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Regulation of vegetation pattern on the hydrodynamic processes of erosion on hillslope in Loess Plateau, China

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Abstract: As vegetation are closely related to soil erosion, hydrodynamic parameter changes under various vegetation pattern conditions can be used as an important basis for the research of the soil erosion mechanism. Through upstream water inflow experiments conducted on a loess hillslope, how the vegetation pattern influences the hydrodynamic processes of sediment transport was analyzed. The results show that the placement of a grass strip on the lower upslope can effectively reduce runoff erosion by 69%, relying on the efficiency of regulated hydrodynamic process. The effective location of grass strip for hillslope alleviating erosion is on the lower part of the upslope, mainly due to the grass strip measure used to regulate the hydrodynamic system. As a result, the underlying surface runoff resistance is increased by 5 times, runoff shear stress is decreased by more than 90%, and runoff power decreased by over 92%. The measure greatly separates the scouring energy of surface runoff that acts on the slope soil. Therefore, the use of grass strips effectively decreases the energy of runoff flowing along the slope, eliminating soil erosion to a great extent and thereby achieving a better regulation of hydrodynamic processe.

Keywords: Soil erosion; Grass strip; Scouring experiment; Sediment transport; Regulating mechanism; Loess Plateau

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Introduction

Soil erosion is one of the most serious eco-environmental issues all over the world. Soil erosion has caused vegetation degradation by decreasing soil water capacity and soil fertility in the Loess Plateau. Due to the special geographic landscape, soil and climatic conditions, and history (over 5 000 years) of human activity, there has been prolonged and intensive soil erosions that have significantly impacted on the environment and the social and economic development in the region (Luo et al. 2020). How to control the soil erosion in an efficient and cost-effective manner is has been challenging to communities of scientists and engineers. The vegetation type and coverage in the river basins within the Loess Plateau have been widely re-established since 1999 through the implementation of "Grain for Green" project, that has transformed the cultivated lands to forest or grassland (Zhang et al. 2010), where the native or planted grass species have regrown (Cui et al. 2019). However, to date, there are relative limited reports on the effect of vegetation on hydrodynamic process of runoff in hillslope. As it is difficult to measure the parameters of hydrodynamic process especially under vegetation conditions, the in-depth research on scope of degree of sustainable development in the Loess Plateau has been restricted (Pan and Shangguan, 2007; Li et al. 2009; Zhang et al. 2014; Chaplot et al. 2016; Wang et al. 2017; Luo et al. 2020). Therefore, it is critical to study the regulation of vegetation patterns on hydrodynamic processes in the hillslope of the Loess Plateau, which are of both scientifically and practically significance.

Many studies have shown that the surface runoff is the main factor affecting soil and water losses in

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hillside area (Yu et al. 2014; Li et al. 2009; Dang et al. 2021). When rainfall occurs, the runoff from the upper slope generally converges on the lower slope due to an excess infiltration, and the energy and scouring force of the runoff, rills tend to develop first on the lower part of a long slope (Wang et al. 2014; Shen et al. 2015; Chang et al. 2019; Luo et al. 2020; Shi et al. 2020; Niu et al. 2020). This hydrodynamic erosion process involves the detachment of soil lumps, transport of soil particles, water storage and runoff, and soil water infiltration (Cui et al. 2019; Qu et al. 2022; Dang et al. 2021). Wu et al. (2014) indicated that soil particles will be detached from soil surface when the water shear stress is more than soil resistance through the research of relationship between runoff shear stress and soil detachment rate. Luo (2020) gave liner equations for estimating the critical shear stress and flow rate. Nearing (1999) indicated that soil detachment rate is not the function of runoff shear stress. Whereas, Shi et al. (2015) used the laboratory scouring experiment in Loess Plateau, showed that soil detachment rates would be expressed by a linear function of flow rate. Then Wang (2014) and Chaplot et al. (2016) found a liner relationship presented between the logarithm of soil detachment rate and runoff shear stress under lower slope, and later provided power function for greater slope. Jiang et al. (2017) produced a conceptual model for shear stress and sediment yield, but this model was not widely used due to their ideal experiment conditions. As a summary, all these erosion processes have not addressed the effect of vegetation that acts on soil erosion.

Using the function of vegetation has been proved the most important measure in controlling soil and water losses in the Loess Plateau region. The spatial configuration of vegetation that regulates soil erosion and sediment transported from hillslope is a key issue related to learning about the erosion and sediment yield as well as how to effectively control the erosion process in a watershed (Zhang et al. 2008; Wang et al. 2014; Zhou et al. 2016; Luo et al. 2020). For example, is it better to apply vegetation function in controlling the erosion at the upper or lower parts of slope? How does vegetation influence the development and spatial distribution of slope erosion? The answers to these questions are important for the implementation of the plant measure. Therefore, more attention needs to be paid to optimization of vegetation pattern, particular in the semi-arid area, due to the limited rainfall and a relatively dry surface soil (Wang et al. 2010; Fu et al. 2011; Ghafari et al. 2017). Field experiments indicated that, on the slope where grass were completely cut, both the resistance to and critical shear stress of sediment translocation in comparison with the slope with a complete grass cover (Xiao et al. 2016). The experimental results also suggest that the grasses significantly reduce sediment yield, and that the presence of moss can reduce water infiltration to soil. Yang et al. (2019) studied the influence of vegetation cover on the erosion and hydrodynamic processes. In addition, an increase in grass soil basal cover improves the carbon content of the topsoil, which has positive feedbacks on soil aggregate stability (Meng et al. 2017). Luo (2020) discovered that the slope, flow rate, sediment concentration, and particle size composition all impact on a grass strip's sediment-trapping effectiveness.

Numerous previous studies conducted on the effect of vegetation on decreasing runoff and sediment, primarily focus on the runoff and soil erosion processes. However, the effects of hydrodynamic processes on topsoil erosion by overland flow under different vegetation pattern remain unclear, especially in the region of the Loess Plateau (Zhang et al. 2002, 2003; Wang et al. 2014). Soil erosion is known to involve a complex physical process as the interaction between overland flow and soil masses. Further research is required to estimate and identify the influence of overland flow hydraulics and erosion processes by various grass strips, in which the scouring force due to overland flow is the key factor that influences the processes of soil erosion, the transport and deposit (Pan and Shangguan, 2007; Sun et al. 2016; Yang et al. 2018). However, few studies have examined runoff resistance, runoff shear stress and runoff power as well as the relationship between these factors in the vegetation-covered plots under scouring conditions (Gao et al. 2013; Zhang et al. 2014; Chaplot et al. 2016; Luo et al. 2020). Thus, consecutive experimental observation is needed to quantify the benefits of vegetation pattern in regulating hydrodynamic processes of erosion in the hillslope. The aims of this research are to measure the effect of vegetation pattern on the hydrodynamic processes of sediment transport in a hillslope and to find the acting mode on the hydrodynamic parameters of the best vegetation pattern.

1 Experimental materials and methods

1.1 Experimental treatments and measurements

The typical hillslope landforms in the loess hilly region can be roughly divided into an inter-downslope zone (including the Loess tableland and ridge mound slope) and a downslope zone (including the downslope slope and downslope bed). Statistical results of the hillslope geomorphic features in the Loess Plateau show that, in the loess hilly region, the slope gradient of the inter-downslope zone is gentle, being 10°–25°, and the slope gradient of the downslope one is 25°–35°. According to the landform characteristics of hillslope, experimental design principles, and the specific facility status in the rainfall-flood erosion laboratory, a conceptual model of the hillslope was established, as shown in Fig. 1.

Physical experimental model of the hillslope system was made of steel tank, with width of 1 m, a slope of 12°, and a length of 8 m, representing the upslope zone; and the slope with a gradient of 25° and a length of 5 m represents the downslope one (Fig. 1). The total horizontal projection area was 11.55 m^2. The length ratio of the upslope to the downslope parts is roughly at 1.6:1.0, representing the actual cases occur in the Loess Plateau (Pan and Shangguan, 2007; Li et al. 2009).

The hillslope soil selected for this experiment is the loessal soil widely occur in the Loess Plateau in the northern Shaanxi. The soil particle gradation analysis showed that, using Malvern 2000 particle size analytical device, the particles with grain size of 0.05–0.1 mm accounted for 6.21% and those with grain size of 0.002–0.05 mm accounted for 91.39%; this soil is classified as silty soil according to the soil classification standard of the United States Department of Agriculture (USDA).

Prior to the experiments, a 20-cm-thick natural sand layer was laid on the bottom of the steel tank to ensure that the water permeability of the experimental soil was close to a natural state and that soil moisture infiltrated uniformly. To ensure consistency of initial conditions, we used the tamping method and pre-wetted the soil by spraying with water. Soil bulk density was controlled at about 1.3 g/cm^3 and the initial soil moisture content controlled at about 21%. Table 1 shows the initial physical parameters of the tested soil. Subsequently, four 5-cm experimental soil layers were laid on top of the sand layer, with a 10 cm space left for a similarly sized grass strip implanted in the reserved part of the upslope. The gaps were then filled with soil and compacted; the grass strip was flushed and jointed closely to the bare slope part in order to prevent it from sliding during rainfall. The grass chosen for the experiment was wild Manila grass (Zoysiamatrella), with the grass strip dimension of 2 m × 1 m and the root system depth of 20 cm. Two weeks prior to the experiments, the grass was transplanted into the tank.

After soil filling and grass planting, the levelness of the sloping surface was measured with a level gradiometer to ensure consistent boundary conditions for each experimental run. Discharge flow was controlled using a constant water head from the top of the laboratory flume based on the design requirements. Before and after each experiment, the discharge was calibrated twice to ensure accuracy.

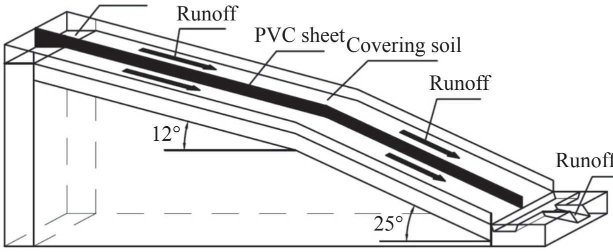

Fig. 1 Set-up of the hillslope scouring experiment

Table 1 Design of the tested scouring–vegetation patterns

Vegetation pattern	Scouring discharge (L/min)	Position relative to slope top	Vegetation coverage (%)	Scouring duration (min)
A	16	Bare slope	0	30
B	16	7–8	25	30
C	16	6–7	25	30
D	16	5–6	25	30
E	16	4–5	25	30
F	16	3–4	25	30

1.2 Experimental design and methods

Upstream water inflow is an important factor influencing erosion and sediment transport in hillslope. On the basis of existing research results and the actual water inflow in the study region, an inflow rate of 16 L/min was applied to study the vegetation patterns that control the hydrodynamic processes in the hillslope. The scouring experiment was carried out based on the hillslope model shown in Fig. 1, with the laboratory soil tank (1 m in width) split into two soil tanks of 0.5 m in width using PVC sheets for testing. Two rounds of the scouring experiments were conducted for each grass strip patterns to reduce errors caused by randomness.

All experiments were recorded from start of runoff generation, and the runoff duration was defined as 30 minutes, as the runoff usually reached a stable state after 30 minutes according to the specific test situation. The runoff volume was measured and the sediment in the storage bucket were collected per minute (Fig. 1). The sediment in the water was separated after settling the water for 24 hours, and the sediment was dried at 105℃ over 8 hours and weighed.

The hillslope was divided into 13 sections with equal spacing, with each section measuring 1 m × 1 m. The slope top cross-section was considered the first hydraulic section and was marked as 1–1, with the other cross-sections 2–2, 3–3,…, down to 13–13 along the direction of water flow. Two flumes with the size of 20 × 50 × 50 cm^3 (length × width × depth) were placed at the upslope top so that the water passed the flumes at a constant head and then through a slow-flowing belt, ensuring that the initial water flow entered the hillslope with a consistent velocity. After calibrating the scouring discharge, the wires were installed at each section line to mark each wetted cross-section for the accurate determination of runoff width and cumulative time for the runoff to pass through each wire. Cross-section 1–1 served as a slow-flowing belt in the experiment and was 1 m in length. To fit the above flume and gutter closely without water leakage, a plastic film was first laid and then plexiglass placed on its top. A level gauge was then used to measure the alignment of the plexiglass surface to ensure that the water flow from the slow-flowing belt passed through the middle of the slope.

In the experiment, the vegetation coverage was here set as 25%, taking into account the actual status of water storage and soil moisture in the loess (Chang et al. 2019). A total of six spatial configurations of the grass strip on the slope were considered, as shown in Fig. 2: Bare soil (Pattern A), and plant placement on the lower part of the upslope (Pattern B), the middle lower part of the upslope (Pattern C), the middle part of the upslope (Pattern D), the middle upper part of the upslope (Pattern E) and the upper part of the upslope (Pattern F).

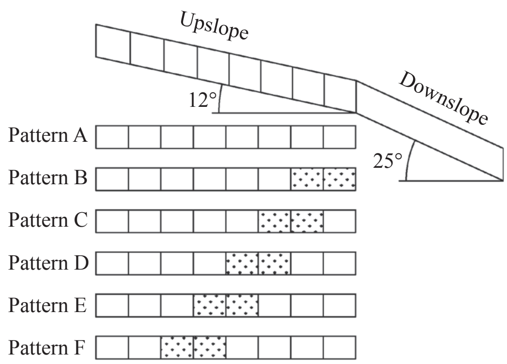

Fig. 2 Schematic of scouring–vegetation pattern design

1.3 Runoff velocity measurement

The runoff velocity (runoff surface velocity) was measured at each part of the hillslope using the $KMnO_4$ dye tracer technique to observe runoff velocity throughout the experiment (Li et al. 1996). The runoff Reynolds number (*Re*) was used to characterize runoff flow states. It was computed as $Re = hU/T$ using the runoff depth (*h*), the runoff surface velocity (*U*), and the associated kinematic viscosity coefficient (T). T is related to the runoff temperature and was obtained from Li et al. (1996). As the runoff belongs to overland flow in the scouring experiment, and according to the basic theory of uniform flow in open channels, the runoff surface velocity was then modified to account for the various flow conditions (0.67 for laminar flow, 0.70 for transitional flow, and 0.80 for turbulent flow) in order to get the average runoff velocity value (Li et al. 1996).

$$V = \alpha U \tag{1}$$

Where: V is the average runoff velocity in m/s; α is correction factor, (0.67 for laminar flow; 0.70 for transitional flow and 0.80 for turbulent flow), U is the runoff surface velocity in m/s.

1.4 Runoff resistance measurement

Slope runoff is subjected to various resistances during flow. In the present study, we focus on sheet flow, which has a shallow water depth and is thus very significantly influenced by surface roughness and vegetation. In most recent studies, as the slope flow is simplified and runoff resistance is calculated based upon the resistance of open channel flow and river hydraulic theory, the Darcy–Weisbach coefficient is generally used to reflect the magnitude of resistance to which slope runoff is subjected during flow (Xiao et al. 2016). The effect of vegetation pattern (i.e. grass strip position) on Darcy–Weisbach resistance was here comprehensively analysed, with the Darcy–Weisbach resistance coefficient calculated as follows (Niu et al. 2020):

$$f = \frac{8gRJ}{V^2} \tag{2}$$

Where: g is acceleration due to gravity (set to 9.8 m^2/s here); R is the hydraulic radius (here replaced by water depth in the conducted experiments because of the focus on sheet flow) in metre; J is the slope gradient (set to a tangent value of α; the surface relief gradient) and V is the average runoff velocity in m/s.

1.5 Runoff shear stress measurement

In a hillslope, surface runoff moves in the direction of the slope gradient and the flow in turn produces a force acting in the movement direction, known as the runoff shear stress. This is the force of soil erosion, which has the potential to disrupt original soil structure and to cause soil lump to depart, so that the scattered soil particles are mixed into the runoff and transported off. Xiao et al. (2016) employed the following formula for calculating the runoff shear stress:

$$\tau = \gamma R S_f \tag{3}$$

Where: τ is the runoff shear stress in Pa; γ is the bulk density in kg/m^3; R is the hydraulic radius of the runoff in metres (here set approximately to the water depth value) and S_f is the slope gradient, set to the tangent value of α, the surface relief gradient.

1.6 Runoff power measurement

Runoff power represents the power required to act power consumption of runoff flow per unit area along a slope. Bagnold first proposed the concept of runoff power as the power consumed by runoff acting on a unit area, expressed as follows:

$$\omega = \gamma q S = \gamma h V S = \tau V \tag{4}$$

Where: ω is the runoff power in N/(m·s); q is the discharge per unit width in $m^3/(m \cdot min)$; h is the average water depth of the wetted cross-section in metres; τ is the runoff shear stress in N; V is the runoff velocity in m/s and S is the surface gradient in degrees.

2 Results

2.1 Spatiotemporal variation in runoff resistance

2.1.1 Runoff resistance under bare-slope conditions

Vegetation can increase surface resistance, playing a role mainly in decreasing flow velocity, even blocking runoff and increasing infiltration. Nevertheless, the effectiveness of improvement in runoff resistance varies with vegetation position.

Under bare-slope conditions, the spatiotemporal characteristics of Darcy–Weisbach resistance are an important reference in studying the effect of vegetation pattern on runoff resistance. Fig. 3 shows the temporal and spatial variation in the Darcy–Weisbach resistance coefficient under bare-

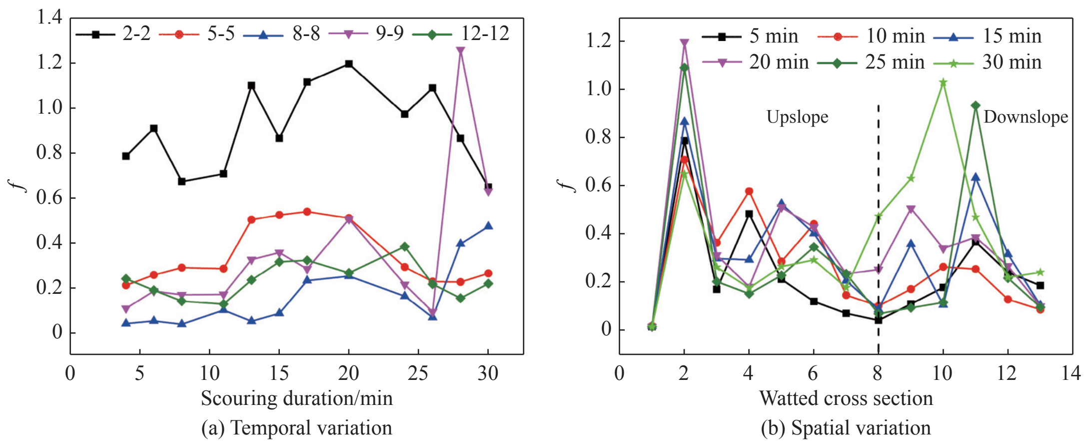

Fig. 3 Temporal and spatial variation in runoff resistance under bare-slope condition

slope conditions. It can be seen from Fig. 3a that runoff resistance remains basically constant with an increase in scouring duration at the different positions indicated by the hydraulic cross-sections. Fig. 3b indicates that the runoff resistance reaches a maximum value at the 2nd cross-section and at a minimum at the 8th cross-section, representing a decreasing and then increasing distance trend between the hydraulic section and slope top. Runoff resistance in the downslope varied between 0.010 and 0.051 with a coefficient of variation of 49.5%, while resistance over the slope varied between 0.003 and 0.056 with a coefficient of variation of 56.3%. Therefore, runoff resistance over the slope fluctuated more violently than that in the downslope.

2.1.2 Variations in runoff resistance with grass strip pattern

As the presence of a grass strip can increase the underlying surface resistance to some extent, the spatiotemporal variation in such resistance would also change depending on the positions of acting grass strip.

The temporal variation in runoff resistance with different vegetation patterns is shown in Fig. 4. As can be seen from this figure that: (1) the presence of vegetation resulted in an evident increase in runoff resistance for each grass strip pattern as the planted grass has elevated underlying surface roughness and thus increased runoff resistance; (2) runoff resistance differed greatly between different grass strip patterns, with the maximum value observed at patterns D and C, especially at the outlet of the flow system; and (3) the runoff resistance increases gradually with an increase in scouring duration, in particular after a scouring duration of 20 minutes.

Fig. 5 shows the spatial variation in runoff resistance at 15 min and 25 min scouring durations under the different vegetation patterns. The figure reveals that: (1) runoff resistance tends to fluctuate with increasing distance between the grass strip and the upslope top, peaking at cross-sections 2–6 (upslope) and cross-sections 9–12 (downslope); and (2) the runoff resistance is the highest at patterns C and D, indicating that the effectiveness

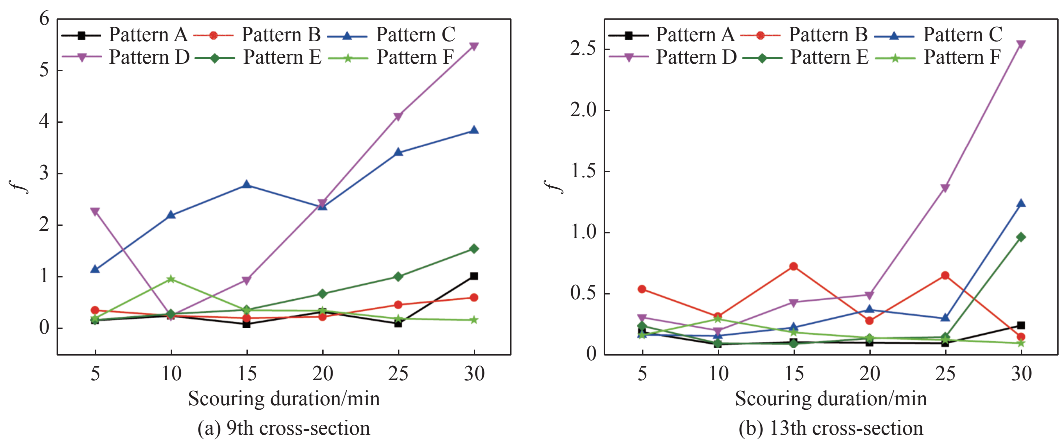

Fig. 4 Temporal variation in runoff resistance at different cross-sections for different vegetation patterns

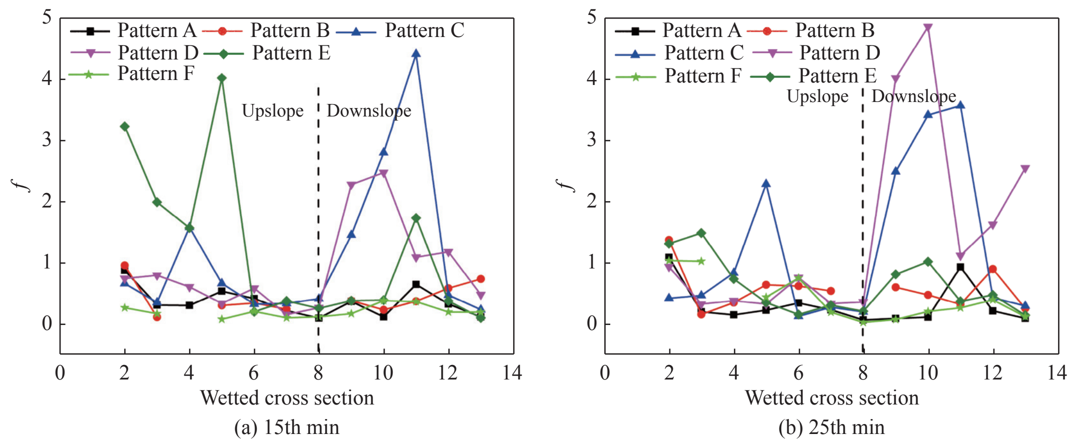

Fig. 5 Spatial variation in runoff resistance at different moments for different vegetation patterns

of improvement in surface resistance was greatest when the grass strip was planted 4–5 m from the upslope top.

With respect to the effect of vegetation pattern on runoff resistance, Fig. 6 illustrates the relationship between vegetation pattern and runoff resistance. As can be seen from this figure, runoff resistance initially tends to increase but then decreases with the increasing distance between the grass strip and slope top. When the grass strip was placed 4–5 m from the slope top, runoff resistance was at its maximum, being more than 5 times greater than that recorded on the bare slope. Therefore, patterns C and D have the largest impact on the runoff resistance of the tested hillslope.

2.2 Spatiotemporal variation in runoff shear stress

2.2.1 Runoff shear stress under bare-slope conditions

The runoff shear stress values at cross-sections 2, 5, 8, 9 and 12 were calculated and plotted against scouring duration at the different hydraulic sections, as shown in Fig. 7a. In addition, runoff shear stress values after 5–25 min of runoff onset were calculated and plotted against wetted cross-sections, as shown in Fig. 7b. It can be seen from Fig. 7a that the runoff shear stress largely remains constant with the increase of scouring duration at the different hydraulic sections. Fig. 7b reveals that the runoff shear stresses reache the maximum values at the 2nd and 8th cross sections, respectively, which tend to decrease and then increase with the increasing distance between the grass strip and slope top. The experiment observed that the erosion at the 2nd cross-section was the most serious. Runoff shear stress in the downslope varied between 0.010 and 0.051 with a coefficient of variation of 49.5%, while runoff shear stress over the slope varied between 0.003 and 0.056 with a coefficient of variation of 56.3%, demonstrating that runoff shear stress over the upslope fluctuated more violently.

2.2.2 Variations in runoff shear stress with grass strip pattern

The temporal variation in runoff shear stress is

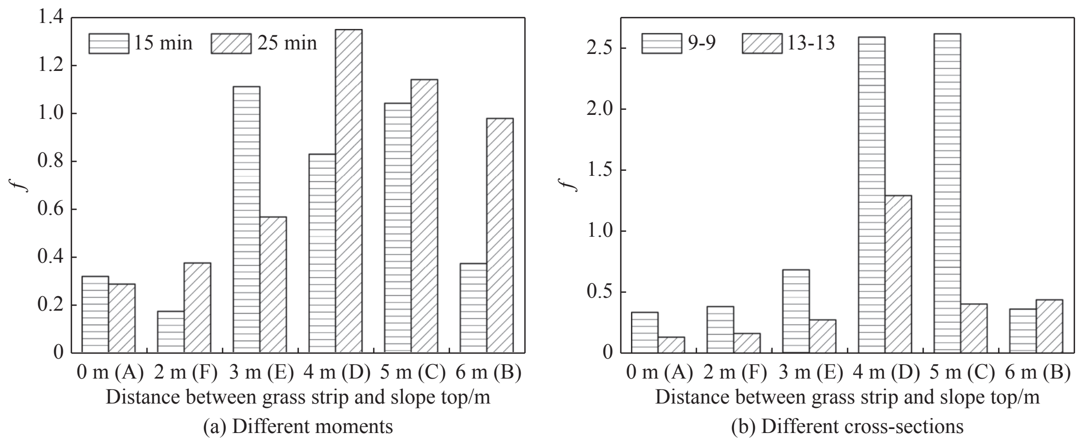

Fig. 6 Effect of vegetation pattern on Darcy–Weisbach resistance f at different moments and cross-sections

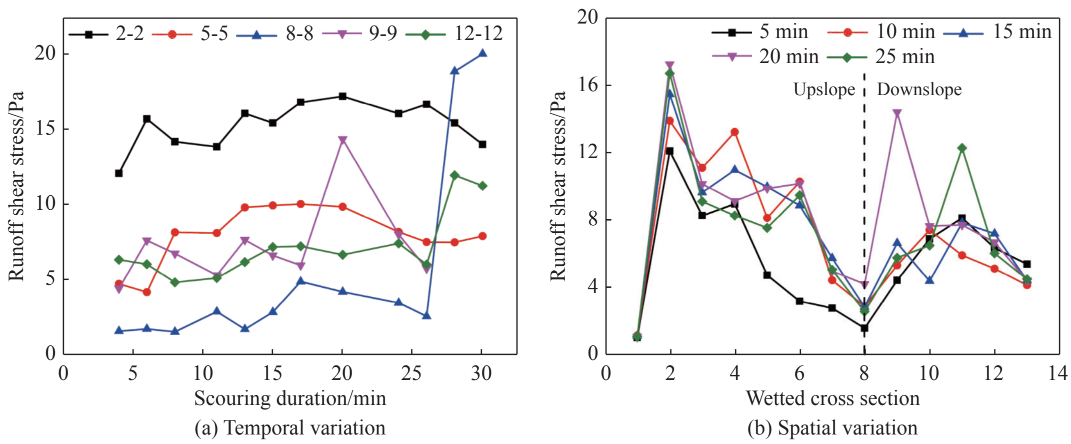

Fig. 7 Temporal and spatial variation in runoff shear stress under bare-slope conditions

represented by that at cross sections 9 and 13 for the different tested vegetation patterns and is shown in Fig. 8. Using the result of bare slope as a reference, the decrease in average runoff shear stress was calculated for each grass pattern, and the results are listed in Table 2.

The obtained data reveal that: (1) runoff shear stress decreased substantially when grass strips were planted, as the vegetation is able to mitigate the runoff scouring and consequently soil detaching on the upslope; and (2) the decrease in runoff shear stress varies considerably with the differences in vegetation pattern. Compared to bare slope, the highest stress reduction by more than 85% occur at the slope with vegetation patterns B and F.

The spatial variation in runoff shear stress at 15 min and 25 min scouring durations under the different vegetation patterns is shown in Fig. 9. This figure reveals that: (1) the variation in runoff shear stress at 15 min and 25 min scouring durations was similar for all vegetation patterns; (2) at both scouring durations, the average runoff shear stress in the downslope is obviously greater than that at the upper slope for all the patterns; (3) the decrease in runoff shear stress is smaller in the downslope than over the hillslope, reflecting the influence of the planted grass; and (4) at both recording times, the grass strips significantly decreased the runoff shear stress, especially in the cases of patterns B and F, suggesting that these two planting layout have a better consequence on

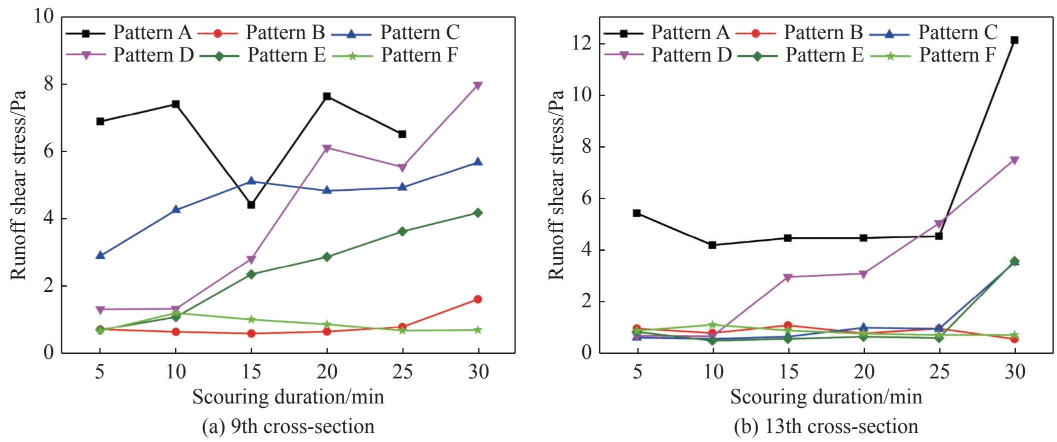

Fig. 8 Temporal variation in runoff shear stress at different cross-sections for different vegetation patterns

Table 2 Reduction in runoff shear stress at different cross-sections for different vegetation patterns (%)

Wetted cross section	**Vegetation pattern**				
	B	**C**	**D**	**E**	**F**
9-9	87.4	29.8	36.4	62.5	87.1
13-13	85.7	79.5	43.5	81.2	85.9

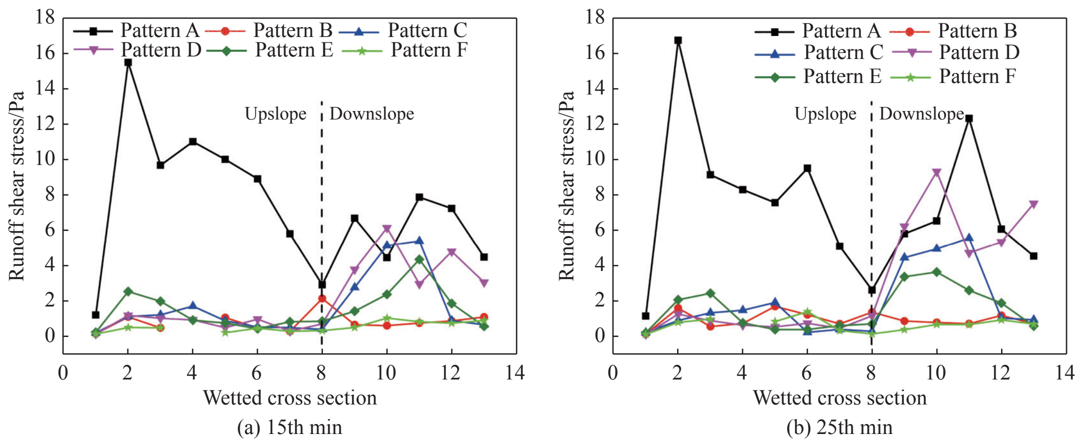

Fig. 9 Spatial variation in runoff shear stress at different moments for different vegetation patterns

soil conservation.

Taking pattern A as a reference, the reduction in the average runoff shear stress at different moments was calculated for each vegetation pattern, with the results listed in Table 3. As can be seen from this table, runoff shear stress generally decreased by >70% for all the studied vegetation configurations. Grass strip pattern F yielded the highest reduction in runoff shear stress, with decreases of 93% and 91% recorded at the 15th and 25th minute of scouring, respectively.

Table 3 Reduction in runoff shear stress at different moments for different vegetation patterns (%)

Time (min)	Vegetation pattern				
	B	C	D	E	F
15	89.3	77.9	72.6	80.3	93.0
25	87.1	75.2	59.2	79.4	91.0

Fig. 10 illustrates the effect of vegetation patterns that act on the slope runoff tend to increase shear stress at the beginning state and then decrease with the increasing distance between the grass strip and the slope top. The lowest values of runoff shear stress were recorded at the positions of 2 m and 6 m (patterns B and F) from the slope top.

2.3 Spatiotemporal variation in runoff power

2.3.1 Runoff power under bare-slope conditions

The spatiotemporal characteristics of runoff power under bare-slope conditions are an important reference in studying the effect of vegetation patterns. In the present study, runoff power values for the runoff generated within 5–25 minutes were calculated and are shown in Fig. 11a. In addition, runoff power values for the tested hillslope at cross-sections 2, 5, 8, 9 and 12 were calculated and are shown in Fig. 11b.

Fig. 11a shows that the runoff power basically remains constant with scouring duration at each cross-section, before increasing in the downslope during the later stages of the experiment. Fig. 11b shows that: (1) the runoff power values tend to increase and then decrease on both the upper slope

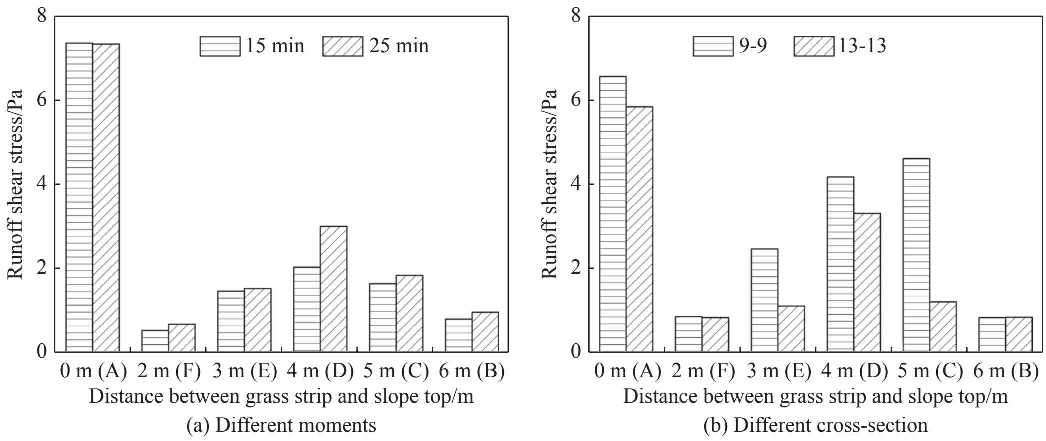

Fig. 10 Effect of vegetation pattern on runoff shear stress τ

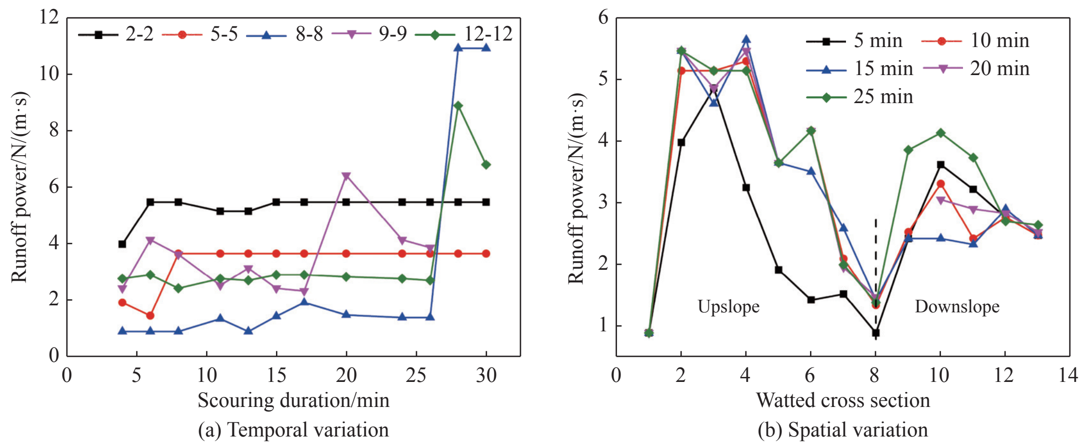

Fig. 11 Temporal and spatial variation in runoff power under bare-slope conditions

and the downslope, peaking at cross-sections 2–4 and 9–10, respectively. This indicates that the most power consumed by runoff occur at these positions, resulting in the strongest erosion of the underlying surface; (2) runoff power is lowest at the last cross-section (section 8), and the soil erosion is weakest at this position; and (3) runoff power on the upper slope is generally higher than that on the downslope.

2.3.2 Variations in runoff power with grass strip pattern

Fig. 12 shows the variation in runoff power with scouring duration at cross-sections 9 and 13 of the tested hillslope for the different vegetation patterns. This figure reveals that the runoff power recorded at the different cross-sections decreased substantially for all vegetation patterns, but to varying degrees.

Taking pattern A (bare slope) as a reference, the decrease in average runoff power was calculated for each vegetation pattern, and the results are listed in Table 4. It can be seen from this table that the runoff power decreases substantially with the grass strip planted in any position, and this reduction follows the order as pattern B > pattern F > pattern E > pattern C > pattern D.

Fig. 13 shows the spatial variation of runoff power at 15 min and 25 min after runoff onset under different vegetation pattern conditions. This figure reveals that: (1) For all the vegetation patterns, the runoff powers at 15 min and 25 min have a similar trend with the increasing distance

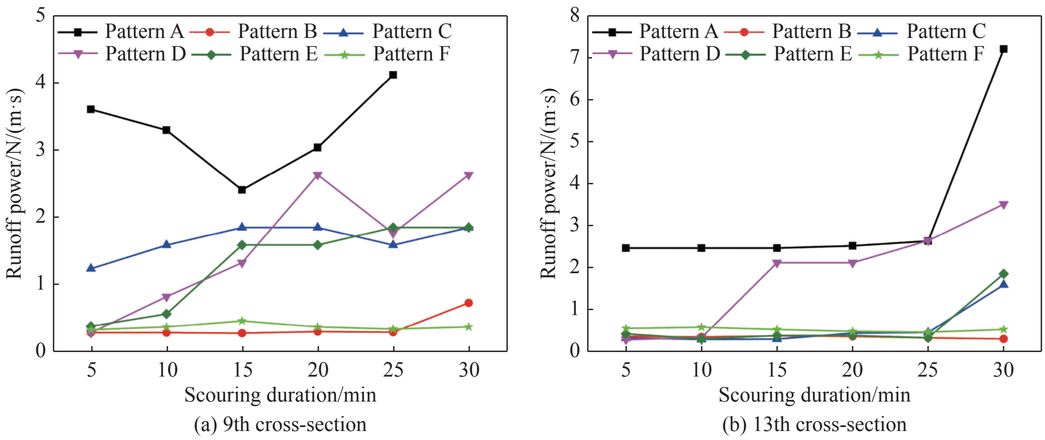

Fig. 12 Temporal variation in runoff power at different cross-sections

Table 4 Decrease in runoff power at different cross-sections for different vegetation patterns (%)

Wetted cross section	Vegetation pattern				
	B	C	D	E	F
9–9	89.4	49.8	52.4	60.7	89.0
13–13	89.9	83.2	44.5	81.8	84.5

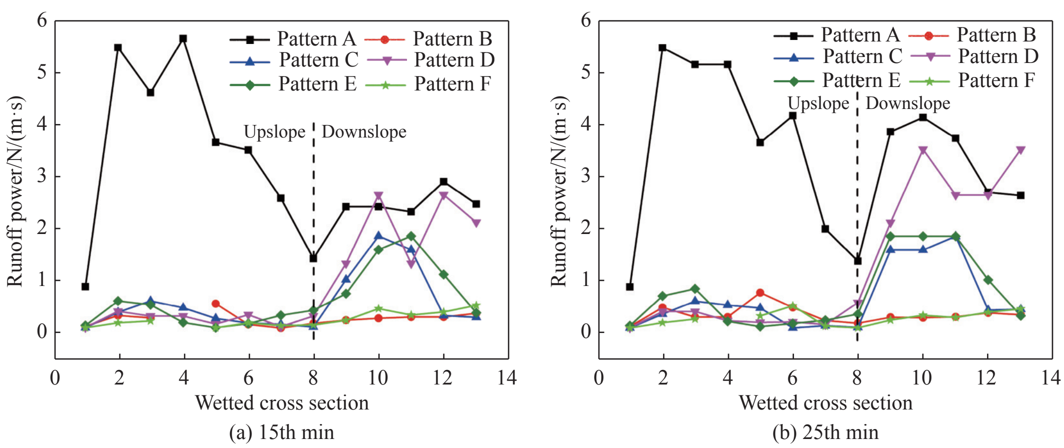

Fig. 13 Spatial variation in runoff power at different moments for different vegetation patterns

between the grass strip and the slope top, which is increasing and then decreasing both over the slope and in the downslope, with the lowest runoff power value recorded at the last cross section 8; (2) the decrease in runoff power value is smaller in the downslope than over the slope, which in generally consistent with that observed from the bare slope; and (3) the presence of a grass strip substantially decreases the runoff power and that is good for soil conservation, especially in the cases of patterns B and F.

Taking pattern A (bare slope) as a reference, the decrease in average runoff power for the different vegetation patterns were calculated, with the results listed in Table 5. It can be seen from this table that runoff power decreased substantially by >70% for most of the analysed vegetation patterns, with the decreases recorded under patterns B and F the largest at >92%.

Fig. 14 illustrates the relationship between grass strip position and runoff power, and reveals that runoff power tends to increase in the beginning and then decrease with the increasing distance between the grass strip and the slope top. This is consistent with the trend observed from runoff shear stress test. Runoff power reached a minimum value for the grass strip planted at 2 m or 6 m from the slope top (as patterns B and F), as the grass plant there effectively has weakened runoff power and thus reduced the soil erosion.

3 Discussion

3.1 The effect of vegetation pattern on hydrodynamic parameters

As presented above, each assessed parameter exhibits a similar trend in the bared slope conditions,

Table 5 Decrease in runoff power at different moments for different vegetation patterns (%)

Time (min)	Vegetation pattern				
	B	C	D	E	F
15	91.7	82.0	70.1	79.9	92.2
25	90.2	81.7	62.9	78.6	92.2

with the extreme values occurring at cross sections 2–4 and 9–10. The result is in consistent with previous research (e.g. Cui et al. 2019; Luo et al. 2020).

The resistance coefficient f represents the relationship between flow depth and velocity, and it is a vital flow parameter for a continuous discharge. Once the grass strip is installed in a slope, the underlying surface roughness of the slope will greatly be increased, and as thus the runoff resistance will also be increased. With respect to the impact of vegetation pattern on the runoff resistance, the experiment result shows that patterns C and D are five times greater than that of the bare slope. The capacity of runoff to move sediment and its shear strength will increase as f increases. In addition, based on the open channel flow requirements, the f value for the grass strip is less than 1.0, indicating the presence of subcritical flow, whereas the f value for the bare-soil plots was greater than 1.0, indicating the presence of supercritical flow. As the resistance coefficient increases, the flow energy, or runoff power dissipation along the flow channel is increased, which hence diminishes the potential for the sediments to be eroded away. The f for the grass strip slope was greater than that of the bare-soil plots, showing that the grass plots were able to withstand soil erosion and sediment movement better than the bare-soil plots. These findings are consistent with those obtained from research conducted in loess regions (Wu et al.

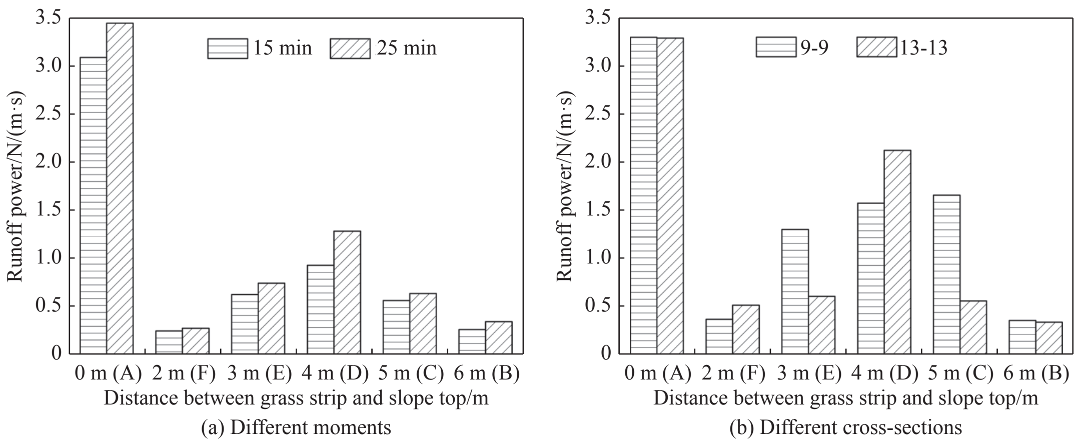

Fig. 14 Effect of vegetation pattern on runoff power

2011; Zhao et al. 2015; Zhou et al. 2016; Wang et al. 2017; Yang et al. 2018; Chang et al. 2019).

Soil detachment is considerably affected by shear stress, and the parameters as soil cohesiveness, bulk density and total porosity, and plant root mass density, and their relationship has been summarized by using power functions (Nearing et al. 1999). Reduced rill erodibility on grass lands often results in lower soil detachment capacity, but the critical shear stress of restored lands varies non-monotonically with detachment capacity (Wang et al. 2014; Sun et al. 2016; Meng et al. 2017). When the grass strip was planted 2 m or 6 m from the slope top (as patterns B and F), runoff shear stress decreased by more than 90%; this indicates that vegetation mainly relies on decreasing the runoff shear stress to eliminate soil detachment capacity of runoff scouring on upslope soil.

Current study showed that runoff power decreased substantially by >70% for almost all the vegetation patterns, comparing to those of bare slope. However, the extent of this reduction in the downslope was minor and essentially consistent with that over the bare slope. Thus, the role of vegetation in reducing runoff power is mainly active in the upper slope part. For example, when the grass strip was planted 2 m or 6 m from the slope top (as patterns B and F), the runoff power was at its lowest and decreased by over 92%; planting in these positions could thus effectively decrease the potential energy of runoff flowing along the slope, and eliminate soil erosion to the greatest extent. Therefore, as the erosion was found to be positively linked with runoff power, the grass strip plot with the lowest sediment output was the one with the lowest runoff power.

Overall, the grass strip decreases soil erosion by (I) lowering the overland flow shear stress (Fig. 10) and stream power (Fig. 14); and (II) raising the hydraulic roughness (Fig. 6), likely due to the presence of the grass strip's aboveground portions (Pan et al. 2016). The Patterns B performs the best among the five designs in terms of retaining water and minimizing soil loss. These findings suggest that the cumulative flow from the higher slope locations leads to the erosion occurs on the lower slope positions by increasing flow velocity, shear stress (Fig. 7), and runoff power (Fig. 11). The upslope inflow may alter the soil surface. On the bare soil plot, for instance, the upslope inflow was channeled into a number of obvious overland flow routes with excellent connectivity and surface rills. This work concurs with Wang et al. (2014) and Luo et al. (2020), who discovered that the buildup of upslope inflow led to the entrainment and transport of sediment downslope on semi-arid soils, hence inducing a greater runoff power. Due to the influence of upslope inflow on flow source and sediment entrainment at the downslope position, restoration techniques using grass strip should aid in the reduction of erosion caused by upslope inflow and soil loss at the outlet of the whole hillslope (Wang et al. 2014; Yang et al. 2018). We conducted that grass strip on the lower part of the upslope portions of hillslopes will be more effective in reducing sediment output than grass strip on the upper part of the upslope portions of the same hillslopes.

3.2 The effect of vegetation pattern on the erosion

Fig. 15 gives the total of runoff and sediment yield under different patterns in the scouring experiment. When the grass strip was installed, the sediment yield and runoff were reduced to different extents under different vegetation patterns. It shows that the vegetation has played a certain role in water storage and sediment reduction. As the distance from the grass strip to hillslope top gradually increased, the runoff and sediment yield basically tended to increase at first but then decrease, and there was a certain fluctuation in the sediment yield under Pattern D.

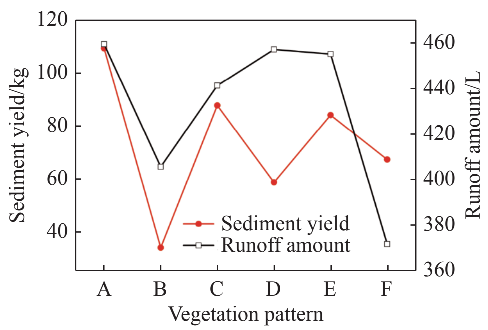

Fig. 15 The total amount of the runoff and sediment yield under different distributions of grass strips

In order to further compare and analyse the regulating strength of the grass strip on runoff and sediment, Fig. 7 shows that the sediment yield and runoff can be reduced to different extents under different vegetation patterns in the scouring experiment, indicating that the layout of the grass strip is effective in water storage and sediment reduction. The results show that the sediment reduction degrees follow the order as: Pattern B > Pattern D > Pattern F > Pattern E > Pattern C, i.e. the lower part > the middle part > the upper part > the middle upper part > the middle lower part of the slope.

The water storage functions of grass strip patterns are different from the sediment reduction functions, with the sequence as follows: Pattern B > Pattern F > Pattern C > Pattern E > Pattern D. The findings suggest that the water storage and sediment reduction functions of Pattern B are optimal; when a grass strip is planted in the lower part of the hillslope. It has the greatest effect on soil and water conservation and could reduce runoff by 11.71% and sediment by 69.02%, respectively.

In general, the water storage function of different patterns is at relative low level in the experimental conditions, the effect of grass strip on the runoff reduction is weak. In particular, the water storage function for vegetation pattern C, D and E is less than 5%. Whereas the sediment reduction function under each vegetation pattern is obviously higher than the water storage function, the minimum value of sediment reduction function is 19.80% and the peak value is up to 69.02%. This reveals that grass strips have a greater sediment interception function than water storage function, which is in agreement with previous research (Zhang et al. 2014). Comprehensive comparison of sediment reduction function at different position of the grass strip on the testing slope, the grass strip at the bottom (Pattern B) could have a better water and soil conservation effect on direct sediment interception. On the other hand, it was also observed that the grass strip on the upper slope did not decrease soil erosion, which is also agreement with previous research (Pan and Ma, 2019).

Soil erosion can be effectively controlled by the application of grass strips at the lower part of slope, and the performance of the grass strip on the lower part is significantly better than that of on the upper part. Meanwhile, it is worth noting that the runoff and sediment yield increase and then decrease with the distance between the hydraulic cross sections and the slope top under different vegetation patterns. This variation trend is basically consistent with the variation characteristics of hydrodynamic parameters, and the sediment yield level of each vegetation pattern is subject to the effects of the runoff velocity of the corresponding pattern. This demonstrates the regulating effect of vegetation on soil erosion and sediment transport is achieved through adjusting the hydrodynamic processes of erosion. In the course of regulating the hydrodynamic processes, although the runoff amount under different vegetation patterns does not change much, that is, the water storage function is small, the effect of the grass strip on the runoff reduction is weak; but the presence of grass strip has reduced the runoff velocity to a certain extent, and finally regulating the erosion and sediment production is realized.

Therefore, in terms of cultivating slopes and protecting soil, it is preferable to restore vegetation on the lower parts of slopes rather than on the upper slopes. Grass strip on the lower part of slope can effectively impact on the variation of hydrodynamic parameters, and so regulate the hydrodynamic process, mitigating soil erosion and promoting sediment and runoff reductions.

4 Conclusions

The runoff and sediment yield increased then decreased with the distance between the hydraulic section and the hillslope top under different vegetation spatial configuration. This variation trend is basically consistent with or similar to the variation characteristics of hydrodynamic parameters. The effect of vegetation on erosion sediment transport is achieved through regulating the hydrodynamic parameter. Reasonable vegetation spatial configuration can effectively weaken runoff erosion by reducing runoff velocity, and regulating hydrodynamic parameter relies on the appropriate position for the installation of controlling measure at the slope, thus greatly eliminating the separation capacity of runoff scouring on the hillslope soil.

The grass strip on the lower part of the slope can effectively weaken runoff erosion, as it efficiently regulates the hydrodynamic process. Spatial configuration of vegetation alters spatiotemporal variation characteristics of hydrodynamic parameter. As a result, the underlying surface runoff resistance is increased by 5 times, runoff shear stress decreased by more than 90%, and runoff power is decreased by over 92%. However, the grass strips on the upper part of the upslope cannot effectively regulate the hydrodynamic parameters, and therefore cannot control soil erosion.

The use of grass strip potentially weakens the runoff power and decrease the potential energy of runoff along the slope, eliminating soil erosion to a great extent and thereby achieving better regulating consequence on the hydrodynamic processes, and thus alleviates erosion and promotes sediment and runoff reduction. The study provides in-depth understanding of how vegetation pattern affects the hydrodynamics process of the hillslope.

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