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Effect of shrub-grass vegetation coverage and slope gradient on runoff and sediment yield under simulated rainfall

Abstract

Evaluating the benefits of sediment and runoff reduction in different vegetation types is essential for studying the mechanisms of soil and water conservation on the Loess Plateau. The experiment was conducted in shrub-grass plots with nine levels of mixed vegetation coverage from 0% to 70%, three slopes (10°,15°, and 20°) and two rainfall intensities (1.0 and 2.5 mm/min). The results showed that the vegetation coverage and slope gradient significantly affect runoff and sediment yield. Shrub-grass vegetation coverage had a significant effect on the runoff start-time, runoff flow velocity, runoff rate, and soil erosion rate on hillslopes. Mixed vegetation coverage could effectively delay the runoff start- time and decrease the runoff flow velocity. However, the effects of the slope gradient on runoff and sediment yield are opposite to those of vegetation coverage. Shrub-grass vegetation coverage could effectively increase runoff and sediment yield reduction benefits, while their benefits were affected by the rainfall intensity. At the 1.0 mm/min rainfall intensity, the reduction in the sediment production rate was greater than that under the 2.5 mm/min intensity. However, when the shrub-grass vegetation coverage exceeded 42%, the runoff reduction benefit was more obvious at higher rainfall intensities. The cumulative sediment yield increased with increasing cumulative runoff, and the rate of increase in the cumulative runoff

was greater than that of the cumulative sediment yield with increasing of shrub-grass vegetation coverage. Moreover, there was a power function relationship between cumulative sediment yield and cumulative runoff yield (P<0.05). Our paper is expected to provide a good reference on the ecological environment and vegetation construction on the Loess Plateau.

Keywords: Simulated rainfall; Shrub-grass coverage; Slope; Runoff and sediment yield

1. Introduction

Soil erosion is the most serious problem on the Loess Plateau in China. The sediment discharge of the middle reach of the Yellow River (flow through the Loess Plateau) was 16×10^8 t (Li, 1983) between 1960 and 1980, reflecting the severity of the soil erosion in the region. To protect the ecological environment, the Chinese government implemented a series of ecological projects. The most representative example is the Grain for Green Project. The "Grain for Green Project" aims to promote the transformation of barren cropland on the Loess Plateau into forestland or grassland and was launched in 1999 (Zhang et al., 2017). With the help of vegetation construction and the implementation of soil and water conservation, the annual sediment discharge of the middle reach of the Yellow River was reduced to 3×10^8 t after 2000 (Zhang, 2011). However, there are still some problems in the region. For example, water shortage is severe on the Loess Plateau, and trees are difficult to grow. "Old and dwarf trees" occur among mature trees rather than young trees. Therefore, the planting of grasses and shrubs was chosen as the main strategy to control soil erosion on the hillslopes of the Loess Plateau.

The vegetation coverage is a major factor in controlling soil and water loss (Wei et al., 2003; Yan et al. 2018). Many studies have investigated the benefits of vegetation construction on the Loess Plateau in reducing runoff generation and soil erosion (Li et al., 2009; Qian et al., 2014; Rustomji et al., 2008; Wainwright et al., 2000). The vegetation can increase soil organic matter and ameliorate soil physical properties, thereby reducing surface runoff and soil erosion and decreasing nutrient loss (An et al., 2013; Qian et al., 2014). Zhao et al. (2013b) showed that the effects of increasing vegetation cover on runoff and sediment reduction were most evident when vegetation cover was between 30% and 40%. Xiao et al. (2017) studied the relationship between the rate of soil erosion and runoff hydrodynamic characteristics during simulated rainfall, and concluded that the runoff and soil erosion rates in shrub plots were lower than those in plots with bare. Soil erosion could be controlled by enhancing soil land use, increasing ground cover and varying the soil type (Ding & Li, 2016; Nunes et al., 2011; Zheng et al., 2008). Li and Pan (2018) found that different vegetation components also influence overland flow and sediment, and that roots played a dominant role in reducing runoff and soil erosion, with a mean contribution of 84%. The runoff and sediment yield reduction benefits of vegetation coverage have been demonstrated on hillslopes (Casermeiro et al., 2004; Zhao et al., 2013a), while there were many deficiencies in the recent studies. As mentioned above, previous studies have focused only on the coverage of a single vegetation type or a single impact factor, which differ from what occurs under natural conditions. Moreover, there has been no conclusion on critical vegetation coverage (Cao et al., 2017; Xiao et al., 2011a). Meng et al. (2018) showed that critical vegetation coverage was higher than 60% could effectively controlling erosion. Therefore, it is necessary to study the effects of vegetation coverage on runoff and sediment yield more deeply.

Runoff generation and erosion processes on hillslopes are closely related to the precipitation, vegetation cover and slope gradient, which could affect the accumulation of surface flow and sediment yield (CerdaÁ, 1998). Li et al. (2009) studied soil erosion from grass plots with scouring experiments, and concluded that sediment yield from grass plots decreased rapidly as the vegetation coverage increased from 0% to 90%. The components of the grass were different from those of the shrubs, so the grass and shrubs had their own mechanisms for reducing runoff and sediment generation. Xiao et al. (2011a) showed that the soil loss rates of grass plots were greater than those of shrub plots in laboratory experiments. Compared with those in other plain areas, the slopes are steeper on the Loess Plateau. Therefore, it is necessary to understand the effects of slope gradients on erosion control in this region. Numerous studies have revealed that the slope gradient has an impact on runoff and sediment production in rainfall simulation experiments (Calvo-Cases et al., 2003;

Daniels & Gilliam, 1996; Wei et al., 2014). El Kateb et al. (2013) found that runoff and soil loss was significantly affected by the slope gradient: the potential runoff and sediment yield increased with an increase in the slope gradient. Most of these studies involved a single vegetation type, e.g., shrub- coverage or grass- coverage, and mostly showed that runoff and soil erosion increased with shrub-coverage or grass- coverage. However, there is little information on the relationship between combined shrub and grass coverage and soil erosion.

Our study focused on the responses of runoff and sediment yield to differences in shrub- grass vegetation coverage (i.e., mixed vegetation coverage) and slope gradient under simulated rainfall conditions. This study also addressed the relationship between runoff/sediment and vegetation coverage, which will help us to evaluate soil and water conservation benefits and provide good reference for the ecological environment and vegetation construction in the Loess Plateau.

2. Materials and methods

2.1 Experimental setup

The experiments were conducted in the artificial rainfall hall of the Institute of Soil and Water Conservation (ISWC), Chinese Academy of Sciences and Ministry of Water Resources, Yangling, China. A side-spraying simulated rainfall system with a rainfall height of 16 m above the soil surface was used in this study. The system can produce desired rainfall intensities ranging from 30 to 200 mm h^{-1} with a uniformity of more than 85% (Chen & Wang, 1991). In addition, the maximum continuous rainfall time was 12 hours, and the effective rainfall area was 9 by 4 m.

The runoff plots constructed in this study were 5 m (length) × 1.0 m (width) × 0.6 m (depth). Each plot was composed of a pair of soil plots containing boxes adopting, variable slopes in the range of 0-20º. At the bottom of each plot, a triangle-shaped drainage outlet was placed for collecting surface runoff and sediment (Fig. 1). To maintain the same rainfall under each condition, the rainfall times were 120 min and 30 min for rainfall intensities of 1.0 mm min^{-1} and 2.5 mm min^{-1}, respectively. In the semiarid region of the Loess Plateau, 60-80% of the annual precipitation falls from June to September, mostly in rainstorms of high intensity and short duration. The higher intensity of 2.5 mm min^{-1} was chosen to determine the effects of grass and shrub coverage on runoff and soil loss at high runoff and sediment yield, while the lower intensity was chosen to represent the effects of grass and shrub coverage on runoff and soil loss at a lower intensity of 1.0 mm min^{-1}. The gradient of the test slope was 10°, 15°, and 20° based on the main range of slopes of 10º to 20º on the Loess Plateau.

2.2 Experimental soil and vegetation

The tested soil was collected from the Zhifanggou watershed (36°42′-36°46′N and 109°13′-109°16′E), Ansai County, Shaanxi Province, China. The district has an average annual temperature of 8.8℃ and annual precipitation of 549 mm. The precipitation in the study area shows clear inter- and intra-annual changes, of with more than 70% of the rainfall falling from June to September. The predominant soil is loessial soil. The soil material used in this study was sandy loam, and the percentages of sand (>0.05 mm), silt (0.05-0.002 mm) and clay (<0.002 mm) were 12.17%, 62.85%, and 24.97%, respectively. The test shrub was *Pittosporum tobira* (Garcia-Garcia et al., 2016), which is a dominant tree species that grown well in the sun and half shade. It has strong adaptability and can grow well in drought and cold conditions. The shrub reached a height of approximately 100 cm after one year of growth and was planted every 30 cm. The grass species chosen was *Ophiopogon japonicus* (He et al., 2012), which is convenient for planting indoors and grows normally in climatic conditions with abundant rainfall at 5-30□. The grass reached a height of approximately 10 cm after one year of growth and was planted every 5 cm. The grass-shrub vegetation coverage ranged from 0 to 70%. A high-resolution digital camera was used to take photographs of the vegetation field, and then the shrub-grass coverage was calculated using ENVI software (Table 1). The percentage of grass-shrub coverage was calculated to represent the proportion of the soil surface in each plot covered by the vegetation canopy.

2.3 Experimental procedures

Before the soil plots were filled, the dry soil was filtered with a 10-mm sieve to remove vegetation roots and stones. The method of stratified- filling in the tank was adopted. First, a 5-cm thick layer of sand was placed at the bottom of each box to facilitate free drainage. Then, a layer of gauze was laid on the sand layer to allow the uniform infiltration of water. The remaining sand was packed and compacted at 5-cm increments in the sieved soil, whose soil bulk density was required to be 1.35 g/cm^3, and the surface was supposed to be flat and parallel to the bottom of the groove.

The initial soil moisture content at the depths of 10, 20, 30, and 40 cm in the soil trough was measured with a soil moisture sensor S-SMC-M005. To maintain the initial soil moisture content at a similar level, a pilot rainfall treatment was conducted to ensure that the soil moisture content fluctuated between 10 and 15%. The surface runoff and sediment produced were collected using plastic buckets every 1- min. The sediment was deposited, separated from the water, dried in a drying oven to a constant weight at 105°C, and then weighed. Surface flow velocities on the upper and lower slopes of the plots were measured every 5- min based on a dye tracer with a gap of 70 cm (Li & Pan, 2018). The earth trough was raised to the highest level after each rainfall event; therefore, the water in the soil can infiltrate into the bottom freely and can be immediately removed.

2.4 Data analysis

The surface runoff depth was calculated based on the volume of the contents in the buckets at 5-min collection-time intervals as follows:

$$RD_i = \frac{RM_i}{A} \quad (1)$$

where RD_i is the runoff depth in sample i in each time interval (mm); RM_i is the runoff amount in sample i in each time interval (mm^3); and A is the area of the soil trough in sample i in each time interval (mm^2). The runoff and sediment production rates were obtained according to the following two formulas:

$$RR_i = \frac{RD_i}{T} \quad (2)$$

$$SR_i = \frac{RY_i}{T} \quad (3)$$

where RR_i is the runoff rate in sample i in each time interval (mm min^{-1}); SR_i is the sediment yield in sample i in each time interval (g/min); RY_i is the sediment production rate in sample i in each time interval (g); and T is the time at 1- min (min). The runoff velocity flow was calculated according to the following formula:

$$RVF_i = \frac{0.7}{T_i} \quad (4)$$

where RVF_i is the runoff velocity flow in sample i in each time interval (m/s); and T_i is the runoff time from 0.7 m to the bottom of the trough (s). Statistical analysis was conducted using SPSS 13.0.

3 Results

3.1 Runoff start- time and runoff flow velocity

The runoff start-time and runoff flow velocity are two major parameters of slope runoff. For the same slope gradient, the runoff start- time was delayed and the runoff flow velocity decreased with an increase in shrub-grass vegetation coverage. Taking a rainfall intensity of 1.0 mm/min and slope gradient of 15° as an example, the runoff start- time for grass coverage of 0, 18, 26, 35, 42, 43, 60, 66, and 70% was 82, 91, 93, 115, 121, 135, 181, and 205, respectively. At the 1.0 mm/min rainfall intensity, as the vegetation coverage exceeded 42%, the runoff flow velocity showed a significant decreasing trend. However, the runoff flow velocity decreased rapidly at the beginning and then tended to stabilize when it reached a peak at a vegetation coverage of 43%. The runoff flow velocity ranged from 0.15 to 0.3 m/s, with an average of 0.25 m/s at the 1.0 mm/min rainfall intensity, and the runoff flow velocity ranged from 0.1 to 0.3 m/s at the 2.5 mm/min rainfall intensity with a mean of 0.24 m/s.

The runoff start- time and the runoff flow velocity were both influenced by the rainfall intensity. The runoff start- time showed a strong increasing trend, with a growth rate of 1.68 s at 1.0 mm/min rainfall intensity and 0.77 s at 2.5 mm/min rainfall intensity (Fig. 2a). Moreover, the increase in the runoff start- time with coverage change at the rainfall intensity of 1.0 mm/min was 2.18 times that of the 2.5 mm/min rainfall intensity. The variation in runoff flow velocity showed strong decreasing trends, with a rate of decline of 0.00182 m/s at 1.0 mm/min rainfall intensity and 0.00154 m/s at 2.5 mm/min rainfall intensity (Fig. 2b). The findings indicate that the effects of vegetation coverage on the runoff start-time and runoff flow velocity affected by rainfall intensity. In addition, the slope gradient was also an important factor affecting the runoff start-time and the runoff flow velocity. With an increase in slope, the runoff start- time was significantly shorten. When the slope gradient was 10º, the average runoff start-time was 132 s at 1.0 mm/min rainfall intensity and 61 s at 2.5 mm/min rainfall intensity. When the slope increased to 15º, the runoff start-time was shortened by 17 s and 38 s, respectively. Moreover, the runoff start-time at 20º was shortened by 4 s and 12 s, respectively. Furthermore, the flow velocity increased with an increase in slope gradient, and the mean runoff flow velocity was 0.149-0.213, 0.157-0.217, and 0.167-0.236 m/s, respectively, corresponding to the slopes of 10, 15, and 20.

The runoff start-time showed a significantly positive correlation with grass vegetation coverage and a negative correlation with the slope according to the regression relation (Table 2). This means that the start time of runoff decreased as the slope increased and increased with increasing vegetation coverage. Moreover, the standard coefficients of vegetation coverage and slope at 1.0 mm/min rainfall intensity were -0.382 and 0.828, respectively; under the 2.5 mm/min rainfall intensity, the standard coefficients of vegetation coverage and slope were -0.342 and 0.876, respectively. Therefore, the slope gradient had a greater effect on the runoff start-time than vegetation coverage. However, the vegetation coverage had a negative correlation with the influence of flow velocity, namely, as the vegetation coverage increased, the velocity of the slope surface decreased. In addition, the runoff flow velocity showed a linear positive correlation with slope. The standard coefficients of vegetation coverage and slope at 1.0 mm/min rainfall intensity were -0.897 and 0.334, respectively; at the 2.5 mm/min rainfall intensity, the standard coefficients of vegetation coverage and slope were -0.841 and 0.324, respectively. Therefore, the effects of vegetation coverage on flow velocity were greater than those of the slope gradient.

3.2Runoff rate

The dynamic changes in the runoff rate calculated after each simulated rainfall experiment were in Fig. 3. The runoff rate increased with an increase slope, and the time to a stable runoff rate on the high slope was lower than that on the low slope. In addition, with increasing vegetation coverage, the runoff rate decreased, and the 70% vegetation coverage presented more obvious effects than other coverages on runoff reduction under two rainfall intensities. The runoff rate associated with each simulated rainfall event began to increase sharply at the initial stage of runoff generation and then tended to stabilize. Under the two rainfall intensities, the runoff rate was reduced and the delay of the started runoff response increased at lower rainfall intensities. At the 1.0 mm/min rainfall intensity, the runoff rate experienced a rapid increase before 20 min and reached a peak value at approximately 10 min (Fig. 3a). For the 2.5 mm/min rainfall intensity, the runoff rate exhibited a rapid increase before 5 min and reached a peak value at approximately 3 min (Fig. 3b).

Under the same rainfall intensity, the reduction in runoff yield decreased with increasing slope (Fig. 4). Under the 1.0 mm/min rainfall intensity, average runoff yield reduction of different slopes of 10, 15 and 20° was 28, 24, and 24%, respectively; at 2.5 mm/min rainfall intensity, the average runoff yield of the slopes of 10, 15, and 20° was 26%, 25%, and 23%, respectively. The reduction in runoff yield at a slope of 10° was greater than that found for the slopes of 15° and 20° at two rainfall intensities, indicating that high runoff was produced by steep hills and that runoff exceeded infiltration so that runoff was produced on the hillslope.

The reduction in runoff yield increased with increasing shrub-grass coverage under the same rainfall intensity (Fig. 4). As the vegetation coverage increased from 0 to 70%, the average runoff yield at 1.0 mm/min rainfall intensity decreased by 12, 18, 19, 23, 26, 33, 34, and 37%, respectively; runoff yield at 2.5 mm/min rainfall intensity decreased by 6, 9, 10, 27, 31, 35, 37, and 38%, respectively. The amplitudes of runoff reduction benefits by increasing vegetation coverage at 2.5 mm/min rainfall intensity showed greater changes than those under 1.0 mm/min, indicating that vegetation coverage could effectively improve runoff yield reduction benefits at two rainfall intensities. Furthermore, as the shrub-grass vegetation exceeded 42%, the runoff yield reduction at the 1.0 mm/min rainfall intensity was obviously greater than that under the 2.5 mm/min rainfall intensity. Under the conditions of a certain rainfall intensity, runoff yield decreased with increasing shrub-grass coverage and increased with increasing slope. High runoff was produced from plots at 2.5 mm/min rainfall intensity regardless of the vegetation coverage compared with those at 1.0 mm/min rainfall intensity. The results show that there was a quadratic function relationship between runoff yield and vegetation coverage with all fitting equations being significant ($P<0.05$) (Table 3).

3.3 Soil erosion rate

The soil erosion rate was strongly correlated with the vegetation coverage and slope gradient in both plots (Fig. 5). Regardless of the level of rainfall intensity, the rate of soil erosion decreased with the increase in shrub-grass vegetation coverage, and exhibited an increasing trend with increasing slope. During the rainfall process, the soil erosion rate experienced a rapid increase at the beginning and then decreased with the change in rainfall duration, and finally tended to become stable. Compared with the 1.0 mm/min rainfall intensity, the soil erosion rate curve changed dramatically at 2.5 mm/min rainfall intensity.

Sediment yield increased with an increase in slope at different levels of shrub-grass vegetation coverage. At the 1.0 mm/min rainfall intensity, the average sediment yield reduction associated with the slopes of 10, 15, and 20° was 44, 38, and 36%, respectively; under the 2.5 mm/min rainfall intensity, the average sediment yield reduction was 32, 30, and 27%, respectively. The reduction in sediment yield associated with an increase in slope at 2.5 mm/min rainfall intensity was less evident than that under the 1.0 mm/min rainfall intensity.

Similar to runoff, sediment yield was significantly correlated with shrub-grass vegetation coverage, and the sediment yield observably decreased with the increase in vegetation coverage (Fig. 6). As the grass coverage increased from 0 to 70%, the average sediment yield at 1.0 mm/min rainfall intensity decreased by 20, 30, 31, 38%, 42, 48, 52, and 53%, respectively; at 2.5 mm/min rainfall intensity it decreased by 15, 17, 18, 29, 33, 38, 41 and 46%, respectively. The reduction in sediment yield as a result of increasing vegetation coverage at the 1.0 mm/min rainfall intensity was lower than that associated with the 2.5 mm/min rainfall intensity, which indicates showed high sediment production at a high rainfall intensity. At the 2.5 mm/min rainfall intensity, it a characteristic of high runoff and high sediment production in combination with different shrubs and grasses during high rainfall events was observed. The sediment yield presented a quadratic function relationship with shrub and grass vegetation coverage, and all fitting equations were significant ($P<0.05$) (Table 4).

3.4 Analysis of the relationship between runoff and sediment yield

The relationships between cumulative sediment yield and cumulative runoff at different vegetation coverage levels under two rainfall intensities are shown in Fig. 7. As cumulative runoff increased, the cumulative sediment yield increased gradually and then increased slowly when shrub and grass vegetation coverage was greater than 60%. Furthermore, with increasing of vegetation coverage, the rate of increase in the cumulative runoff was greater than that of the cumulative sediment yield (Fig. 7a). At 2.5 mm/min rainfall intensity, the amplitudes of cumulative sediment yield obviously decreased as the vegetation coverage was greater than 40% (Fig. 7b). These results indicate that as the rainfall intensity increased, more vegetation coverage was needed to prevent water loss and soil erosion.

The relationships between cumulative runoff and sediment yield at two rainfall intensities can be fitted with a power function $S=aV^b$, where S represents the cumulative sediment yield (g), V represents the cumulative runoff (L), and a and b are the equation coefficients. The coefficient of determination (R^2) of all fitting equations was greater than 90% and significant at $P<0.05$ (Table 5). At the same rainfall intensity, the coefficients (*a* and *b*) of the power function decreased significantly with increasing shrub-grass coverage, indicating that vegetation coverage played a dominant role in reducing sediment production and runoff. Otherwise, the coefficients (*a* and *b*) for the 1.0 mm/min rainfall intensity of the power function were smaller than those of the 2.5 mm/min rainfall intensity.

4 Discussion

In this study, grass-shrub vegetation coverage significantly influenced runoff and soil erosion. The study results show that the runoff rate and sediment production rate decreased with increasing vegetation coverage; in particular, the 70% vegetation coverage presented more obvious effects than the other coverage levels on runoff and soil loss under two rainfall intensities. The vegetation coverage could reduce the kinetic energy of the raindrops, and delay the runoff start- time. Vegetation covered plots and stems parts protect soil surface, and increase soil surface roughness. Moreover, vegetation roots can improve soil physical properties such as soil cohension, soil aggregate, soil orangic matter (Zhang et al., 2015). Rainfall intensity and slope are the major controlling factors that influence runoff and soil erosion. Under the same rainfall intensity, the reduction in runoff and sediment yield decreased with increasing slope. The speed of runoff flow and rate of infiltration were influenced by the slope gradient (Abrahams et al., 2003; Alaoui et al., 2011; Zhao et al., 2013b). The high runoff produced by steep hills and runoff exceeded infiltration, and the amount of erosion and sediment production increased (El Kateb et al., 2013;

Gilley et al., 1990; Xiao et al., 2011a; Zheng et al., 2008). At the different rainfall intensities, the reduction in runoff and sediment yield at higher rainfall intensities was greater than that at lower rainfall intensities. Characteristics of high runoff and high sediment production in combination with different shrubs and grasses during high rainfall events, which was observed consistent with previous findings (Wei et al., 2014; Xiao et al., 2011b). The lower rainfall intensity might allow more time to destroy the topsoil and increase the infiltration time and delay runoff generation. Runoff start- time and runoff flow velocity are two important parameters affecting runoff and soil erosion. The runoff start- time was delayed and the runoff flow velocity decreased with increasing of shrub-grass vegetation coverage. Moreover, the increase in runoff start- time with increasing coverage at the rainfall intensity of 1.0 mm/min was 2.18 times that of the 2.5 mm/min rainfall intensity. The shrub-grass vegetation coverage was improved on natural hillslopes, which was beneficial for surface runoff infiltration into the deep layers of soil and increased the resistance coefficient of slope flow, to prolong the start- time and reduce runoff flow velocity (Alaoui et al., 2011). In addition, a power function existed between the cumulative sediment yield and cumulative runoff yield at different shrub-grass coverage levels, which was similar to the results found by Zhao et al. (2013b). Furthermore, the result show that the coefficients (*a* and *b*) of the power function for the higher rainfall intensity were greater than those of the lower rainfall intensity. The energy of raindrops may be larger and the surface erosion was stronger at the high rainfall intensity.

The dynamic changes of in the sediment production rate are illustrated for the three slopes and two rainfall intensities at different shrub-grass coverage levels in Fig. 5. During the rainfall process, the soil erosion rate experienced a rapid increase and rapid decrease and finally tended to become stable. In the early stage of rainfall, soil particles were dispersed and had little cohesive force due to the low soil humidity sand were easily to be separated by raindrop splash erosion. With the rapid increase in soil moisture, the soil particles become more cohesive, and the soil erosion resistance increased. At the same time, because the erosion force of the rainfall increased slightly, it was not sufficient to damage the underlying soil and tended to be stable (Casermeiro et al., 2004). However, compared with the dynamic changes in the sediment production rate, the runoff rate associated with each simulated rainfall intensity started to increase sharply at the initial stage of runoff generation and then tended to stabilize. This was consistent with previous observations (Xiao et al., 2017； Zhao & Hou, 2018; Zhao et al., 2013a). This because the damage to the soil structure was not serious at the beginning of rainfall. Furthermore, the soil gradually became saturated and and the relatively small soil particles affected by splash erosion infiltrated into the lower soil. Thereafter, a soil crust was formed, and the runoff rate gradually became stable (Chen & Hao, 2017).

In the semiarid region of the Loess Plateau, 60~80% of the annual precipitation falls from June to September, mostly in rainstorms of high intensity and short duration.

Water loess and soil erosion on the slopes might be due to slope surface scouring during heavy rains (Pan et al., 2006). In this study, as the shrub and grass coverage increased, the reduction in runoff and sediment increased at the 1.0 mm/min rainfall intensity. In contrast, for a rainfall intensity of 2.5 mm/min, the runoff and sediment reduction varied greatly under different vegetation coverage levels, exhibiting the characteristics of high runoff and high sediment yield. In addition, the amplitudes of runoff reduction benefits by increasing vegetation coverage at 2.5 mm/min rainfall intensity showed greater changes than those under 1.0 mm/min, which was inconsistent with previous findings, such as those by Ding and Li. (2016) and Zhao et al. (2013b). This may be caused by difference in the soil environments and vegetation compositions. The runoff reduction benefit associated with different combinations of grass and shrub vegetation coverage was more obvious at the higher rainfall intensity. The reason for this was mainly as follows: the shrub plants are taller than 0.5 m, and their leaves can intercept rainfall, but they have little effect on the surface runoff, and only the roots and stems had a blocking effect on the runoff (Xiao et al., 2011b; Yu et al., 2014). Thus, as grass coverage increasing, the interception and blocking the effect of the grass on the raindrops increased, and the effect of splashing substantially decreased (Chen & Hao, 2017; Dai et al., 2016). Thereafter, more shrub and grass vegetation was planted for use in water and soil conservation.

4 Conclusions

Underlying surface conditions have significantly changed as a result of the implementation of large-scale vegetation recovery measures, which have inevitably affected the hydrologic process on the Loess Plateau, China. In this study, the processes of runoff and sediment yield in the shrub-grass plots with different shrub-grass coverage (0, 18, 26, 35, 42, 43, 60, 66, and 70%) and slopes (10°, 15°, and 20°) at two rainfall intensities (1.0 and 2.5 mm/min) were studied. The conclusions can provide a good reference for ecological environment management and vegetation construction on the Loess Plateau. The main findings are listed below.

Under the same rainfall intensity, vegetation coverage had a significant effect on runoff start- time, runoff flow velocity, runoff rate, and soil erosion rate on hillslopes. As vegetation coverage increased, the runoff start- time was delayed, and the runoff flow velocity decreased. Moreover, as the slope increased, the runoff start- time shortened, and the runoff flow velocity increased. The runoff start- time and runoff flow velocity both showed a significantly linear correlation with shrub-grass vegetation coverage. Moreover, the vegetation and slope gradient were important factors affecting the runoff start- time and slope flow velocity. In addition, the slope gradient played a dominant role in delaying the runoff start- time, while vegetation coverage was the main factor affecting flow velocity.

Runoff and sediment yield decreased with increasing of vegetation coverage, and increased as the slope increased. Vegetation coverage could effectively improve runoff yield reduction benefits at two rainfall intensities. At the 1.0 mm/min rainfall intensity, the reduction in the runoff rate and soil erosion rate was greater than that at 2.5 mm/min. Moreover, there was a quadratic function relationship between runoff (sediment) yield and vegetation coverage. In addition, there was a power function relationship between cumulative sediment yield and cumulative runoff yield ($P=0.05$). The cumulative sediment yield increased with increasing cumulative runoff, but there was a threshold value.

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References

Abrahams A.D., Parsons A.J., & Wainwright J. (2003). Disposition of rainwater under creosotebush. *Hydrological Processes*, *17*, 2555-2566. *doi*: 10.1002/hyp.1272

Alaoui A., Caduff U., Gerke H.H., & Weingartner R. (2011). A preferential flow effects on infiltration and runoff in grassland and forest soils. *Vadose Zone Journal, 10*, 367-377. *doi*: 10.2136/vzj2010.0076

An S.S., Darboux F., & Cheng M. (2013). Revegetation as an efficient means of increasing soil aggregate stability on the Loess Plateau (China). *Geoderma, 209-210*, 75-85. *doi*:org/10.1016/j.geoderma

Calvo-Cases A., Boix-Fayos C., & Imesonb A.C. (2003). Runoff generation, sediment movement and soil water behaviour on calcareous (limetone) slopes of some Mediterranean environments in southeast Spain. *Geomorphology*, *50*, 269-291.

Cao Z. H., Zhao Q.H., Deng S. Y., Zhang Y. F., & Liu P. (2017). Effect of grass coverage on sediment yield of rain on slope. *Acta Pedologica Sinica*, *32*, 1892-1904 *(In chinese)*.

Casermeiro M.A., Molina J.A., Cruz Caravaca M.T., Hernando Costa J., Hernando Massanet M.I., & Moreno P.S. (2004). Influence of scrubs on runoff and sediment loss in soils of Mediterranean climate. *Catena*, *57*, 91-107. *doi*:10.1016/S0341-8162(03)00160-7

CerdaÁ A (1998). The influence of geomorphological position and vegetation cover on the erosional and hydrological processes on a Mediterranean hillslope.

Hydrological Processes, 12, 661-671.

Chen C., & Hao Z. (2017). Research on Slope Runoff, Sediment and P and K Loss Characteristics on Slopes with Different Gradients Under Artificial Simulation of Rainfall. *Research of Soil and Water Conservation, 24*, 70-77 *(In chinese)*. *doi*:10.13869/j.cnki.rswc.2017.02.012

Chen W., & Wang Z. (1991). An experimental study of rainfall simulation characteristics. *Soil and Water Conservation bulletin, 11*, 55-62.

Dai J., Cheng J., & Zhang H. (2016). The changing law of overland flow resistance under vegetation covers. *Journal of Soil and Water Conservation, 30*, 44-49 *(In chinese)*. *doi*: 10.13870/j.cnki.stbcxb.2016.02.008

Daniels R.B., & Gilliam J.W. (1996): Sediment and chemical load reduction by grass and riparian filters. *Soil Science Society of America Journal*, *60*, 246-251.

Ding W., & Li M. (2016). Effects of grass coverage and distribution patterns on erosion and overland flow hydraulic characteristics. *Environmental Earth Sciences, 75*, 2-14. *doi*: 10.1007/s11442-009-0321-8

El Kateb H., Zhang H., Zhang P., & Mosandl R. (2013). Soil erosion and surface runoff on different vegetation covers and slope gradients: A field experiment in Southern Shaanxi Province, China. *Catena, 105*, 1-10. *doi*:org/10.1016/j.catena.2012.12.012

Garcia-Garcia M.J., Sánchez-Medina A., Alfonso-Corzo E., & Gonzalez Garcia C. (2016). An index to identify suitable species in urban green areas. *Urban*

Forestry & Urban Greening, 16, 43-49. *doi*:org/10.1016/j.ufug.2016.01.006

Gilley J.E., Kottwitz E.R., & Simanton J.R. (1990). Hydraulic characteristics of rills. *Transactions of the ASAE, 33*, 1900-1906.

He Y., Zhang X., & Cheng F. (2012). Correlative analysis on the biomass and effective components contents in root tuber of wild Sichuan ophiopogon japonicus from Santai County. *Medicinal Plant, 3,* 25-28.

Meng Z. G., Dang X.H., Gao Y., Ren X. M., Ding Y. L., & Wang M. (2018). Interactive effects of wind speed, vegetation coverage and soil moisture in controlling wind erosion in a temperate desert steppe, Inner Mongolia of China. *Journal of Arid Land, 10,* 534-547.

Li C., & Pan C. (2018). The relative importance of different grass components in controlling runoff and erosion on a hillslope under simulated rainfall. *Journal of Hyorology, 558,* 90-103. *doi*: 10.1016/j.jhydrol.2018.01.007

Li M., Yao W., & Ding W. (2009). Effect of grass coverage on sediment yield in the hillslope-gully side erosion system. *Journal of Geographical Sciences, 19,* 321-330. *doi*: 10.1007/s11442-009-0321-8

Li Q. (1983). On the agricultural policy of loess plateau in China. *The Journal of Humanities*.14-17 *(In chinese).*

Nunes A.N., Almeida A.C., & Coelho C.A. (2011). Impacts of land use and cover type on runoff and soil erosion in a marginal area of Portugal. *Appplied Geography, 31*, 687-699. *doi:* 10.1016/j.apgeog.2010.12.006

Pan C., & Shangguan Z. (2006). Runoff hydraulic characteristics and sediment generation in sloped grassplots under simulated rainfall conditions. *Journal of Hydrology, 331*, 178-185. *doi:* 10.1016/j.jhydrol.2006.05.011

Qian J., Zhang L., & Wang W. (2014). Effects of vegetation cover and slope length on nitrogen and phosphorus loss from a sloping land under simulated rainfall. *Environ. Stud, 23,* 835-843.

Rustomji P., Zhang X.P., Hairsine P.B., Zhang L., & Zhao J. (2008). River sediment load and concentration responses to changes in hydrology and catchment management in the Loess Plateau region of China. *Water Resources Research, 44,* 2-17. *doi:* 10.1029/2007wr006656

Wainwright J., Parsons A.J., & Abrahams A.D. (2000). Plot-scale studies of vegetation, overland flow and erosion interactions. *Hydrological Processes, 14,* 2921-2943.

Wei T. X., & Zhang X. M. (2003). Study on Function of Vegetation Controlling Soil Erosion in Small Watershed of the Loess Area. Proceedings of sino-us seminar on water&soil conservations.

Wei W., Jia F., Yang L., Chen L., Zhang H., & Yu Y. (2014). Effects of surficial condition and rainfall intensity on runoff in a loess hilly area, China. *Journal of Hydrology, 513*, 115-126. *doi:* 10.1016/j.jhydrol.2014.03.022

Xiao P., Yao W., & Römkens M.J. (2011a). Effects of grass and shrub cover on the critical unit stream power in overland flow. *International Journal of Sediment*

Research, 26, 387-394. *doi:* 10.1016/s1001-6279(11)60102-9

Xiao P., Yao W., & Shen Z. (2011b). Experimental study on erosion process and hydrodynamics mechanism of alfalfa grassland. *Journal of Hydraulic Engineering, 42*, 232-237. *doi:* 10.13243/j.cnki.slxb.2011.02.017

Xiao P., Yao W., & Shen Z. (2017). Effects of shrub on runoff and soil loss at Loess Slopes under simulated rainfall. *Chinese Geographical Science, 27,* 589-599. *doi:* 10.1007/s11769-017-0889-3

Yan R., Chen H., Zhangga X. P., Muratjan A., Lu D., Ren Q. F., …Lin P. F.. (2018). Effects of vegetation and rainfall types on surface runoff and soil erosion on steep slopes on the Loess Plateau, China. *Catena, 170,* 141-149. *doi: 10.1016/j.catena.2018.06.006*

Yu X., Zhang X., & Wu S. (2014). The effect of vegetation and precipitation upon runoff and sediment production in sloping lands of Loess Area. *Journal of Mountain Sciences, 24*, 19-26 *(In chinese)*.

Zhang J. (2011). Variation ofsediment load at the major tributaries in the middle reaches of Yellow River and its impact on the sediment flux to the sea. Ocean University of China *(In chinese)*.

Zhang J., Zhang X., Li R., Chen L., & Lin P. (2017). Did streamflow or suspended sediment concentration changes reduce sediment load in the middle reaches of the Yellow River. *Journal of Hydrology, 546,* 357-369. *doi:*org/10.1016/j.jhydrol.2017.01.002

Zhang L., Wang J. M., Bai Z. K., & Lv C. J. (2015). Effects of vegetation on runoff and soil erosion on reclaimed land in an opencast coal-mine dump in a loess area *Catena, 128,* 44-53. Retrieved from http://dx.doi.org/ 10.1016/j.catena.2015.01.016

Zhao L., & Hou R. (2018). Effects of collection time intervals of surface runoff and sediment on soil erosion analysis during rainfall. *Catena, 165,* 201-206. *doi:* 10.1016/j.catena.2018.02.003

Zhao X., Chen X., & Huang J. (2013a). Effects of vegetation cover of natural grassl and on runoff and sediment yield in loess hilly region of China. *Journal of the Science of Food and Agriculture, 94*, 497-503. *doi:* 10.1002/jsfa.6275

Zhao X., Wu P., Chen X., Helmers M.J., & Zhou X. (2013b). Runoff and sediment yield under simulated rainfall on hillslopes in the Loess Plateau of China. *Soil Research*, *51*, 50-58. *doi:* 10.1071/sr12239

Zheng H., Chen F., Ouyang Z., Tu N., Xu W., Wang X., … Tian Y. (2008). Impacts of reforestation approaches on runoff control in the hilly red soil region of Southern China. *Journal of Hydrology, 356*, 174-184. *doi:* 10.1016/j.jhydrol.2008.04.007

Tables:

Table 1 Calculation results of vegetation coverage

	Vegetation coverage				Vegetation coverage		
	Mixed	Grass	Shrub		Mixed	Grass	Shrub
1# Plot	70%	50%	35%	2# Plot	66%	50%	18%
	60%	30%	35%		43%	30%	18%
	42%	10%	35%		26%	10%	18%
	35%	0%	35%		18%	0%	18%

Table 2 Liner regression of runoff start-time and vegetation coverage and slope

Rainfall intensity (mm min^{-1})	Nonstandard equation	Standard equation	R^2	n
1.0	T=117.353+1.676C-4.244S	T=-0.392C+0.828S	0.84	27
2.5	T=50.501+0.767C-1.6S	T=-0.342C+0.876S	0.88	27
1.0	V=0.250-0.002C+0.003S	V=-0.897C+0.334S	0.92	27
2.5	V=0.214-0.001C+0.002S	V=-0.841C+0.324S	0.81	27

Where T is the runoff start-time (s), V is runoff flow velocity, C is vegetation coverage (%), S is slope (°).

Table 3 The relationship between runoff yield and vegetation coverage by fitting

Rainfall intensity	Slope	Regression equations	R^2	Samples
1.0 mm/min	10º	$Q=99.71VC^2-276.78VC+385.33$	0.863	9
	15º	$Q=61.39VC^2-254.32VC+399.27$	0.888	9
	20º	$Q=-16.53VC^2-78.75VC+119.69$	0.887	9
2.5 mm/min	10º	$Q=124.08VC^2-456VC+754.26$	0.985	9
	15º	$Q=127.08VC^2-507VC+728.01$	0.979	9
	20º	$Q=200.88VC^2-523.59VC+801.87$	0.980	9

Where Q is runoff yield (L); VC is vegetation coverage.

Table 4 The relationship between sediment yield and vegetation coverage by fitting

Rainfall intensity	Slope	Regression equations	R^2	Samples
1.0 mm/min	10º	$S=3.43VC^2-523.5VC+36547$	0.979	9
	15º	$S=2.01VC^2-438.55VC+39277$	0.985	9
	20º	$S=1.99VC^2-434.65VC+41804$	0.985	9
2.5 mm/min	10º	$S=0.12VC^2-242.3VC+34226$	0.979	9
	15º	$S=0.72VC^2-281.83VC+36944$	0.950	9
	20º	$S=0.4VC^2-246.46VC+38222$	0.949	9

Where S is sediment yield (L); VC is vegetation coverage.

Table 5 Correlation analysis between cumulative sediment yield (S) and cumulative runoff (V) under different shrub-grass coverage and 15º slope at two rainfall intensities

Vegetation coverage	1.0 mm/min rainfall intensity			Vegetation coverage	2.5 mm/min rainfall intensity		
	Regression equation	R^2	n		Regression equation	R^2	n
18%	$S=902V^{0.51}$	0.97	13	18%	$S=1021V^{0.58}$	0.99	16
26%	$S=853V^{0.50}$	0.98	13	26%	$S=1052V^{0.56}$	0.98	16
35%	$S=600V^{0.56}$	0.96	13	35%	$S=961V^{0.59}$	0.99	16
42%	$S=479V^{0.58}$	0.96	13	42%	$S=1119V^{0.53}$	0.97	16
43%	$S=669V^{0.51}$	0.97	13	43%	$S=453V^{0.69}$	0.97	16
60%	$S=401V^{0.57}$	0.96	13	60%	$S=211V^{0.81}$	0.98	16
66%	$S=412V^{0.55}$	0.98	13	66%	$S=111V^{0.90}$	0.99	16
70%	$S=241V^{0.64}$	0.99	13	70%	$S=177V^{0.81}$	0.98	16


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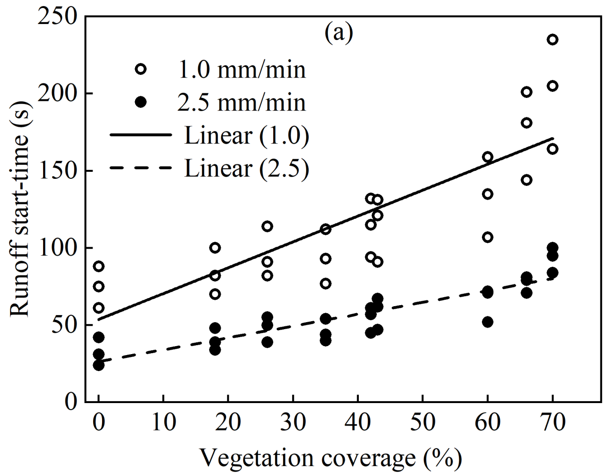
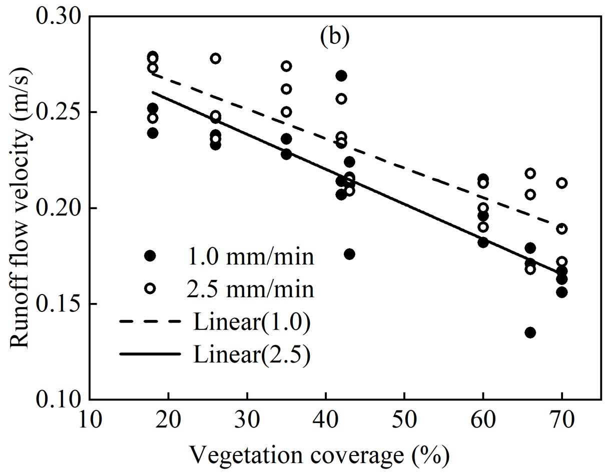
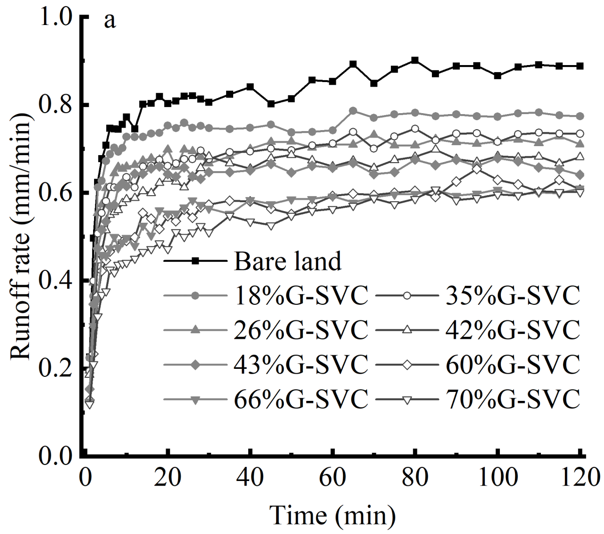
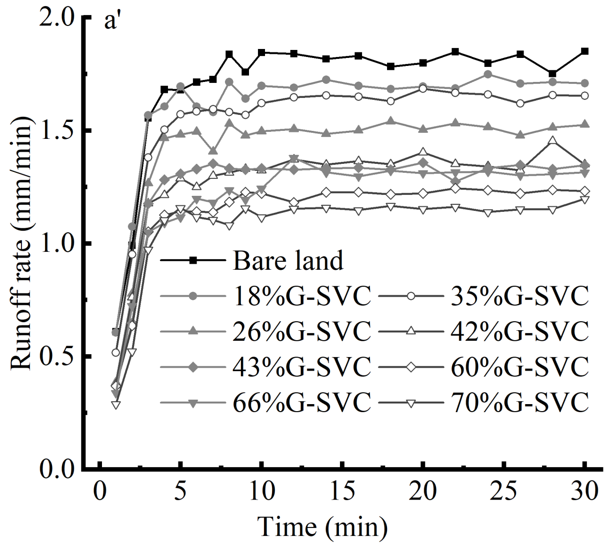
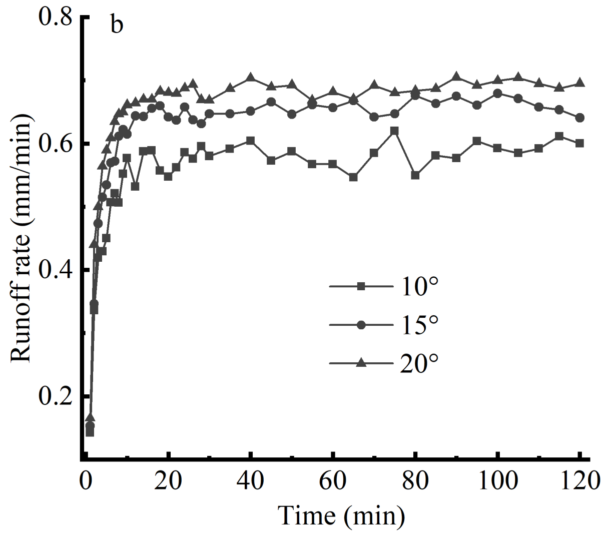
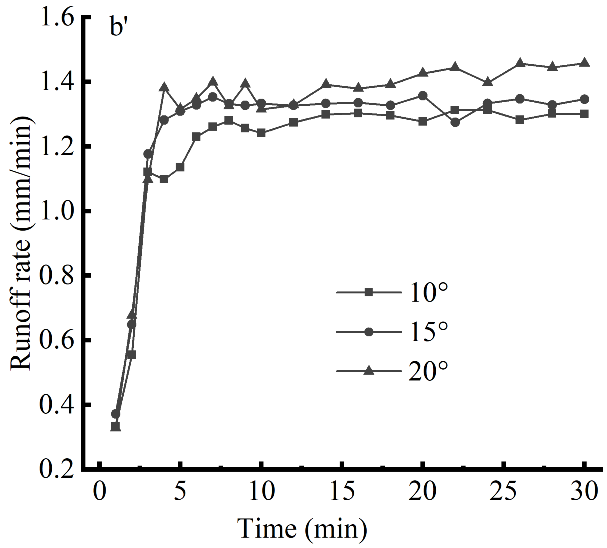

(a)
1.0 mm/min
2.5 mm/min
Linear (1.0)
Linear (2.5)
Runoff start-time (s)
Vegetation coverage (%)
0
50
100
150
200
250
0
10
20
30
40
50
60
70

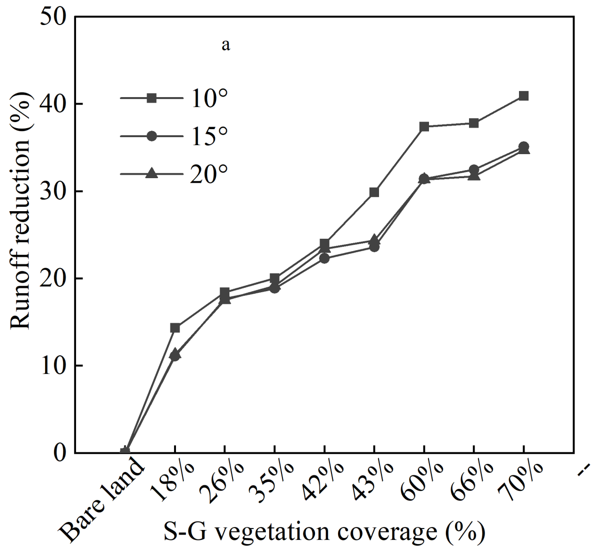

(b)
Runoff flow velocity (m/s)
0.30
0.25
0.20
0.15
0.10
10
20
30
40
50
60
70
Vegetation coverage (%)
1.0 mm/min
2.5 mm/min
Linear(1.0)
Linear(2.5)


a
Runoff rate (mm/min)
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
Time (min)
Bare land
18%G-SVC
35%G-SVC
26%G-SVC
42%G-SVC
43%G-SVC
60%G-SVC
66%G-SVC
70%G-SVC

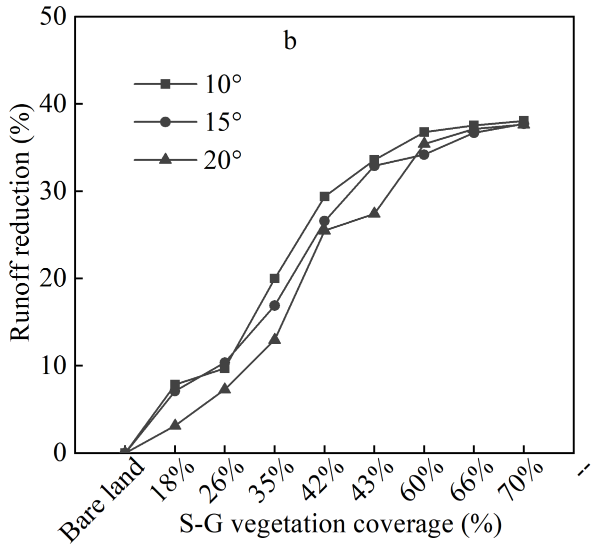

a'
Runoff rate (mm/min)
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
30
Time (min)
Bare land
18%G-SVC
35%G-SVC
26%G-SVC
42%G-SVC
43%G-SVC
60%G-SVC
66%G-SVC
70%G-SVC

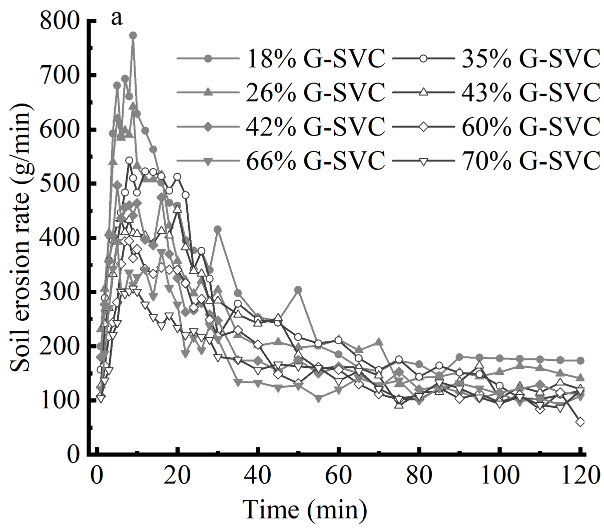

b
0.8
0.6
0.4
0.2
Runoff rate (mm/min)
10°
15°
20°
0
20
40
60
80
100
120
Time (min)

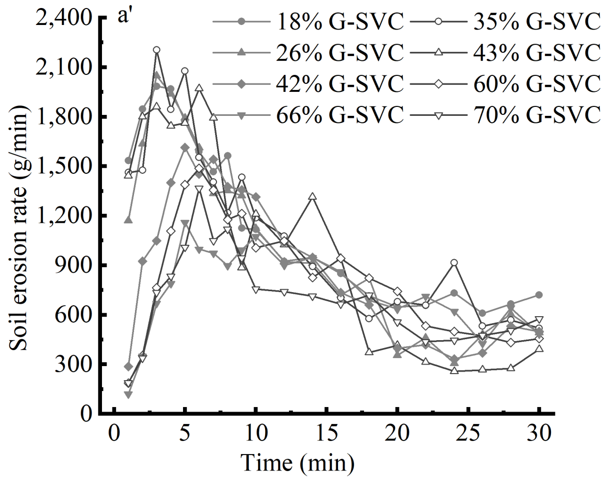

b'
Runoff rate (mm/min)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
5
10
15
20
25
30
Time (min)
10°
15°
20°

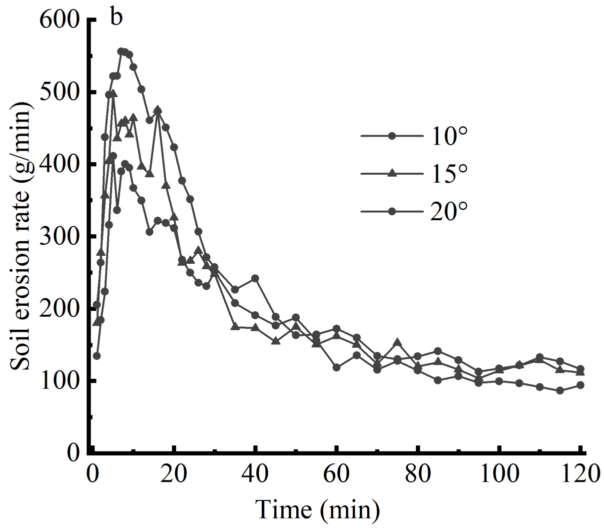


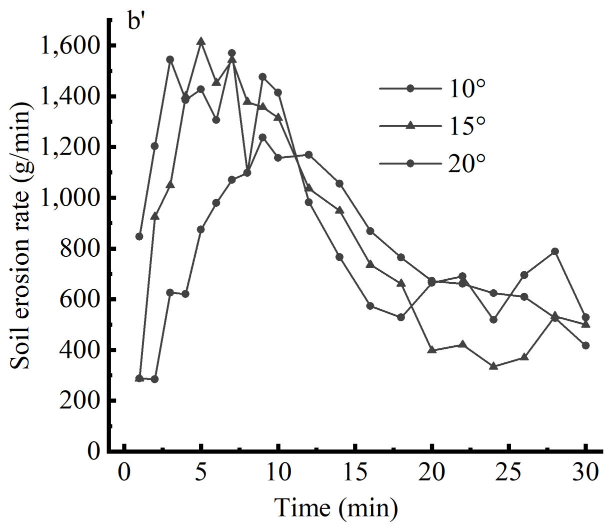
a
10°
15°
20°
Runoff reduction (%)
0
10
20
30
40
50
Bare land
18%
26%
35%
42%
43%
60%
66%
70%
S-G vegetation coverage (%)

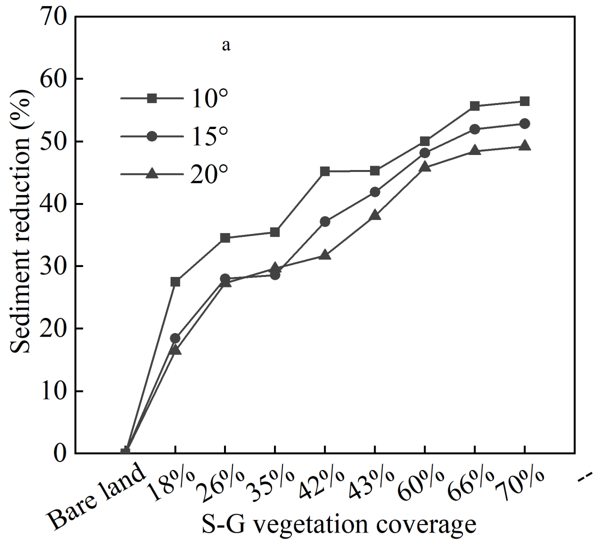

50
40
30
20
10
0
b
10°
15°
20°
Runoff reduction (%)
Bare land
18%
26%
35%
42%
43%
60%
66%
70%
S-G vegetation coverage (%)

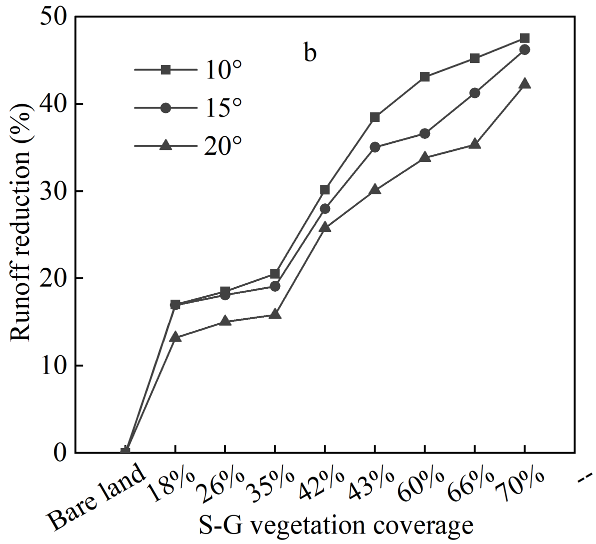

a
Soil erosion rate (g/min)
Time (min)
18% G-SVC
35% G-SVC
26% G-SVC
43% G-SVC
42% G-SVC
60% G-SVC
66% G-SVC
70% G-SVC
0
100
200
300
400
500
600
700
800
0
20
40
60
80
100
120

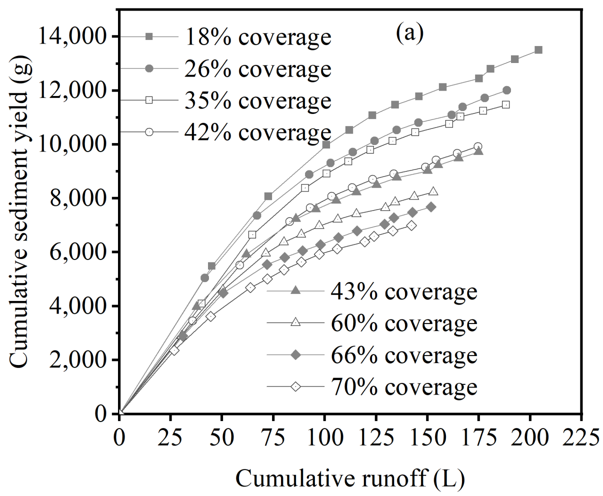

a'
18% G-SVC
35% G-SVC
26% G-SVC
43% G-SVC
42% G-SVC
60% G-SVC
66% G-SVC
70% G-SVC
Soil erosion rate (g/min)
Time (min)
2,400
2,100
1,800
1,500
1,200
900
600
300
0
0
5
10
15
20
25
30

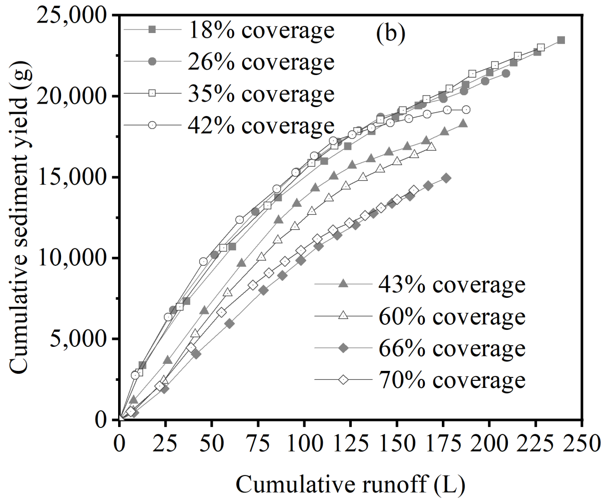

b
Soil erosion rate (g/min)
Time (min)
10°
15°
20°
0
100
200
300
400
500
600
0
20
40
60
80
100
120


b'
Soil erosion rate (g/min)
1,600
1,400
1,200
1,000
800
600
400
200
0
10°
15°
20°
0
5
10
15
20
25
30
Time (min)


a
10°
15°
20°
Sediment reduction (%)
0
10
20
30
40
50
60
70
Bare land
18%
26%
35%
42%
43%
60%
66%
70%
S-G vegetation coverage


b
10°
15°
20°
Runoff reduction (%)
0
10
20
30
40
50
Bare land
18%
26%
35%
42%
43%
60%
66%
70%
S-G vegetation coverage


(a)
Cumulative sediment yield (g)
Cumulative runoff (L)
18% coverage
26% coverage
35% coverage
42% coverage
43% coverage
60% coverage
66% coverage
70% coverage
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
0 25 50 75 100 125 150 175 200 225



25,000
20,000
15,000
10,000
5,000
0
Cumulative sediment yield (g)
0
25
50
75
100
125
150
175
200
225
250
Cumulative runoff (L)
(b)
18% coverage
26% coverage
35% coverage
42% coverage
43% coverage
60% coverage
66% coverage
70% coverage

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: