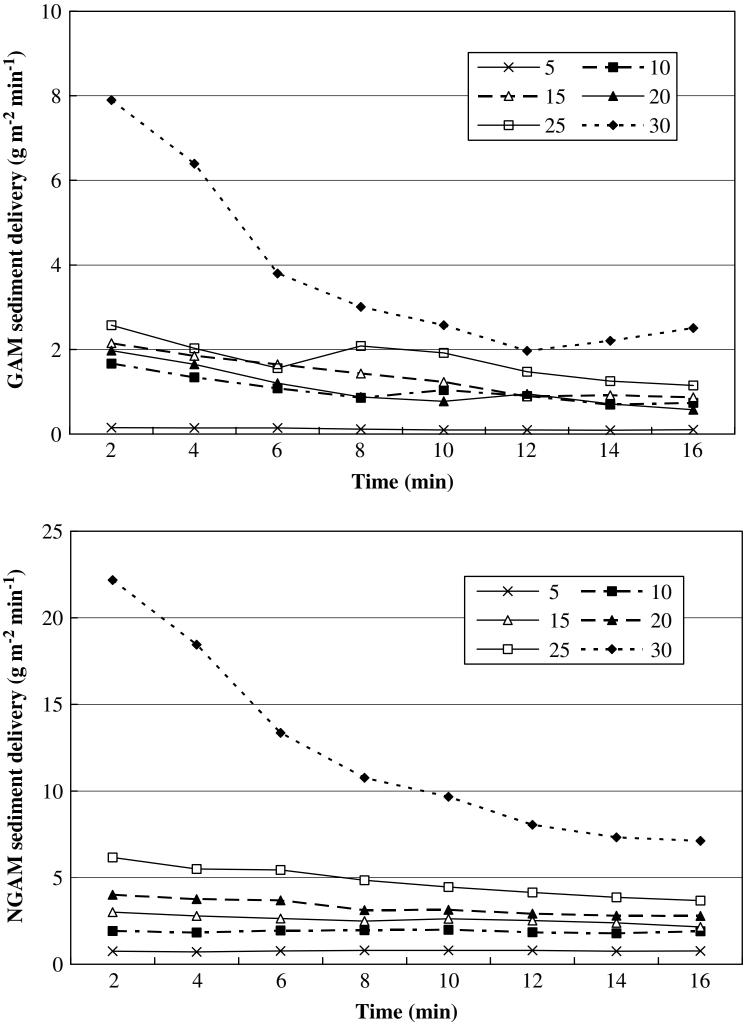

Figure 4. Sediment delivery versus rainfall time from GAM and NGAM plots for different slopes

11·4 kg m^{-3}. The coefficients of variation of sediment concentration for different slopes are 1·20 for the NGAM plots and 0·83 for the GAM plots, which may further testify that slope gradient has a more notable effect on sediment from the NGAM plot than from the GAM plot.

The GAM and NGAM treatments behaved similarly in terms of sediment delivery over time at the experimental gradients. On average, sediment delivery at a given gradient decreased with rainfall time (Figure 4). Sediment delivery at 30° varied from 2·0 to 7·9 g m^{-2} min^{-1} for the GAM plots and from 7·1 to 22·2 g m^{-2} min^{-1} for the NGAM plots, and both were significantly higher than those from plots at the other gradients. However, at 5°, sediment delivery ranged from 0·1 to 0·15 g m^{-2} min^{-1} for the GAM plots and was nearly constant at 0·77 g m^{-2} min^{-1} for the NGAM plots throughout rainfall duration. For each treatment, sediment delivery reached steady state at a rainfall duration of 14 min, which was why rainfall duration of 16 min was used. This behaviour was clearly different from that of the sediment delivery increase with rainfall time on bare sloped land under similar experimental conditions (Song *et al.*, 2003). The difference in the sediment-producing process mainly results from rill development on bare sloped land, but no

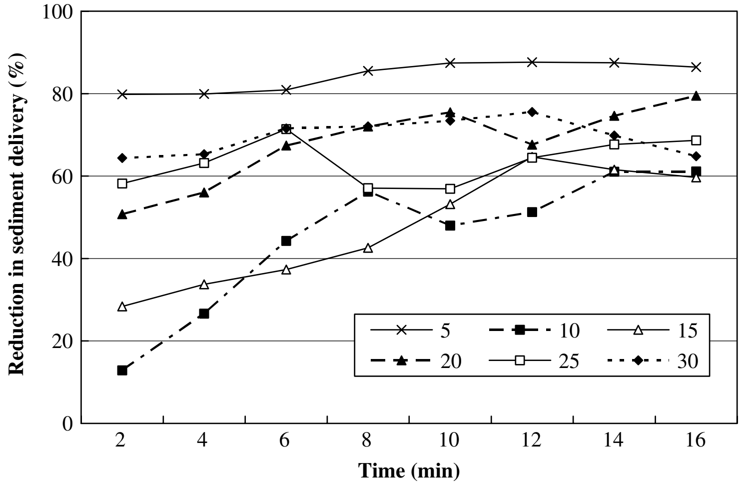

Figure 5. GAM percentage reduction in sediment deliveries compared with NGAM plots versus rainfall time for different slopes

rills occurred at any slope on either the GAM or NGAM plots in our study. The sediment deliveries decrease and then remain constant over time. This may be due to the relatively greater availability of soil materials and the stronger detachment from raindrop splash due to lower flow depth at the beginning of rainfall (Ferreira and Singer, 1985; Wainwright *et al.*, 2000). At the same time, the runoff scouring abilities were lower than the critical shear stress of the soil with grass roots reinforcement. As rainfall went on, the soil materials available for raindrop detachment and runoff scouring impacts became exhausted, so less sediment was produced and this remained steady in the final stage of rainfall.

In all cases, the percentage reduction in sediment delivery from the GAM plots, compared with those from the NGAM plots, generally increased over rainfall time (Figure 5), and the increase for the 10° slope was greater than at the other slopes. The percentage reduction at 5° was higher than at the other gradients, and varied from 80 to 88%. For plots at 20°, 25° and 30°, the percentage reduction varied from 50 to 75%. Sediment reduction at all gradients ranged from 13 to 80% at the initial time and from 60 to 85% at the final stage of rainfall. These results suggest that the aboveground grass portion and moss are relatively more effective in sediment delivery reduction at the final time than at the initial time of rainfall. The relatively greater reduction in sediment from the GAM plots at the later time may be due to less availability of soil materials to raindrop impacts.

CONCLUSIONS

Laboratory experiments were conducted to compare runoff and sediment yield from GAM and NGAM plots under simulated rainfall of 85 mm h^{-1} to quantify the effects of aboveground grass portion and moss on runoff and erosion for different slopes.

Under the simulated rainfall, average runoff rate under different slope gradients generally ranged from 1·10 to 1·26 mm min^{-1} on both the GAM and the NGAM slopes. The runoff rates from the NGAM plots were a little less than those from the GAM plots, except for the 5° slope. The differences in runoff between the GAM and NGAM plots varied between 1·4 and 8%. There were significant differences in runoff rate between the GAM and NGAM plots under experimental slopes, except for 5° and 20°. Average runoff rates from both the GAM and the NGAM plots increased up to a slope gradient of 10° and decreased at higher slopes. However, the runoff coefficients of the two treatments increased with gradient. The runoff processes of most treatments basically remained steady, except for the 5° slope on the GAM plots.

The aboveground grass portion and moss had a more significant impact on sediment yield than on runoff. Average sediment deliveries for different gradients varied from 0·119 to 3·794 g m^{-2} min^{-1} from the GAM plots and 0·765 to 16·128 g m^{-2} min^{-1} from the NGAM plots. The percentage reduction of sediments from the GAM plots, compared with the NGAM plots, ranged from 45·2 to 84·5%, and the percentage reduction was lowest at 10° and increased at higher slopes. There were statistically significant differences ($\alpha = 0{\cdot}05$) in average sediment delivery and sediment concentration between the GAM and NGAM plots. For both the GAM and the NGAM plots, the total sediment yields S had a significantly positive relationship with gradient G. The total sediment yield increased linearly with gradient ($S = 9{\cdot}25G - 39{\cdot}6$, $R^2 = 0{\cdot}77^*$) for the GAM plots, and exponentially with gradient ($S = 40{\cdot}4\ \exp(0{\cdot}1042G)$, $R^2 = 0{\cdot}93^{**}$) for the NGAM plots. Sediment delivery from the GAM and NGAM plots decreased with rainfall time, and reached a steady state at 14 min. At all slopes, the percentage reduction in sediment delivery from the GAM plots, compared with those from NGAM plots, generally increased with rainfall time, and the final percentage reductions ranged from 60 to 85%.

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