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Effects of mixed vegetation restoration modes on soil remediation at slope using wastewater

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ABSTRACT

The Loess Plateau is the area with the most serious soil erosion, and soil restoration is urgently needed. As the basic unit of soil erosion, slope is of great significance to the study of soil erosion factors, and slope vegetation is an effective means to improve soil conditions. To remediate the slope soil on the Loess Plateau, a mixed vegetation restoration model was used to remediate the soil in this study. In the experiment, the factors related to soil remediation of different vegetation patterns on the slope scale were quantitatively analyzed, and the configuration optimization of slope mixed vegetation coverage, relative distance and patch pattern was carried out. When the rainfall intensity is 55 mm/h, the best coverage when the slope is below 15° is 69.3%; the relative distance is better when it is 0.2, and the optimal relative position for runoff and sediment reduction is 0.0–0.22. When the connectivity of mixed vegetation patches is better, the density of patches is greater, and the shape of patches is more complex, the runoff and sediment yield rates are lower, and the sediment accumulation is significantly reduced. Based on the results, the key indexes that affect slope soil remediation were screened out, and the optimized pattern of slope vegetation was obtained. Through data analysis, the erosion mechanism of the Loess Plateau is clarified, which provides data support for soil restoration in this area. At the same time, the optimal pattern of vegetation is given in the experiment, which provides a specific model for soil remediation in the Loess Plateau, and is conducive to soil remediation in the Loess Plateau.

Keywords: Slope; Vegetation; Soil remediation; Response surface analysis; Regression analysis; Hydrodynamic parameters

1. Introduction

Soil erosion is one of the main problems affecting the ecological environment in the Loess Plateau area, causing serious land loss in the Loess Plateau area, leading to floods and other phenomena. Soil remediation research is of great significance to the maintenance and improvement of the ecological environment, and soil remediation in the Loess Plateau region is an important means to prevent the aggravation of ecological environment damage in the Yellow River Basin [1,2]. In the study of the ecological restoration of the Loess Plateau, the change of vegetation characteristics in the Loess Plateau has an important effect on the mechanism of runoff and sediment production. Slope is the basic unit for studying the occurrence and influencing factors of soil erosion. Quantitative analysis of the change of slope vegetation and its relationship with soil erosion can provide corresponding theoretical basis and data support for the prevention and control of soil erosion in the Loess Plateau. A good soil environment is an important factor affecting the restoration of the ecological environment. Vegetation can increase soil nutrients and water by changing soil bulk density, porosity and other functions [3,4]. Different vegetation restoration models have different effects on soil physical

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properties. A single vegetation restoration model has problems such as single vegetation, low vegetation conservation rate, and low biodiversity and ecological stability to a certain extent, which may affect soil quality. Soil remediation [5]. The mixed vegetation restoration model forms a relatively stable ecological community. In addition, the vegetation restoration model has a certain degree of impact on the runoff and sediment production on the slope, which needs to be paid attention to during the soil restoration process [6]. Vegetation coverage on slopes is closely related to soil conservation and restoration. At present, about the relationship between soil and vegetation coverage, evenly distributed vegetation patterns are often used. However, in the study of soil erosion and restoration, there is a significant difference between the evenly distributed vegetation pattern and the naturally distributed vegetation. Reasonable vegetation distribution and vegetation restoration mode have positive effects on soil restoration and water and soil conservation. The influence of vegetation distribution, coverage on soil remediation and other factors in the Loess Plateau area is still unclear. To explore the mechanism of the mixed vegetation restoration model on slope runoff and sediment production, the quantitative analysis of the slope runoff and sediment production process by mixed vegetation restoration models under different patterns was used in the experiment to provide theoretical and data support for Loess Plateau's soil restoration.

2. Research on the content and methods of different vegetation restoration models and soil restoration on slopes

In the study of soil remediation, the problem of soil erosion needs to be solved. As the basic research unit of soil erosion, the study of soil and water loss on slopes can help researchers clarify the mechanism of soil erosion, and propose targeted governance for soil remediation based on the research results measures [7]. The research on slope soil erosion shows that factors such as vegetation type, vegetation coverage, topography, slope, rainfall degree and other factors will cause slope soil erosion. Through the quantitative analysis of these influencing factors and soil erosion, including hydrodynamic characteristics Studies have revealed the mechanism of slope soil erosion and provided targeted suggestions for soil restoration [8]. The main role of vegetation to reduce soil erosion is reflected in the change of soil structure caused by vegetation, the interception of rainfall, and the interception of runoff by vegetation and litter. Vegetation coverage, spatial distribution and plant types are closely related to soil erosion. The vegetation's type affects soil surface runoff and soil restoration differently [9]. Shrubs and grasslands have a better effect on soil maintenance and can reduce soil erosion. Among them, shrubs have a stronger effect of reducing runoff, while grasslands have a better effect of reducing sand and can maintain the stability of runoff at the same time [10,11]. Since some areas of the Loess Plateau have less rainfall, rainfall has become an important factor affecting soil recovery in these areas. The degree of vegetation coverage will affect the sediment yield on the slope, and it will also affect the runoff [12]. The degree of vegetation coverage is greater, the runoff and sediment is less. However, the effect of plant coverage is limited. After exceeding a certain threshold, its effect on reducing sediment and runoff is not significant. Therefore, the appropriate coverage is one of the important research objectives to improve the efficiency of soil remediation. In the process of soil remediation, if the distribution of vegetation is unreasonable, the degree of soil erosion will be aggravated, resulting the loss of water and soil. On slopes, different vegetation patterns may have an effect on the runoff and sediment yield, and different patch patterns can prolong the runoff time on slopes to a certain extent [13]. To solve the problem of soil loss in tropical gardens, researchers used high-performance ester materials to repair the soil, which is conducive to the growth of grass and shrubs [14]. The research shows that protective agricultural measures have a good effect on land health and water and soil conservation, and emphasizes the importance of continuous vegetation coverage of soil [15]. Because of land resources' limitation in the Loess Plateau region, plants need to be allocated rationally, so it is necessary to conduct a comprehensive analysis of many factors that may cause soil erosion.

Hydrodynamic parameters are the basis for the study of slope soil erosion principles. Through the calculation of hydrodynamic parameters, the movement characteristics of runoff can be analyzed, and the mechanism affecting soil runoff and sediment production can be clarified [16,17]. Affected by gravity, slope runoff fluctuates greatly in the process of movement, and is easily affected by the surface and the outside world [18,19]. The analysis of hydrodynamic characteristics can be used to quantitatively study the relationship between slope runoff and soil erosion, and the commonly used parameters include runoff velocity and unit runoff power [20]. Because the calculation of hydrodynamic parameters in real scenes is relatively complicated, artificial rainfall experiments are often used to calculate slope runoff parameters in laboratory research [21]. The flow velocity in the hydrodynamic parameters is measured by the dye method, high-speed camera shooting method, etc. To reduce the error of flow velocity measurement, empirical coefficients can be used for correction [22]. In existing studies, vegetation coverage and vegetation distribution have a greater impact on hydrodynamic parameters, and slope and rainfall intensity can change runoff velocity, runoff and sediment production, and so on. In addition to the study of the hydrodynamic parameters of the slope, the use of the landscape pattern index to study soil erosion has become a more commonly used analysis method. The landscape pattern index can conduct quantitative research on the vegetation pattern, reflect the soil erosion process under different conditions through index screening, and provide a reference for soil restoration under different vegetation patterns.

To clarify the influence of the mixed vegetation restoration model on the soil restoration in the Loess Plateau region, this experiment chooses to study the mixed vegetation pattern from three parts: vegetation coverage, spatial distribution and patch pattern. The situation of runoff and sand production under different conditions. Quantitative analysis method is one of the important means to explain the mechanism of soil erosion, but there are few quantitative studies on different vegetation patterns and soil erosion. In the experiment, the factors related to different vegetation patterns and soil remediation on the slope scale were quantitatively analyzed, such as runoff and sediment yield, hydrodynamics, etc., and were analyzed using response surface methodology (RSM), Pearson correlation analysis, etc. The method is to optimize the configuration of slope mixed vegetation coverage, relative distance and patch pattern, hoping to provide data support for soil restoration in the Loess Plateau region.

3. Experimental content and experimental method

3.1. Experimental content

To clarify the influence of the mixed vegetation restoration model on the soil restoration in the Loess Plateau region, this experiment chooses to study the mixed vegetation pattern from three parts: vegetation coverage, spatial distribution and patch pattern. The situation of runoff and sand production under different conditions. The main research content is to explore the runoff and sediment process, hydrodynamic characteristics, soil erosion mechanism and optimal configuration of mixed vegetation on slopes under different patterns of mixed vegetation. Fig. 1 shows the schematic diagram of the experimental design of the research object, content and process.

3.2. Experimental design

The main factors affecting soil erosion in the Loess Plateau include rainfall, topography, and vegetation, which are easily affected by natural factors under field conditions, and have a great influence on the quantitative analysis of runoff and sediment volume. Therefore, the experiment uses artificial rainfall to simulate the impact of mixed vegetation on soil remediation. The artificial simulated rainfall device comes from Jingyi Instrument (Model: JY-4849). Since the growing season of herbs, shrubs and crops is mainly from May to September, and the rainfall is relatively sufficient at this time, the time selected for the experiment is from May 2019 to September 2021. The soil used in the experiment comes from the Weihe River Basin in Shaanxi. Since the mixed vegetation restoration model forms a relatively stable ecological community, this vegetation restoration model was selected in this experiment for the study of Loess Plateau's soil restoration. The Loess Plateau region's vegetation mainly includes grassland, cultivated farmland, shrubs, forests, etc. To facilitate the laboratory management, *Actinidia chinensis*, rhododendron and alfalfa, which are common in the Weihe River Basin in Shanxi, were selected as mixed vegetation to study the impact of soil erosion on the Loess Plateau. According to the rainfall characteristics and landform types of the Weihe River Basin in Shanxi and contents of references [23–27], three artificial rainfalls of 25, 55 and 85 mm/h were set up, respectively, and the slopes were set at 8°, 13° and 18°, when analyzing the types and distribution of mixed vegetation patches. When the location is selected, the selected slope is set to 13°, and Table 1 shows the specific experimental design.

In order to facilitate the comparison of distribution locations in Table 1, the concept of relative distance (relative distance, RD) is defined, namely:

$$\text{RD} = \frac{\text{Length of bare land at the lower edge of vegetation grass belt}}{\text{Slope length} - \text{Vegetation width}} \tag{1}$$

The experimental process mainly includes soil tank filling, vegetation layout, artificial rainfall pre-experiment, and each experimental design is repeated twice.

3.3. Experimental method

3.3.1. Index calculation

In the experiment, the yield rate of runoff and sediment were selected as the quantitative calculation indicators to describe the change of soil and water. Eq. (2) shows the calculation of the runoff yield rate.

$$R_y = \frac{V}{t \times S} \tag{2}$$

where V is the total runoff of the sample, the unit is mL; t is the time spent to collect the sample, the unit is min; S is the area of the experimental area where the sample is located (m^2). Eq. (3) for the calculation of sediment production rate.

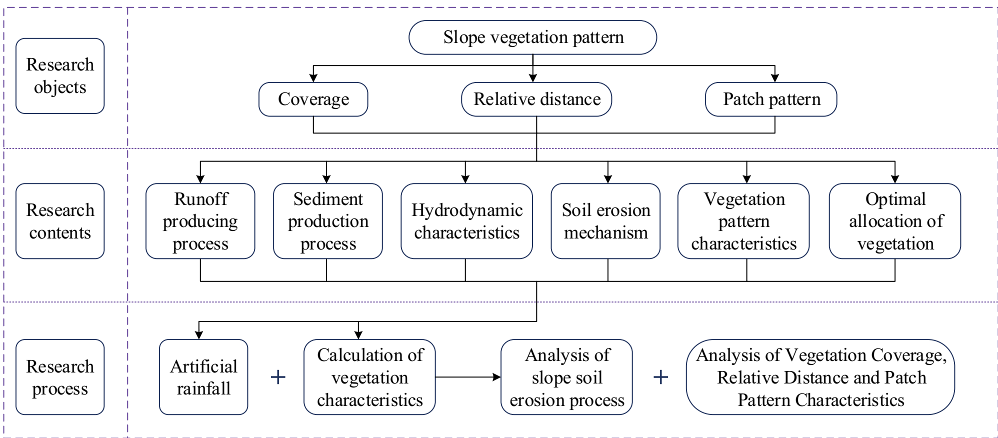

Fig. 1. Schematic diagram of experimental design.

Table 1
Experimental design

Controls	Rainfall intensity	Slope	Experimental design	Experimental group number
Control group	25 mm/h	8°	Bare area	18
	55 mm/h	13°		
	85 mm/h	18°		
Vegetation coverage	25 mm/h	8°	Coverage levels: 10%, 40%, 60%, 90%	72
	55 mm/h	13°		
	85 mm/h	18°		
Relative distance	25 mm/h	13°	Coverage level: 40%, 60%	36
	55 mm/h		RD: 0, 0.2, 0.4, 0.6, 0.8, 1	
	85 mm/h			
Vegetation patch type	25 mm/h	13°	Coverage level: 40%, 60%	24
	55 mm/h		Vegetation patch type: horizontal bar, grids	
	85 mm/h		patterns, S-road strips, random patches	

$$R_y = \frac{M}{t \times S} \tag{3}$$

where M is the total sediment amount of the sample (g). Unit runoff power U can reflect water and soil loss's situation, Eq. (4) is the specific calculation.

$$U = J \cdot v \tag{4}$$

where J represents the hydraulic gradient (°); v represents the slope velocity (m/s).

3.3.2. Response surface analysis method

RSM is often used in optimal design, mainly by obtaining experimental data under different conditions, and establishing a multiple quadratic regression equation to quantitatively analyze the relationship between influencing factor variables. In the response surface analysis method, the functional relationship between the dependent variable and the independent variable is expressed as $Y = f(x_1, x_2, \ldots, x_n)$, and Eq. (5) shows the calculation of the response value $y(x)$.

$$y(x) = \beta_0 + \sum_{i=1}^{p} \beta_i X_i + \sum_{i=1}^{p} \sum_{j=1,i<j}^{p} \beta_{ij} X_{ij} + \sum_{i=1}^{p} \beta_{ij} X_i^2 + \varepsilon \tag{5}$$

where Y and X denote the dependent and independent variable, respectively. β_0 denotes the constant term. β_{ij} and X_{ij} denote the linear and interaction effects, respectively. ε denotes the error term.

3.3.3. Multiple stepwise regression analysis method

Multiple stepwise regression analysis can be used to represent the relationship between a dependent variable and multiple independent variables, and Eq. (6) shows its mathematical expression.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_p X_p + \varepsilon \tag{6}$$

where Y and X_1, X_p denote the dependent and independent variable, respectively. β_0 is the constant item. $\beta_1 \ldots \beta_p$ is the coefficient of the independent variable. ε represents the error term, and p is the number of independent variables. In Eq. (7), by substituting the experimental data into the regression equation, different regression models can be obtained.

$$Y = X\beta + \varepsilon = \left(Y_1 Y_2 \ldots Y_n\right)', X = \begin{bmatrix} 1 X_{11} \ldots X_{1p} \\ 1 X_{21} \ldots X_{2p} \\ \vdots \; \vdots \quad \vdots \\ 1 X_{n1} \ldots X_{np} \end{bmatrix}, \quad \beta = \left(\beta_0 \beta_1 \ldots \beta_p\right)', \varepsilon = \left(\varepsilon_0 \varepsilon_1 \ldots \varepsilon_p\right)' \tag{7}$$

where X represented the regression design matrix $n \times (p+1)$ in Eq. (7), and β represents the overall coefficient of the regression equation. In this experiment, the yield rate of runoff and sediment are the two main dependent variables, and vegetation pattern is the independent variable.

4. Quantitative analysis of factors related to different vegetation patterns and soil remediation at the slope scale

4.1. Effects of different vegetation patterns

4.1.1. Research of different coverage degrees about initial runoff time

Slope runoff needs to go through multiple steps to start the initial runoff. The degree of mixed vegetation coverage can change the physical properties of the slope soil, thereby affecting the infiltration process of rainwater in the soil, leading to the change of runoff generation time on the slope. Table 2 shows the influence of different coverage of mixed vegetation on the initial runoff time when the rainfall intensity and slope are different.

In Table 2, when the rainfall intensity and slope remain unchanged, the mixed vegetation coverage is proportional to the initial runoff time, and the initial runoff time prolongs as the coverage increases. Compared with the bare land without vegetation coverage, the initial runoff time of the former increased by 0.15 to 2.43 min. The increase time of the initial runoff time is 2.43 min at most when the rainfall intensity is 25 mm/h, the slope is 8°, and the coverage is 90%. In the study of the relationship between rainfall intensity and runoff time, the initial runoff time was significantly shortened with the increase of rainfall intensity ($p < 0.05$). When the rainfall intensity increased from 25 to 55 mm/h and the slopes were 8°, 13° and 18°, the initial runoff time of 90% mixed vegetation coverage decreased by 1.66 min, 1.67 and 1.91 min, respectively, and the initial runoff generation time of bare land without plant cover decreased by 1.37, 1.33 and 1.34 min, respectively. When the rainfall intensity increased from 55 to 85 mm/h and the slopes were 8°, 13° and 18°, the initial runoff time of 90% mixed vegetation coverage decreased by 0.27, 1.34 and 1.24 min, respectively, and the initial runoff generation time of bare land without plant cover decreased by 0.40, 0.45 and 0.45 min, respectively. When the rainfall intensity and coverage are consistent, the increase of slope will reduce the initial runoff time, but the effect of slope is less than that of rainfall intensity.

4.1.2. Effects of different relative distances on initial runoff time

Fig. 2 shows the effect of different relative distances on the initial flow time. From Fig. 2, in the case of 40% and 60% coverage, the increase of rainfall leads to initial runoff time's significant decrease ($p < 0.05$). When the coverage degree changed from 40% to 60%, the initial flow time increased to varying degrees. When the rainfall intensity and slope are consistent, the increase of the relative distance leads to the

Table 2
Effect of different coverage of mixed vegetation on initial runoff time/min

Rainfall intensity	Slope	Vegetation coverage				
		0	10%	40%	60%	90%
25 mm/h	8°	2.61 ± 0.21Ae	3.02 ± 0.27Af	3.45 ± 0.45Ag	4.16 ± 0.58Ah	5.06 ± 0.22Am
	13°	2.57 ± 0.22Ae	2.94 ± 0.25Af	3.14 ± 0.47Af	3.67 ± 0.69Ag	4.82 ± 0.41Ah
	18°	2.50 ± 0.19Ae	2.78 ± 0.19Ae	3.05 ± 0.36Af	3.21 ± 0.23Af	4.91 ± 0.37Ag
55 mm/h	8°	1.25 ± 0.12Be	1.73 ± 0.09Bfg	1.91 ± 0.27Bg	1.95 ± 0.14Bg	3.29 ± 0.25Bh
	13°	1.24 ± 0.05Be	1.68 ± 0.10Bfg	1.79 ± 0.10Bg	1.78 ± 0.33Bg	3.15 ± 0.45Bh
	18°	1.16 ± 0.08Be	1.62 ± 0.25Bf	1.63 ± 0.33Bf	1.68 ± 0.21Bg	3.01 ± 0.39Bh
85 mm/h	8°	0.84 ± 0.16Ce	1.58 ± 0.12Cf	1.66 ± 0.21Cf	2.37 ± 0.24Cg	3.12 ± 0.32Ch
	13°	0.79 ± 0.11Ce	1.29 ± 0.09Cf	1.43 ± 0.14Cf	1.52 ± 0.09Cg	1.81 ± 0.15Ch
	18°	0.71 ± 0.27Ce	0.86 ± 0.08Cf	1.36 ± 0.36Cg	1.55 ± 0.18Ch	1.77 ± 0.14Cm

Note: When the vegetation coverage and slope in the same column are the same, the same capital letters mean no significant difference existing between the initial runoff time and rainfall intensity ($p > 0.05$), and different capital letters indicate the initial runoff. There is a significant difference between time and rainfall intensity ($p < 0.05$); when the rainfall intensity and slope are the same in the same row, the same lowercase letters mean no significant difference existing between vegetation coverage and initial runoff time ($p > 0.05$), different lowercase letters indicate that there is a significant difference between initial vegetation coverage and initial runoff time ($p < 0.05$).

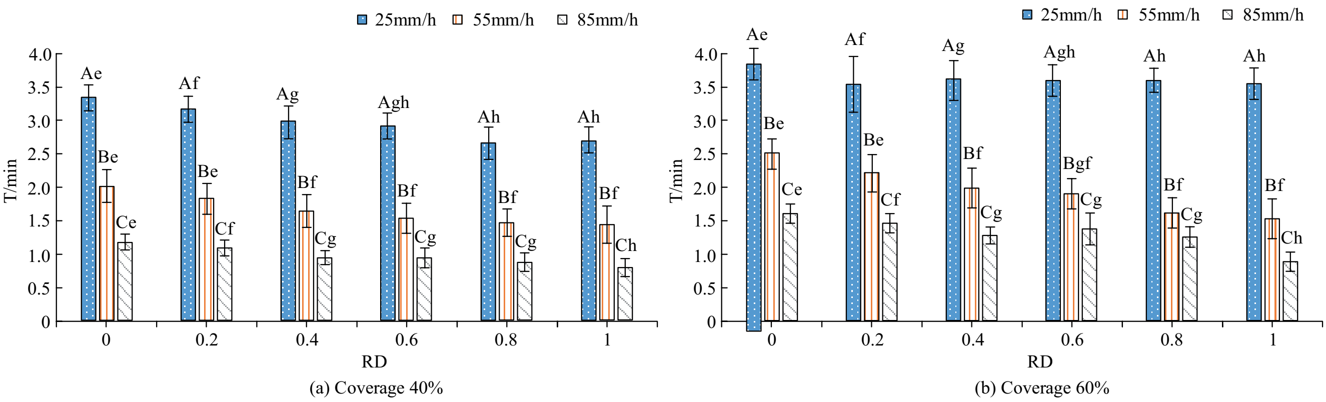

Fig. 2. Influence of different relative distances on the initial runoff generation time. Note: When the relative distances are the same, the same uppercase letters mean no significant difference existing between the initial runoff time and rainfall intensity ($p > 0.05$), and different capital letters mean no significant difference existing between the initial runoff time and rainfall intensity. When the rainfall is the same, the same lowercase letters mean no significant difference existing between the relative distance and the initial runoff time ($p > 0.05$), and the different lowercase letters indicate the relative distance and the initial runoff time. There was a significant difference between flow times ($p < 0.05$).

decrease of the initial runoff time. In the case of coverage of 40% and 60%, the initial delivery time at relative distances of 0 and 0.2 was significantly longer than that at other relative distances ($p < 0.05$), and the change of initial delivery time decreases with increasing relative distance. This may be because the closer the vegetation is to the outlet of the slope, the higher the soil infiltration and the smaller the runoff.

4.1.3. Effects of different vegetation patterns on initial runoff time

For the four different vegetation patterns of horizontal stripes, grid patterns, S-roads, and random patches, the experiment carried out a study on the influence of different patterns on the initial runoff time.

From Fig. 3, under the coverage of 40% and 60%, different vegetation patterns can prolong the initial runoff time ($p < 0.05$). In Fig. 3a, when the coverage is 40%, the initial runoff generation time of the random patch pattern is significantly higher than that of other vegetation patterns, and the effect of delaying runoff is better. In Fig. 3b, when the coverage is increased to 60%, there is no significant difference between the initial runoff generation time of the random patch pattern and the pattern of the square pattern and the horizontal strip patch. It shows that the influence of vegetation patch pattern on initial runoff generation time is not only caused by patch type, but also by coverage. To sum up, among the four vegetation patterns, the effect of the S road on the prolongation of the initial runoff time was smaller than that of the other vegetation patterns ($p < 0.05$). When the coverage is 40% and 60%, the runoff retarding effect of random patches is the best.

4.1.4. Influence of different coverage degrees on runoff and sediment amount

With the change of the experimental conditions, the runoff and sediment amount on the slope changes. Fig. 4 shows the effect of mixed vegetation with different coverage on the runoff and sediment.

In Fig. 4, when the slope is consistent with the rainfall intensity, the increase of mixed vegetation coverage can effectively reduce the amount of runoff sediment. In Fig. 4b, when the mixed vegetation coverage was 20%, the average runoff sediment content was 7.6% lower than that of the bare land. When the coverage of mixed vegetation is 90%, the average sediment content is 27.8% lower than that of the bare land. In Fig. 4b, when the coverage of mixed vegetation increases, the sediment content of runoff under different slopes decreases significantly, and the sediment content of runoff decreases the most when the slope is 8°. In Fig. 4c, when the rainfall intensity is increased to 85 mm/h, the runoff sediment amount decreases with the increase of coverage, indicating that the increase of plant coverage can effectively reduce the runoff sediment amount. According to the comprehensive contents in Fig. 4a–c, when the slope is consistent with the coverage, the increase of rainfall intensity can significantly increase the runoff sediment content, resulting in Soil damage is further aggravated. Since there is a certain linear correlation between slope runoff sediment volume (T) and mixed vegetation coverage (C) in Fig. 4, the experiment conducted a linear regression analysis on the two, and Table 3 shows the results.

From the fitting Eqs. (8)–(16) in Table 3, there is a good linear relationship between T and C. When the rainfall degree increases, the coefficient of the fitting equation decreases, indicating that the linear relationship between T and C gradually decreases with the change of the rainfall degree, but when the rainfall degree is the same, the coefficient of the fitting equation does not change significantly. The regression equation in Eq. (17) can be obtained by performing multiple regression analysis on the influencing factors rainfall intensity (R), slope (S) and coverage (C) and runoff sediment volume (T).

$$T = 56.69R^{-0.73} \times S^{-0.217} \times (1-C)^{-0.279}, R^2 = 0.967 \tag{17}$$

where T decreases with the increase of R and S, indicating that the initial runoff time is accelerated by the increase of rainfall intensity.

4.1.5. Influence of different relative distances on runoff and sediment amount

In Fig. 5, the effect of different relative distances on the amount of runoff sediment. When the rainfall intensity

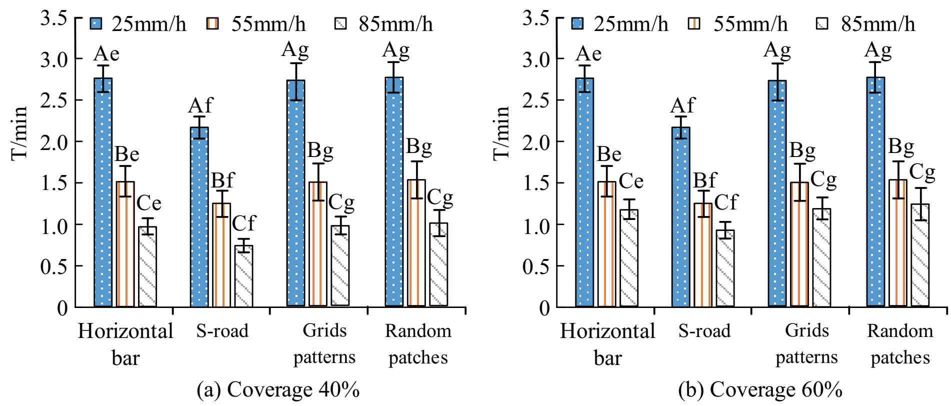

Fig. 3. Effect of different vegetation patterns on initial runoff time.

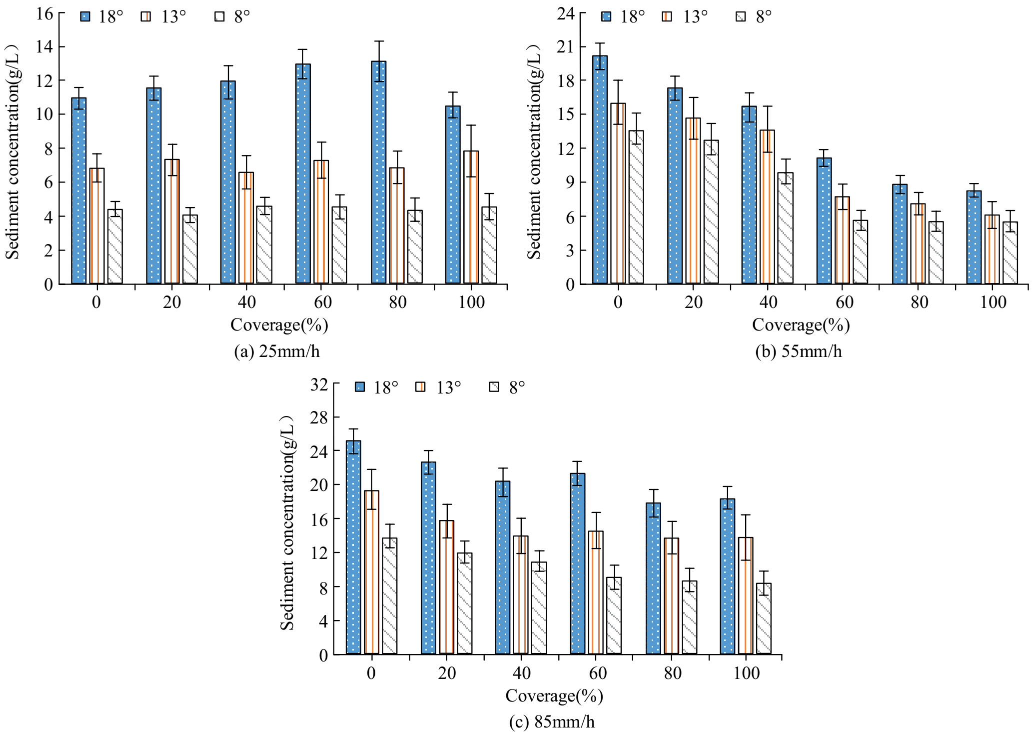

Fig. 4. Influence of different coverage.

Table 3
Linear regression analysis of runoff sediment volume and mixed vegetation coverage

Rainfall intensity	Slope	Fitting equation		R^2
25 mm/h	8°	$T = 2.379e^{0.742C}$	(8)	0.995
	13°	$T = 2.284e^{0.648C}$	(9)	0.951
	18°	$T = 2.139e^{0.657C}$	(10)	0.901
55 mm/h	8°	$T = 1.197e^{0.943C}$	(11)	0.897
	13°	$T = 1.105e^{0.917C}$	(12)	0.854
	18°	$T = 1.063e^{0.896C}$	(13)	0.859
85 mm/h	8°	$T = 0.901e^{1.351C}$	(14)	0.907
	13°	$T = 0.877e^{0.957C}$	(15)	0.823
	18°	$T = 0.678e^{1.065C}$	(16)	0.899

increases, the content of runoff sediment tends to increase; the increase of the relative distance leads to an increase in the amount of runoff sediment to a certain extent; the increase in the coverage of mixed vegetation can reduce the amount of runoff sediment. sand content. When the mixed vegetation coverage is 40%, the overall runoff and sediment amount at a relative distance of 0 is 13.7%, which was less than that at a relative distance of 1.

4.1.6. Influence of different vegetation patterns on runoff and sediment amount

For the four different vegetation patterns of horizontal stripes, grid patterns, S-roads and random patches, the experiment carried out research on the influence of different patterns on the amount of runoff and sediment. From

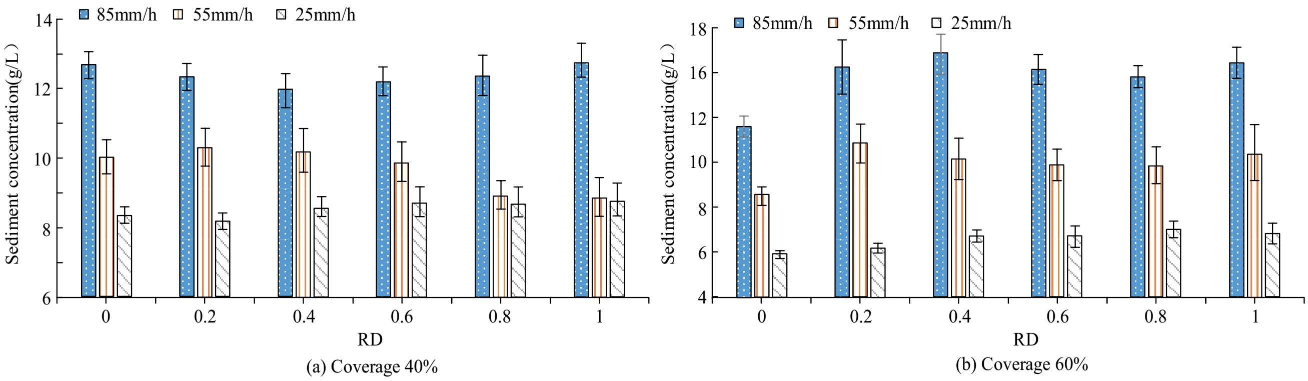

Fig. 5. Influence of different relative distance.

Fig. 6, when the coverage is 40% and 60%, vegetation patterns can make the amount of runoff and sediment reduce. Among the four vegetation patterns, the effect of the S-roads was smaller than that of other vegetation patterns. When the coverage is 40% and 60%, the sediment reduction effect of random patches is the best.

4.2. Hydrodynamic characteristics of slope runoff with different mixed vegetation patterns

4.2.1. Effects of different coverage degrees on runoff velocity

Runoff velocity is an important hydrodynamic feature that affects soil erosion and sediment transfer. Further analysis of the impact of different mixed vegetation patterns on runoff velocity is required in order to take appropriate measures to delay soil erosion. In Fig. 7, taking the rainfall intensity of 25 mm/h as an example, it shows the change diagram of different mixed vegetation coverage and water flow rate. When the rainfall intensity is 25 mm/h, in the mixed vegetation coverage of 0%–90%, the runoff velocity gradually increases with the change of rainfall time. With the increase of mixed vegetation coverage, the runoff velocity decreased gradually. The average runoff velocity was reduced by 58.2% when the mixed vegetation coverage was increased to 90% compared to the bare land with 0 coverage.

4.2.2. Effects of different relative distances on runoff velocity

In the experiment, the influence of different relative distances of mixed vegetation on the runoff velocity was studied when the coverage was 40% and 60%. Fig. 8 shows

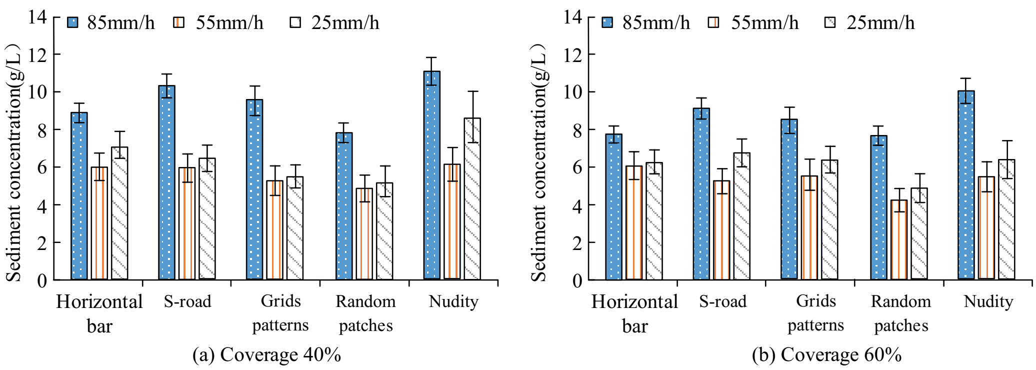

Fig. 6. Influence of different vegetation patterns.

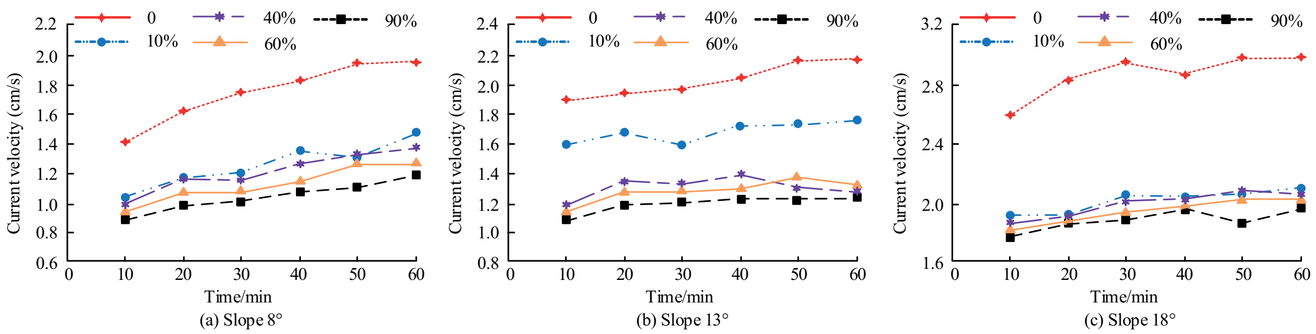

Fig. 7. Change chart of different mixed vegetation coverage and water velocity.

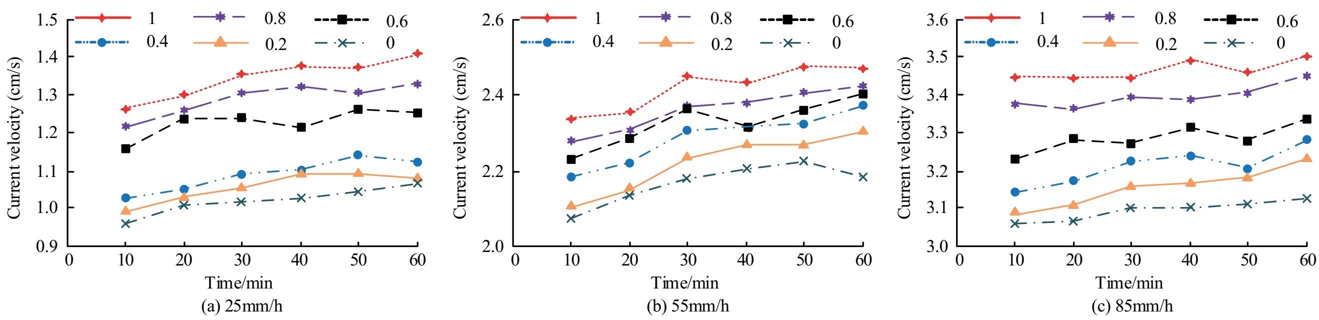

Fig. 8. Influence of different relative distances on runoff velocity.

the variation of runoff velocity when the coverage is 40% and the slope is 13°. When the coverage is 40% and the slope is 13°, as the duration of rainfall increases, the change of runoff velocity is proportional to the relative distance. When the plant coverage is 40% and 60%, when the relative distance is less than 0.4, the runoff velocity has a significant reduction effect.

4.2.3. Influence of different vegetation patterns on runoff velocity

Under the condition that the slope is 13° and the coverage of mixed vegetation is 40% and 60%, the experiment has carried out the research on the influence of different mixed vegetation patterns on the runoff velocity under different rainfall intensities. Fig. 9 shows the change of runoff velocity with an example of 40% coverage.

In Fig. 9 a represents the bare land, *B* represents the S road pattern, *C* represents the horizontal bar pattern, *D* represents the grid pattern, and *E* represents the random mixed vegetation pattern. The runoff velocity of bare land is the largest, and the runoff velocity of other mixed vegetation patterns is lower significantly ($p < 0.05$). Among them, the overall runoff velocity of the random patch pattern is the smallest, which is 38.2% lower than that of the bare land.

4.3. Mechanism of soil erosion on slopes with different mixed vegetation patterns

4.3.1. Unit runoff power of different mixed vegetation coverage

The process of soil erosion is affected by runoff, and the unit runoff power can be used to explain the mechanism of the physical process of slope soil erosion. By changing the coverage of different mixed plants, Table 4 shows the results of unit runoff power and variance analysis under different coverage.

The unit water flow power under different coverage degrees of 10%–90% is 22.98% to 47.36% lower than that of bare land. The variance analysis results of unit water flow power under different coverage showed that the mixed vegetation coverage of 10%–90% was significantly smaller than the unit runoff power of bare land ($p < 0.05$). In addition, when the slope is the same, the increase of rainfall intensity also leads to the increase of unit runoff power.

4.3.2. Unit runoff power of different mixed vegetation relative distances

Under the condition of different relative distances, the unit runoff power was analyzed in Table 5. The unit runoff power when the relative distance is 0.2 is smaller than the unit runoff power at other relative distances, and the unit runoff power is arranged in ascending order as RD = 0.2 < RD = 0.4 < RD = 0 < RD = 0.6 < RD = 0.8 < RD = 1. The results of variance analysis showed that the unit runoff power when RD = 0, RD = 0.2 and RD = 0.4 was significantly smaller than that when RD = 0.6, RD = 0.8 and RD = 1 ($p < 0.05$). In the case of the same mixed plant coverage, when the rainfall intensity increases, the unit runoff power increases. The unit runoff power decreases as the coverage increases under the same rainfall intensity.

4.3.3. Unit runoff power of different mixed vegetation patterns

Table 6 shows the influence of different patterns of mixed vegetation on unit runoff power and the results of variance analysis. Among all the mixed vegetation patterns, the unit runoff power has the smallest value in the random pattern, followed by the unit runoff power in the matt pattern, and the largest in the bare land. When the mixed vegetation coverage was 40%, there were significant differences in unit runoff power among different patterns ($p < 0.05$). When

Table 4
Result of unit flow power and variance analysis under different coverage

Rainfall intensity	Slope	Vegetation coverage				
		0%	10%	40%	60%	90%
25 mm/h	8°	0.0025a	0.0016b	0.0016b	0.0015c	0.0014d
	13°	0.0043a	0.0031b	0.0024c	0.0023d	0.0023d
	18°	0.0082a	0.0051b	0.0049c	0.0048d	0.0046e
55 mm/h	8°	0.0043a	0.0031b	0.0029c	0.0025d	0.0017e
	13°	0.0076a	0.0051b	0.0046c	0.0039d	0.0036e
	18°	0.0127a	0.0108b	0.0107b	0.0054c	0.0052d
85 mm/h	8°	0.0055a	0.0049b	0.0047c	0.0044d	0.0031e
	13°	0.0102a	0.0081b	0.0072c	0.0065d	0.0059e
	18°	0.0168a	0.0138b	0.0123c	0.0113d	0.0099e

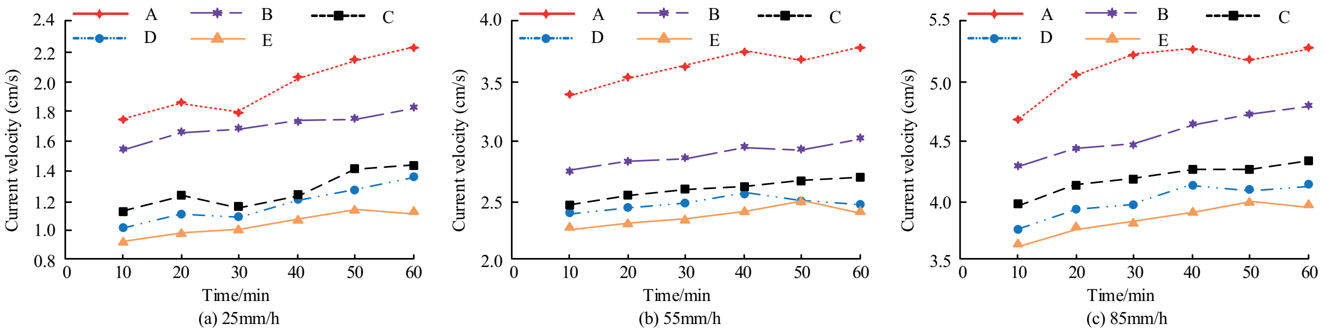

Fig. 9. Effects of different vegetation patterns on runoff velocity.

the mixed vegetation coverage was 60%, there was no significant difference in the unit runoff power between the horizontal and grid patterns ($p > 0.05$).

5. Analysis of the optimal configuration of mixed vegetation on the slope scale

5.1. Method analysis of mixed vegetation coverage on the slope

Soil remediation on the has significant improvement on Loess Plateau's ecological environment. To prevent and control soil erosion and realize soil remediation, this experiment uses the response surface analysis method to optimize the coverage of mixed vegetation on the slope. According to the multiple regression analysis results in Section 4.1 – Effects of different vegetation patterns, the degree of rainfall is the primary factor affecting the sediment yield on the slope. On this basis, the coverage is divided according to the level of rainfall intensity, and Table 7 shows the results of response surface analysis.

When rainfall intensity is on the condition of 85 mm/h, the slope of the mixed vegetation needs to be less than 10.3° and the coverage must be greater than 90% to achieve the purpose of soil and water conservation. When rainfall intensity is on the condition of 55 mm/h, it is necessary to satisfy that the coverage of mixed vegetation is greater than 90 and the slope is less than 18.6°, or the coverage is greater than 78% and the slope is less than 17°, or the coverage is greater than 69.3% and the slope is less than 15°, or the coverage. The degree of coverage is greater than 35.6% and the slope is less than 14°, or the coverage is greater than 9.7% and the slope is less than 12°, or the slope is less than 15° and there is no plant coverage. When rainfall intensity and slope are 25 mm/h and below 20° separately, the purpose can be achieved if the coverage of mixed vegetation is higher than 5%. The Loess Plateau's slope is about 15° generally. According to the statistics of rainfall intensity in this area for many years, when the rainfall intensity is 55 mm/h, the coverage of 69.3% can be considered as the optimal coverage of mixed vegetation.

5.2. Quantitative comparison of relative distances of mixed vegetation on slopes

In the experiments in Section 4, the relative distance has an important influence on the physical properties of the slope soil. The increase of the relative distance will lead to the trend of first decrease and then increase of slope runoff and

Table 5
Results of unit runoff power of different mixed vegetation relative distance

Vegetation coverage	Rainfall intensity	Relative distance					
		0	0.2	0.4	0.6	0.8	1
40%	25 mm/h	0.0026a	0.0025a	0.0025a	0.0029b	0.0031c	0.0032d
	55 mm/h	0.0054a	0.0051b	0.0054c	0.0055d	0.0055d	0.0057e
	85 mm/h	0.0076a	0.0072b	0.0074c	0.0077d	0.0081e	0.0083f
60%	25 mm/h	0.0025a	0.0024b	0.0024b	0.0026c	0.0027e	0.0028f
	55 mm/h	0.0041a	0.0040b	0.0041c	0.0044d	0.0046e	0.0046e
	85 mm/h	0.0072a	0.0069b	0.0071c	0.0074d	0.0074d	0.0075e

Table 6
Results of unit runoff power of different mixed vegetation pattern

Vegetation coverage	Rainfall intensity	Vegetation patch type				
		Nudity	Horizontal bar	Grid patterns	S-road strips	Random patches
40%	25 mm/h	0.0049a	0.0031b	0.0029c	0.0036d	0.0027e
	55 mm/h	0.0085a	0.0056b	0.0054c	0.0063d	0.0053e
	85 mm/h	0.0113a	0.0086b	0.0084c	0.0089d	0.0080e
60%	25 mm/h	0.0049a	0.0027b	0.0027b	0.0028c	0.0026d
	55 mm/h	0.0085a	0.0046b	0.0046b	0.0048c	0.0043d
	85 mm/h	0.0113a	0.0078b	0.0078b	0.0081c	0.0074d

Table 7
Results of response surface analysis

Rainfall intensity	85 mm/h	55 mm/h						25 mm/h	
Slope optimization	<10.3°	<17.8°	<17°	<15°	<14°	<12°	<11.2°	<20°	<17.6°
Coverage optimization	>90%	>90%	>78%	>69.3%	>35.6%	>9.7%	>0%	>5%	>0%

sediment yield, but there are some differences in the results under different conditions. Based on the existing experiments, when the relative distance is 0.2, the change of soil physical properties is small. Since the previous experimental results show that the relative distance has a certain linear relationship with the sediment yield, the linear distance function is used to further optimize the relative distance between 0.2 and 1.

To further determine the optimal location of vegetation space, the linear regression equation in Table 8 can be obtained by regression analysis of relative distance and runoff and sediment yield. From Table 8, there is a linear correlation between the relative distance and the runoff and sediment yield. Combined with the sediment yield on the slope when RD = 0, the relative distance of mixed vegetation can be determined. When the coverage is 40%, the relative distance can reduce runoff within the range of 0–0.35, and the relative distance can reduce sediment within the range of 0–0.30. When the coverage is 60%, the relative distance can reduce runoff within the range of 0–0.42, and the relative distance can reduce sediment within the range of 0–0.22.

5.3. Optimal allocation of patch patterns of mixed vegetation on slopes

In the existing research, there is little information on the quantitative study of the mixed vegetation pattern on the slope. To further study the effect of the mixed vegetation pattern on soil restoration, in this study, different pattern indexes were selected to evaluate the horizontal strips and fields in the experiment. Different pattern indexes were selected to conduct quantitative analysis on the pattern of four vegetation types. The main selected pattern indexes include largest patch index (LPI), patch density (percentage of landscape, PLAAND), patch density index (patch density, PD), number of patches (NP), edge density (ED), landscape shape index (landscape similarity index, LSI), aggregation index (AI), connectivity index (patch cohesion index, COHESION), landscape split index (landscape division index, DIVISION). The calculation of the pattern index is carried out through the artificial rainfall experiment carried out under the coverage of 60% in the study in Section 4. In Table 9, correlation analysis was carried out between the calculated results and the runoff and sediment production rates.

The runoff rate and sediment production rate have a significant negative correlation with the LSI index at the level of 0.05, a significant negative correlation with the COHESION and PD index at the level of 0.01, and a significant negative correlation with the DIVISION index at the level of 0.01. There is a significant positive correlation at the level. The connectivity of the mixed vegetation patch is better; the density of the patch is greater. The shape of the

Table 8
Optimization results of relative distance

Index	Coverage	Rainfall intensity	Fitting function	R^2	Optimize relative distance
Runoff yield	40%	25 mm/h	$y = 7.258x + 9.574$	0.953	0–0.35
		55 mm/h	$y = 9.327x + 38.952$	0.951	0–0.26
		85 mm/h	$y = 11.996x + 42.767$	0.941	0–0.21
	60%	25 mm/h	$y = 4.652x + 8.901$	0.903	0–0.42
		55 mm/h	$y = 7.968x + 36.557$	0.947	0–0.36
		85 mm/h	$y = 10.369x + 53.606$	0.927	0–0.39
Sediment yield	40%	25 mm/h	$y = 0.0069x + 121.36$	0.947	0–0.30
		55 mm/h	$y = 129.65x + 317.42$	0.991	0–0.22
		85 mm/h	$y = 181.26x + 702.81$	0.972	0–0.28
	60%	25 mm/h	$y = 34.357x + 68.761$	0.903	0–0.20
		55 mm/h	$y = 57.692x + 179.30$	0.873	0–0.22
		85 mm/h	$y = 180.69x + 653.87$	0.839	0–0.20

Table 9
Correlation analysis results

Pattern index	Plan	LPI	LSI	ED
Flow rate	–0.589	–0.439	–0.729*	–0.517
Sand rate	–0.632	–0.532	–0.763*	–0.543
Pattern index	AI	COHESION	DIVISION	PD
Flow rate	0.579	–0.938**	0.856**	–0.839**
Sand rate	0.542	–0.941**	0.877**	–0.864**

Note: *significantly correlated at 0.05 level (both sides), **significantly correlated at 0.01 level (both sides);
Largest patch index (LPI), patch density (PLAND), patch density index (PD), patch number (NP), edge density (ED), landscape similarity index (LSI), aggregation index (AI), connectivity index (COHESION), landscape division index (DIVISION).

patch is more complex, the runoff and sediment yield rate is lower, which can significantly reduce the accumulation of sediment.

6. Conclusion

Soil erosion can affect Loess Plateau's ecological environment, and the appropriate vegetation restoration model has a positive effect on the soil restoration of the slopes of the Loess Plateau. In the previous experiments, artificial rainfall experiments were used to quantitatively analyze different mixed vegetation patterns. From the results, slope and rainfall intensity are significant factors affecting the initial runoff time of slope runoff and the amount of sediment in slope runoff. Increasing the coverage of mixed plants can make runoff and sediment's amount reduce effectively, and the reduction of runoff and sediment is more obvious when the relative distance is 0.2. The random patch pattern had the best effect on improving the initial runoff time and the runoff sediment concentration. In hydrodynamic studies on slope runoff, rainfall intensity has the greatest impact. The increase of mixed vegetation coverage reduces the unit runoff power, and there is a direct proportional relationship between the unit relative vegetation distance and the unit runoff power. The configuration optimization of slope mixed vegetation coverage, relative distance and patch pattern was carried out. When the rainfall intensity is 55 mm/h, the best coverage when the slope is below 15° is 69.3%; the relative distance is better when it is 0.2, and the optimal relative position for runoff and sediment reduction is 0–0.22; when The better the connectivity of the mixed vegetation patch, the greater the density of the patch, and the more complex the shape of the patch, the lower the runoff and sediment yield rate, which has a significant effect on reducing the accumulation of sediment. In this experiment, the soil erosion in the watershed of the Loess Plateau was quantitatively analyzed. Based on the results, the key indexes affecting soil restoration on the slope were screened out, and a better mixed vegetation optimization pattern on the slope was obtained. However, the selected indicators are not yet comprehensive, and further evaluation indicators need to be added to analyze different influencing factors. In addition, the types and proportions of mixed vegetation have not yet been subdivided, and further research is needed in subsequent experiments, hoping to provide more theoretical and experimental data support for soil restoration on the Loess Plateau.

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