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Vegetation restoration restricts rill development on dump slopes in coalfields

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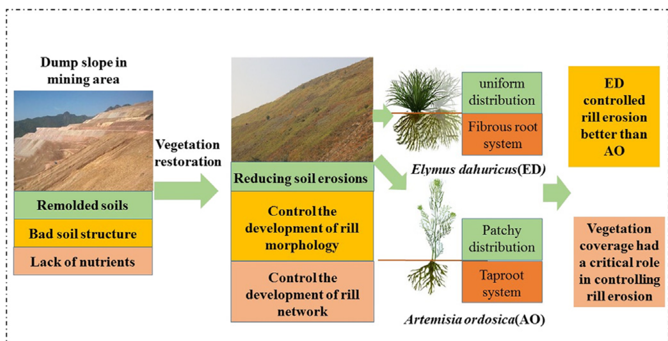
HIGHLIGHTS

- Temporal effect revegetation on rill erosion of dump slope was assessed.
- *Elymus dahuricus* controlled rill development better than did *Artemisia ordosica*.
- The rill-restricted effect of *Elymus dahuricus* weakened with recovery age.
- Vegetation coverage had a critical role in controlling rill erosion on dump slopes.

GRAPHICAL ABSTRACT



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ABSTRACT

Severe rill erosion on dump slopes poses a great threat to the ecological environment in mining areas. Vegetation restoration is an effective measure for controlling soil erosion on dump slopes. However, few studies have identified the long-term influence of vegetation restoration on rill development on dump slopes. Therefore, we investigated the rill development characteristics of dump slopes with three typical restoration models (CK: natural restoration; ED: *Elymus dahuricus*; and AO: *Artemisia ordosica*) and three recovery time (1 y, 3 y and 5 y). The results showed that vegetation adequately controlled rill erosion on dump slopes. ED and AO could effectively control the development of rills with widths >15 cm and depths of 10–20 cm. ED vegetation restoration inhibited the development rill morphology and network better than AO. The rill erosion modulus of the ED slope and AO slope decreased by 76.29%–90.77% and 46.66%–61.49%, respectively, compared with that of natural restoration slopes with recovery time of 1 y, 3 y, and 5 y. ED controlled rill erosion better than AO, but this effect gradually weakened with recovery time. Vegetation coverage contributed 34.99% of the total variation in rill morphology and was the main factor affecting the development of rills on dump slopes. Furthermore, vegetation coverage had a more important role in controlling rill development than did the root system on dump slopes. This study provides valuable information for optimizing vegetation construction for soil loss control on dump slopes.

1. Introduction

Soil erosion is one of the major challenges facing humankind (Pimentel et al., 1995). Land degradation caused by soil erosion seriously threatens the survival and safety of humankind (Rhodes, 2014). An estimated 60% of existing soil erosion has been induced by human activity (Yang et al., 2003). For example, degradation caused by human activity amounts to

Abbreviations: CK, natural restoration; ED, *Elymus dahuricus*; AO, *Artemisia ordosica*.

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approximately 3.3 million ha in China and is growing at an unprecedented rate of 0.14 million ha annually (China Agenda 21 Management Center, 1994), of which 0.02 million ha per year is caused by mining activities (Miao and Marrs, 2000). The mining process can not only destroy original landforms and vegetation but also cause severe pollution to water, air and soil. Coal mining is accompanied by serious soil erosion. The land degradation caused by opencast mining is 2–11 times that caused by underground mining (Miao and Marrs, 2000).Therefore, it is particularly urgent to restore abandoned land caused by coal mining.

Dumps are one of the most serious areas of erosion in opencast mining. Compared with natural soil, as remolded soil, dumps are more prone to soil erosion due to their worse soil physical structure (Bradshaw, 2000; Frouz et al., 2013; Zhao et al., 2013). Riley (1995) has also shown that unmanaged surfaces of dumps are 10–100 times more erodible than adjacent natural hillslopes. Rill erosion has been shown to be the main form and source of soil erosion on dump slopes (Shi et al., 2016). In addition, rills often develop very quickly (from a single rainfall event to a season) and can develop into gullies if sufficient runoff is available to continue their development (Hancock et al., 2008). As rills develop, more nutrients are washed away by runoff, which affects the long-term development of dumps (Polyakov and Lal, 2004). As a result, the land in dumping sites becomes increasingly barren over time, hindering vegetation growth (Zhang et al., 2015). Soil erosion caused by rill development also hinders the vegetation restoration of the dump and further induces soil erosion, which seriously threatens local ecological stability and economic security (Guerrero-Campo and Montserrat-Martí, 2004).

Vegetation restoration is a necessary strategy for ecological restoration and dump stability (Bao et al., 2012; Drazic et al., 2012; Sever and Makineci, 2009). However, natural vegetation restoration requires long succession times and complex processes such as alteration or destruction of macro- and micro-vegetation elements, the invasion of exotic species, destruction of soil stabilizers and increased erosion. (Lovich and Bainbridge, 1999). The natural restoration strategy cannot meet the actual needs of soil and water conservation in mining areas. Therefore, planting vegetation is very important for controlling dump slope erosion. Many researchers have analyzed the effects of different types of vegetation restoration on soil erosion, as well as the mechanisms by which vegetation inhibits soil erosion (Bochet et al., 1999; Cao et al., 2008; Casermeiro et al., 2004; Gu et al., 2013; Reubens et al., 2011). Soil erosion is usually negatively correlated with vegetation coverage (Krümmelbein et al., 2010; Zhang et al., 2011; Zuo et al., 2010). Vegetation coverage can reduce the kinetic energy of raindrops, protect the soil surface, and increase the surface roughness of the soil, thus hindering surface runoff, increasing the infiltration time, and reducing erosion (Zhang et al., 2015). Vegetation root systems can improve soil physical properties (soil structural stability and aggregate stability), which are closely related to soil erodibility, contributing to soil erosion control (Gao et al., 2009). Zhang and Zhou (2015) have shown that grassland aboveground parts can weaken rainfall energy and runoff erosion power, and grass roots were able to enhance soil anti-erodibility by improving soil properties and winding soil mass. Casermeiro et al. (2004) have also shown that Scrubland communities protect the soil in different ways including the interception of raindrops (which lowers their erosive capacity) and the provision of organic carbon (necessary for the formation of organomineral aggregates). Overall, previous studies on vegetation that controls soil erosion have focused on vegetation that protects the underlying surface and that improves soil erosion resistance (Casermeiro et al., 2004; Gao et al., 2009; Zhang et al., 2015; Zhang and Zhou, 2015). However, research on vegetation that controls soil erosion by influencing rill development is rare. In particular, on dump slopes, few kinds of vegetation can grow because of poor soils; rills develop rapidly; and soil erosion is serious (Frouz et al., 2013; Zhang et al., 2015). It is essential to study the influence of revegetation on rill development on dump slopes.

Therefore, this study investigated the rill development characteristics on 3 types of dump slopes (CK: natural restoration; ED: *Elymus dahuricus*; and AO: *Artemisia ordosica*) with three recovery time of 1 y, 3 y and 5 y. The development characteristics of the rill and the corresponding soil and vegetation indexes were measured and analyzed. The purpose of this study is (1) to reveal the development characteristics and temporal processes of rills with two vegetation restoration models and to identify the reducing benefit compared to natural restoration; (2) to explore the main factors that control rill development; and (3) to provide a theoretical basis for guiding vegetation restoration in mining areas.

2. Material and methods

2.1. Study area

The study was conducted in the Minda coal mine, which is located in Inner Mongolia, China (39°48′18″-39°51′47″N, 110°10′03″-110°12′56″ E). As of March 2020, the area of disturbed original landforms, damaged land and vegetation in this opencast coal mine had reached 546.54 hm^2, which caused an additional soil erosion of 46,533 t. The study area is part of the hill and gully region of the Loess Plateau of China and has a mid-temperate dry continental monsoon climate. The annual average temperature is 6.3 °C. The annual evaporation is 2100 mm. The mean annual precipitation is approximately 350 mm, with most of the total rainfall occurring between July and September in the form of short-duration, heavy rainstorms. Based on the classification system of the World Reference Base for Soil Resources (WRB), the soil type is Cumulic, which is characterized by a loose structure and complex particle composition. In this study area, vegetation cover is only herbaceous, and plant diversity is low. The main grass species include *Agriophyllum squarrosum* (L.) Moq., *Lotus Corniculatus L.*, ED and AO.

2.2. Site selection and investigation process

By conducting a field survey, the formation time, slope gradient and a series of slope parameters and vegetation restoration conditions of the dump slopes in the mining area were investigated. On the basis of statistics and analysis of the survey results, bare slopes (only natural restoration, no artificial vegetation) (Fig. 1a), ED slopes (artificial planting) (Fig. 1b) and AO slopes (artificial planting) (Fig. 1c) with vegetation recovery time of 1 y, 3 y and 5 y were selected.

In the study area, most heavy rainstorm events mainly occurred between July and September, and rill erosion mainly developed in this period. Therefore, the investigation was carried out in October 2020. On each selected slope, three plots with a length of 20 m and a width of 5 m were randomly set. A combination of visual and photographic methods was used to measure vegetation coverage (*VC*) in each plot. On each selected plot, five points were randomly selected, and the slope gradient (*SG*) was measured and averaged by using a slope meter. In each plot, a cross-section was set every 2 m in the downslope direction and was marked as L_1, L_2…, L_{10} (Fig. 2a). The middle position of each measuring section was selected, and the rills that did not pass through the midline of the slope section were disregarded. The length ($l_{i,j}$), top width ($w_{b-i,j}$), bottom width ($w_{t-i,j}$) and depth ($d_{i,j}$) of rill j were measured by a ruler in cross-section i (Fig. 2a). The average rill width (W) and depth (D) were calculated, and the results were grouped and counted. Three points in each slope section were randomly selected to collect approximately 200 cm^3 of topsoil. After natural air drying for one week, the soil was passed through a soil sieve with a diameter of 2 mm; the soil sample was ground and sampled by the quartering method; the soil particles were dispersed by dispersant and the organic matter was removed by H_2O_2. The volume percentage of each soil particle size fraction (International System) was determined by using a Mastersizer 2000 laser particle size analyzer (UK). The organic matter content was determined by external heating with potassium dichromate. In addition, the soil water content (*WC*) and soil bulk density (*BD*) were determined in each rill plot by the diagonal method. A total of 18 (0–30 cm) samples for *WC* and 18 samples *BD* were collected along with the plot diagonal. As a result, the average values of *WC* and *BD* were used to participate in the calculation. The basic information from 27 rill survey sites is provided in Table 1.

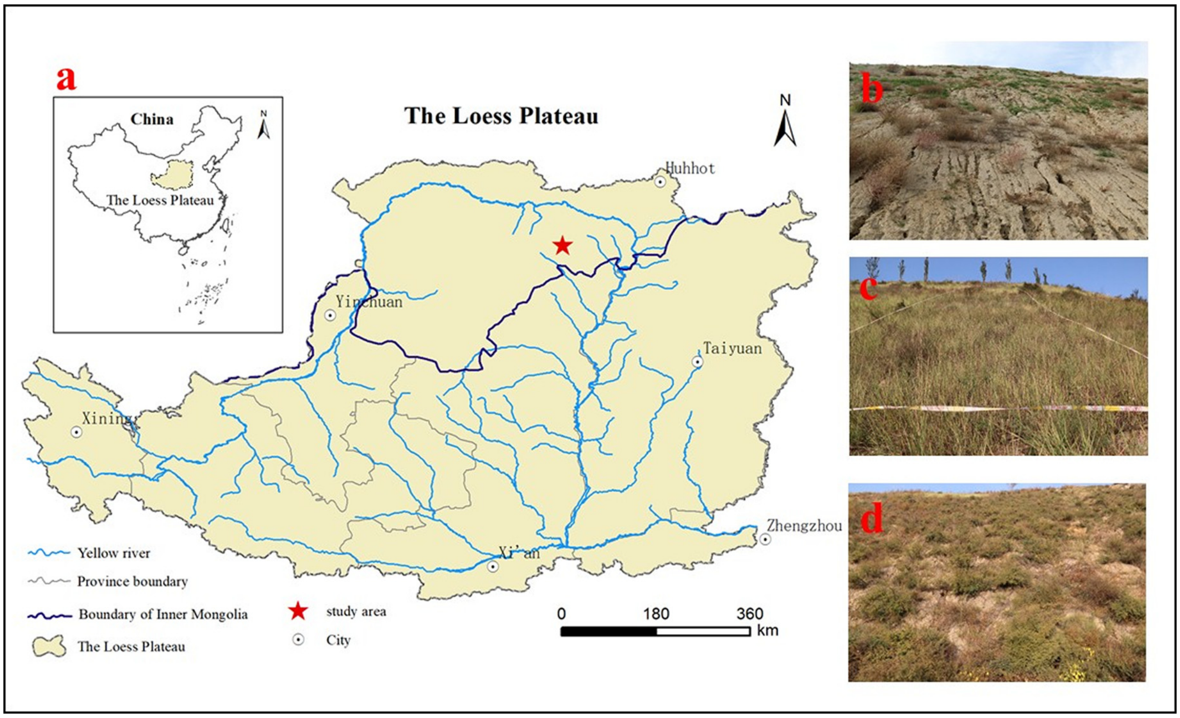

Fig. 1. Location of survey sites in the Loess Plateau of China (a) and three restoration conditions of dump slopes (b, c and d represent natural restoration, planting *Elymus dahuricus*, and planting *Artemisia ordosica, respectively*.

Three 1 m × 1 m quadrats were randomly selected in the rill survey plot, and plant roots (0–10 cm, 10–20 cm, and 20–30 cm) were collected by the excavation method (Fig. 2b and c). After excavation, the samples were collected by a special sampler with a length of 20 cm, width of 5 cm and depth of 5 cm, put into bags and numbered. Nine samples were collected from each quadrant; the soil samples were taken back to the laboratory; each soil sample was placed into the screen and washed repeatedly; and all the roots were removed. The root scanner Epson Twain pro (32 bit) and professional root morphology and structure analysis application system WinRhizo were selected to analyze the root parameters (Root length density (*RLD*), root surface area density (*RSAD*), root volume density (*RVD*)). The scanned fine root samples were placed in an 80 °C oven and dried to constant weight. The root mass was recorded and the root mass density (*RMD*) was calculated.

3. Calculation

3.1. Parameter calculation

Three basic rill indicators, including total rill length (L, m), average rill width (W, cm), and average rill depth (D, cm), were calculated as follows:

$$L = \sum_{i=1}^{m} \sum_{j=1}^{n} l_{i,j} \tag{1}$$

$$W = \frac{1}{2} \sum_{i=1}^{m} \sum_{j=1}^{n} \left(w_{t-i,j} + w_{b-i,j} \right) \tag{2}$$

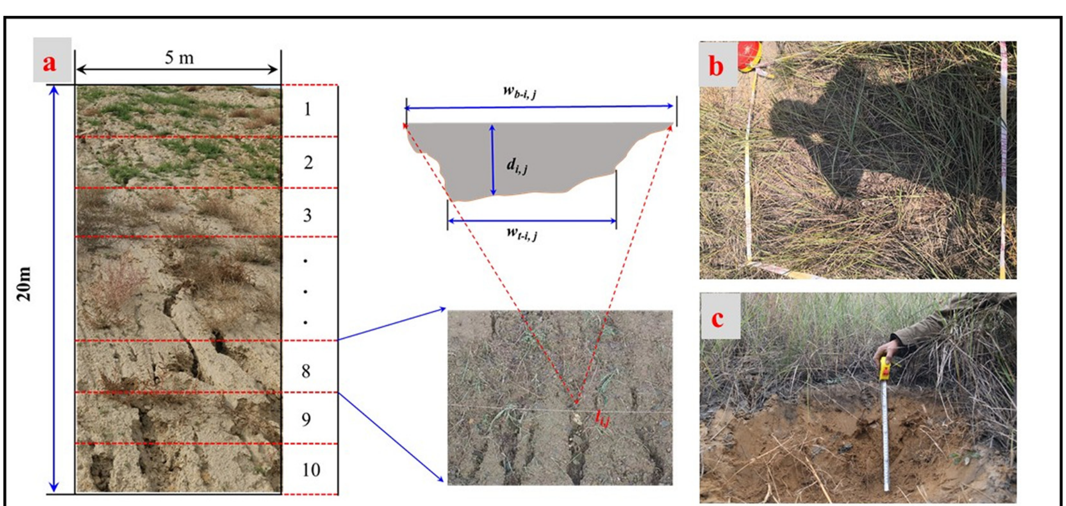

Fig. 2. Sketch of the rill cross-section measurement (a), vegetation quadrat (b) and soil sampling profile (c).

Table 1
Basic information of each site for rill measurement.

Site code	Recovery time (y)	Recovery model	*SG* (°)	*VC* (%)	Clay (%)	Silt (%)	Sand (%)	*BD* (g/cm^3)	*OM* (g/kg)	Slope direction
1	1	CK	34.12	5.43	4.73	18.14	77.13	1.51	3.58	South
2	1	CK	33.56	5.12	4.68	18.34	76.98	1.53	3.26	South
3	1	CK	33.87	4.98	5.12	17.24	77.64	1.53	3.64	South
4	3	CK	34.11	6.13	8.88	24.44	66.68	1.55	3.57	South
5	3	CK	33.52	6.24	7.69	22.19	70.12	1.50	3.76	South
6	3	CK	33.21	6.27	7.94	23.72	68.34	1.51	3.66	South
7	5	CK	33.24	7.13	9.94	24.17	65.89	1.60	3.46	South
8	5	CK	32.98	6.88	9.25	24.37	66.38	1.63	3.66	South
9	5	CK	34.15	7.21	8.96	23.9	67.14	1.54	4.32	South
10	1	ED	33.66	60.55	4.28	20.38	75.34	1.53	5.89	South
11	1	ED	33.25	63.14	4.69	22.15	73.16	1.53	5.93	South
12	1	ED	33.12	62.43	5.13	22.43	72.44	1.53	4.81	South
13	3	ED	33.13	66.54	8.69	28.06	63.25	1.57	6.26	South
14	3	ED	33.15	67.13	7.92	27.12	64.96	1.53	5.32	South
15	3	ED	33.12	66.28	8.33	26.53	65.14	1.53	5.67	South
16	5	ED	33.14	67.16	8.81	29.94	61.25	1.45	5.86	South
17	5	ED	33.21	68.34	9.64	27.91	62.45	1.53	6.25	South
18	5	ED	33.13	66.38	9.87	26.98	63.15	1.53	7.35	South
19	1	AO	34.12	43.26	5.02	19.64	75.34	1.51	3.16	South
20	1	AO	34.11	42.12	5.24	20.90	73.86	1.54	3.90	South
21	1	AO	34.13	41.35	5.31	20.50	74.19	1.55	3.60	South
22	3	AO	34.12	42.31	6.12	20.00	73.88	1.55	5.00	South
23	3	AO	34.15	42.56	6.13	20.71	73.16	1.50	3.31	South
24	3	AO	34.12	43.32	6.35	20.70	72.95	1.51	3.90	South
25	5	AO	34.13	44.31	7.81	26.03	66.16	1.42	5.55	South
26	5	AO	34.12	44.26	8.03	24.13	67.84	1.50	5.32	South
27	5	AO	34.16	43.57	8.26	24.43	67.31	1.51	4.00	South

Note: *SG*, *VC*, clay, silt, sand, *BD* and *OM* refer to the slope gradient, vegetation coverage, clay content, silt content, sand content, soil bulk density and soil organic matter, respectively. CK: natural restoration and ED: *Elymus dahuricus*

$$D = \sum_{i=1}^{m} \sum_{j=1}^{n} d_{i,j} \tag{3}$$

where $d_{i,j}$ refers to the depth of the *j*-th rill in the *i*-th measured section; $i = 1, \ldots, m$ represents the number of measured sections; and $j = 1, \ldots, n$ represents the number of rills in the *i*-th measured section, as shown in Fig. 2a.

Four derivative rill indexes, including rill width-depth ratio (*RR*), rill density (*RD*, m·m^{-2}), rill cleavage (rill coverage per unit area, *RDD*, %), and rill erosion modulus (*REM*, t·km^{-2}·y^{-1}), were calculated as follows:

$$RR = \frac{W}{D} \tag{4}$$

$$RD = \frac{L}{A} \tag{5}$$

$$RDD = \frac{L \cdot W}{A} \tag{6}$$

$$REM = \frac{L \cdot W \cdot D \cdot BD}{A \cdot t} \tag{7}$$

where *A* represents the area of the study area, which is 100 m^2; *BD* is the soil bulk density (kg·m^{-3}); and *t* is the recovery time (y).

The root mass density (*RMD*, g·cm^{-3}) was calculated as follows:

$$RMD = \frac{M}{V} \tag{8}$$

where *V* represents the volume of soil sample, which is 500 cm^3; and *M* is the root mass of root sample (g).

3.2. Statistical analysis

The Shapiro-Wilk test and Levene test were performed to detect the normality and homogeneity, respectively, of the data in each group. The two-way analysis of variance (ANOVA) was performed to evaluate the weather the influence of vegetation restorations or recovery time on rill development characteristics was significant. Detrended correspondence analysis (DCA) was employed to determine the feasibility of using redundancy analysis (RDA) to analyze the relationships between the rill development characteristics and the influencing factors by using the R software package "vegan" (v.2.5.7) (Oksanen et al., 2020). Furthermore, the R package "rdacca.hp" (v.1.0.3) (Lai et al., 2021) was utilized for hierarchical and variation partitioning of the RDA. Pearson correlation was applied to analyze the correlation between rill development characteristics (*W*, *D*, *RR*, *RD*, *RDD* and *REM*) and influencing factors (*WC*, *BD*, *OM*, clay content, silt content, sand content, *VC*, *RLD*, *RSAD*, *RVD* and *RMD*). For all statistical analyses, the significance was accepted at 5%. Overall, all statistical analyses and figure production were performed using R software (version R 3.6.3) and Origin software (version 2017, OriginLab Crop., Northampton, MA, USA), respectively.

4. Results

4.1. Rill distributions under different restoration conditions

The distribution of rill width under different restoration conditions is shown in Fig. 3. The rill width was divided into 6 classes (0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm, 20–25 cm and > 25 cm). The rills on the CK slope had widths concentrated within 15–20, 15–20, and > 25 cm, with rill numbers of 42.22%, 36.32% and 35.2% at recovery time of 1 y, 3 y and 5 y, respectively.

Rill width on the ED slope with recovery time of 1 y and 3 y was concentrated in the range of 5–10 cm, and their proportions in this range reached 48.05% and 53.57%, respectively. Rills on the ED slope had widths concentrated within 10–15 cm and had rill number proportions of 32.65% with the recovery time of 5 y. Rill width on the AO slope with a restoration age of 1 y was concentrated in the range of 10–15 cm, and their proportion was 58.73%. The distribution of rill width in the ranges of 10–15 cm, 15–20 cm and > 20 cm on the AO slope with a restoration age of 3 y was relatively homogeneous, and their distribution proportion was nearly 23%. The distribution of rill width on the AO slope with the recovery time of 5 y was bimodal and concentrated in the ranges of 15–20 cm and > 25 cm; their distribution proportions were 33.63% and 30.09%, respectively. In conclusion, the rill distribution on the AO slope was similar to that on the CK slope, and the rill width on the ED slope was mostly less than 15 cm.

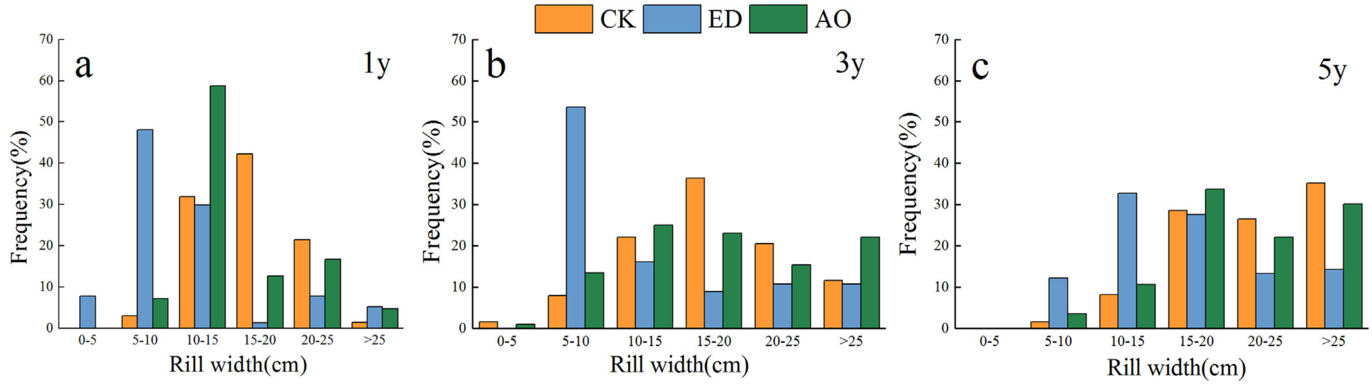

Fig. 3. Distribution of rill width under different restoration conditions. CK: natural restoration, ED: *Elymus dahuricus* and AO: *Artemisia ordosica*. Rill width distribution with recovery time of 1 year (a), rill width distribution with recovery time of 3 year (b), and rill width distribution with recovery time of 5 year (c).

The distribution of rill depth under different restoration conditions is shown in Fig. 4. The rill depth on the CK slope with recovery time of 1 y and 3 y was concentrated in the range of 15–20 cm, and the distribution proportions were 51.11% and 54.2%, respectively. The rill depth distribution on the CK slope with a recovery time of 5 y showed a bimodal pattern and was concentrated in the ranges of 10–15 cm and 20–25 cm, which had the same proportion (28.57%).

The rill depth on the ED slope was concentrated in the range of 5–10 cm, and their proportions were 45.45%, 57.14% and 58.16% with restoration ages of 1 y, 3 y and 5 y, respectively. The rill depth distribution on the ED slope with a recovery time of 1 y was bimodal, and the proportion of rill depth distribution was 45.45% in the ranges of 0–5 cm and 5–10 cm (Fig. 4a). The rill depth distribution on the AO slope with recovery time of 1 y and 3 y was also concentrated in the range of 5–10 cm (Fig. 4c), and the corresponding proportions were 53.17% and 38.46%, respectively. However, for the AO slope with a recovery time of 5 y, 71.68% of the rills had a depth of 10–15 cm. In conclusion, the rill depth on the ED slope was mostly in the range of 5–10 cm, and that on the AO slope were mostly in the range of 5–15 cm.

4.2. Rill development under different restoration conditions

4.2.1. Rill width, depth and width-depth ratio

Vegetation restorations and recovery time have significant effects on *W*, but interactive effects of vegetation restorations and recovery time are non-significant on *W* (Table 2). Compared with CK, ED significantly decreased the *W* by 37.2%, 25.75% and 20.29% for recovery time of 1 y, 3 y and 5 y, respectively (Fig. 5a). The *W* under AO restoration conditions with recovery time of 1 y and 5 y only decreased by 11.05% and 3.19%, respectively but increased by 2.53% with a recovery time of 3 y. The *W* increased significantly with recovery time under different restoration conditions.

Vegetation restorations and recovery time have significant effects on *D*, and the interaction of vegetation restorations and recovery time on *D* is also significant (Table 2). The average rill depth (*D*) was significantly reduced by vegetation restoration and increased significantly with recovery time under different restoration conditions (Fig. 5b). Compared with CK, ED significantly decreased the *D* by 55.58%, 31.91% and 47.99% for the recovery time of 1 y, 3 y and 5 y, respectively. AO significantly decreased the *D* by 30.47%, 14.58% and 31.13% for recovery time of 1 y, 3 y and 5 y, respectively.

Vegetation restorations and recovery time have no significant effects on *RR*, but the interaction of vegetation restorations and recovery time on *RR* is significant (Table 2). The *RRs* for the ED restoration model with recovery time of 1 y, 3 y and 5 y were 34.89%, 4.34% and 34.01%, respectively, which were higher than those of CK (Fig. 5c). The *RRs* for the AO restoration model with recovery time of 1 y, 3 y and 5 y were 32.44%, 21.69% and 16.67%, respectively, which were higher than those for CK.

4.2.2. Rill density and degree of rill dissection

Vegetation restorations and recovery time have significant effects on *RD* and *RDD*, and the interaction of vegetation restorations and recovery time on *RD* and *RDD* is also significant (Table 2). Vegetation restorations significantly reduced the *RD* and *RDD* (Fig. 6). The *RDD* under ED restoration conditions with recovery time of 1 y, 3 y and 5 y was 81.71%, 79.66% and 57.47%, respectively. Compared with CK, ED significantly decreased the *RD* by 70.81%, 74.72% and 44.97% for recovery time of 1 y, 3 y and

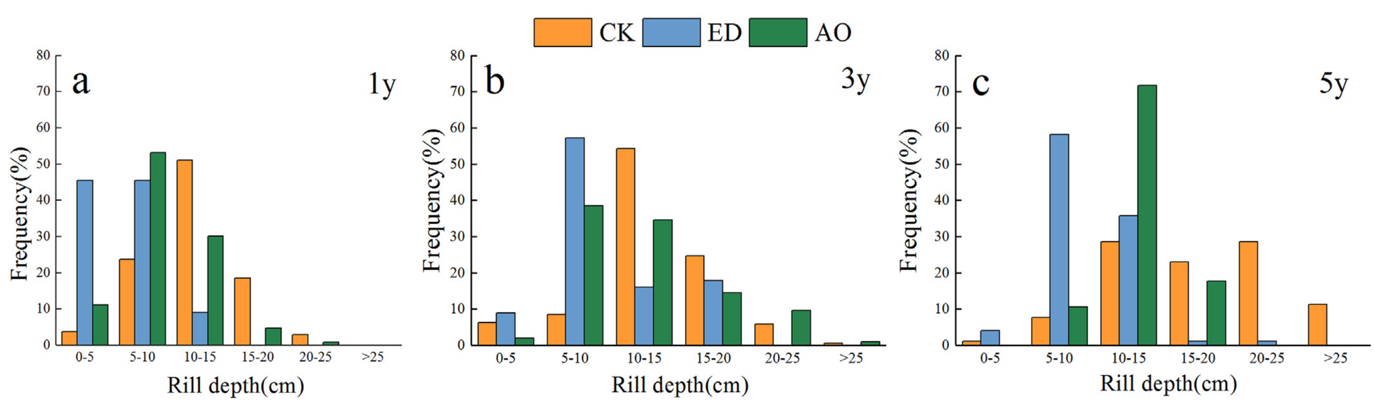

Fig. 4. Distribution of rill depth under different restoration conditions. CK: natural restoration, ED: *Elymus dahuricus* and AO: Artemisia ordosica. Rill depth distribution with recovery time of 1 year (a), rill depth distribution with recovery time of 3 year (b), and rill depth distribution with recovery time of 5 year (c).

Table 2
Results of the two-way ANOVA about the influences of vegetation restorations and recovery time on rill development characteristics.

Dependent variable	Factor	Degree of freedom	mean-square	*F*-value	*P*-value
W	Recovery time	2	116.47	56.71	0.000
	Vegetation	2	134.82	65.6465	0.000
	Vegetation* time	4	2.67	1.30	0.307
D	Recovery time	2	41.85	47.69	0.000
	Vegetation	2	136.31	155.35	0.000
	Vegetation* time	4	5.17	5.89	0.003
RR	Recovery time	2	0.07	2.95	0.078
	Vegetation	2	0.06	2.57	0.104
	Vegetation* time	4	0.20	7.95	0.001
RD	Recovery time	2	0.28	139.83	0.000
	Vegetation	2	0.62	305.36	0.000
	Vegetation* time	4	0.01	6.90	0.001
	Recovery time	2	248.03	110.96	0.000
RDD	Vegetation	2	329.80	147.54	0.000
	Vegetation* time	4	17.49	7.82	0.001
REM	Recovery time	2	36.80	18.96	0.000
	Vegetation	2	750.39	386.64	0.000
	Vegetation* time	4	27.83	14.34	0.000

Note: *W*: Rill width, *D*: Rill depth, *RR*: Rill width-depth ratio, *RD*: Rill density, *RDD*: Degree of rill dissection, *REM*: Rill erosion modulus.

5 y, respectively. Similarly, the *RDD* under AO restoration with recovery time of 1 y, 3 y and 5 y was 347.25%, 40.93% and 34.70%, respectively, compared with CK, which significantly decreased the *RD* by 42.16%, 43.12% and 32.21% for recovery time of 1 y, 3 y and 5 y, respectively. Furthermore, the *RD* and *RDD* increased significantly with recovery time under different restoration conditions.

4.2.3. Rill erosion modulus

Vegetation restorations, recovery time, and their interactions are all significant on *REM* (Table 2). Fig. 7 shows that vegetation restorations significantly reduced the *REM*. Compared with the CK slope, the *REM* on the ED slope decreased by 90.77%, 82.94% and 76.29% for recovery time of 1 y, 3 y and 5 y, respectively. The *REM* on the AO slope decreased by 61.49%, 46.66% and 53.25% for 1 y, 3 y and 5 y, respectively. Moreover, we discovered that the *REM* on the ED slope was significantly lower than that on the AO slope. The *REM* for the CK and AO restoration models decreased with recovery time, but the *REM* for the ED restoration model increased with recovery time.

4.3. Factors influencing rill development under different restoration conditions

4.3.1. Contribution of factors to the rill development

The DCA results indicated that the lengths of the first four axes were less than 3 (Fig. 8). Therefore, an RDA can directly show the relationships between rill development characteristics and influencing factors, including soil factors (soil water content, *WC*; soil bulk density, *BD*; soil organic matter, *OM*; slope gradient, *SG*; clay content; silt content; and sand content), vegetation factors (vegetation coverage, *VC*; root length density, *RLD*; root surface area density, *RSAD*; root volume density, *RVD* and root mass density, *RMD*). The results of the Monte Carlo test showed that the significance of the two axes (RDA1 and RDA2) was at the level of 0.05 ($F = 8.1314$, $P = 0.001$). The first axis and second axis explained 68.89% and 10.68%, respectively, of the total variation in rill morphology development. *REM* could best reflect rill development under different restoration conditions, and all vegetation factors (*VC*, *RLD*, *RSAD*, *RVD* and *RMD*) showed negative correlation with *REM*, among which *VC* showed the most significant negative correlation with *REM*. The distribution order of different vegetation restorations on *VC* axis was ED > AO > CK. The distribution order of recovery time on the silt axis was 5y > 3y > 1y. The sequence characteristics of ED and AO samples were more similar, but ED samples corresponded to higher *VC*. The corresponding silt content of the sample with a recovery time of 5 y was higher.

The degree of explanation for each factor of rill development is shown in Table 3. The interpretation degree of *VC* was the highest (34.99%). The root characteristics of vegetation had a relatively lower interpretation degree for rill development. The *RVD*, *RSAD*, *RLD* and *RMD* were 4.49%, 4.37%, 3.67% and 0.67%, respectively, and the overall cumulative interpretation degree of root characteristics was only 13.2% (Fig. 8).

4.3.2. Correlation between different factors and rill development characteristics

A correlation analysis was performed between the factors influencing rill development and the characteristics of rill development (Table 4). The results showed that VC had a very significant negative correlation with *W*, *D*, *RD*, *RDD*, and *REM* ($P < 0.01$) and that VC had a very significant positive correlation with *RR* ($P < 0.01$). Clay had a very significant and positive correlation with *W*, *RD* and *RDD* ($P < 0.01$) and had a significant and positive correlation with *D* ($P < 0.05$). Vegetation root factors (*RLD*, *RVD* and *RSAD*) were significantly positively correlated with *RR* ($P < 0.05$). The vegetation root factors (*RLD*, *RVD* and *RSAD*) were significantly negatively correlated with *D*, *RD*, *RDD* and *REM*, with the exception that *RVD* was not significantly correlated with *RDD*.

5. Discussion

5.1. Effects of ED and AO on rill development on dump slopes

Our results showed that the ED and AO restoration models reduced the *REM* by 76.29%–90.77% and 53.25%–61.49%, respectively (Fig. 7), which

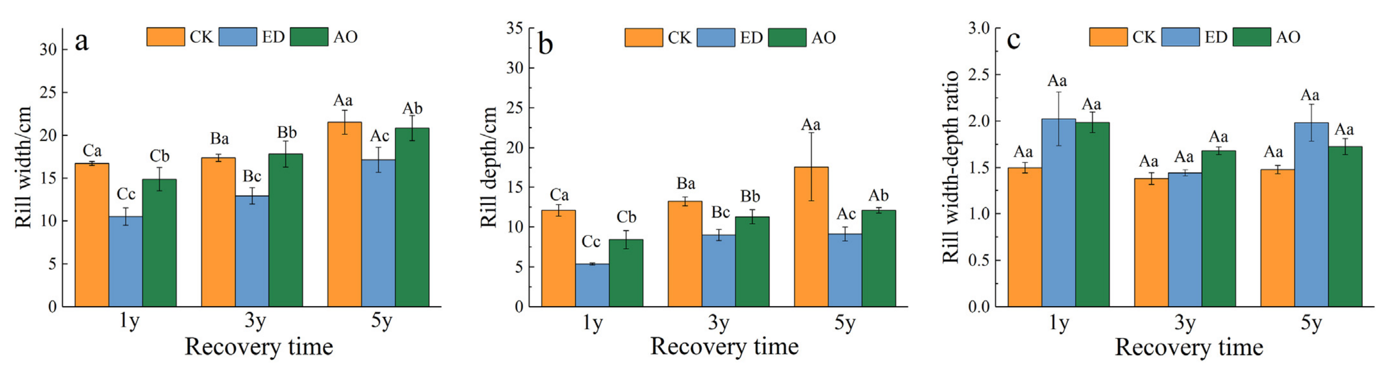

Fig. 5. Morphological characteristics of rills under different restoration conditions. CK: natural restoration, ED: *Elymus dahuricus* and AO: Artemisia ordosica. Different lowercase letters indicate significant differences among restoration conditions ($P < 0.05$); different capital letters indicate significant differences among recovery times ($P < 0.05$). The average rill width under different restoration conditions (a), the average rill depth under different restoration conditions (b), and rill width-depth ratio under different restoration conditions (c).

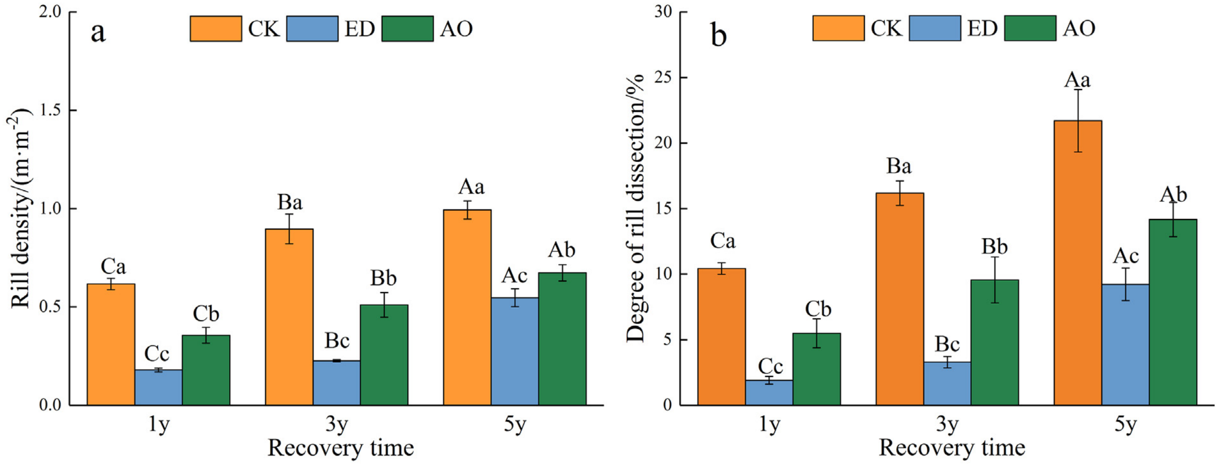

Fig. 6. Degree of slope breakage under different restoration conditions. CK: natural restoration, ED: *Elymus dahuricus* and AO: Artemisia ordosica. Different lowercase letters indicate significant differences among restoration conditions ($P < 0.05$); different capital letters indicate significant differences among recovery times ($P < 0.05$). Rill density under different restoration conditions (a), and degree of rill dissection under different restoration conditions (b).

illustrated that both ED and AO were effective treatments for rill erosion control on dump slopes and that ED had higher effectiveness than AO. The reduction in REM was mainly dependent on revegetation, effectively containing the development of rill networks and morphology.

In terms of the rill network, this study found that the *RD* and *RDD* on ED and AO slopes were significantly lower than those of the CK slope, and the ED slope had lower *RD* and *RDD* values than the AO slope (Fig. 6). This result suggested that the two vegetation restoration techniques can effectively inhibit the development of rill networks, and ED has a better inhibition efficiency. The main reason for these results is the difference in distributions between the two vegetation types. The distribution of ED was uniform (Fig. 1c), while AO grew as clusters (Fig. 1d). In the degraded land, the distribution of soil water was uneven, and the growth of AO was obviously affected by the soil moisture. The AO distribution had spatial heterogeneity, and the clusters grew into small islands (Guo, 2000; Wang et al., 2007). After the occurrence of erosive rainfall on the dump slope, there was a significant difference in the impact of raindrops between the areas with AO coverage and those without AO coverage. This difference enabled runoff

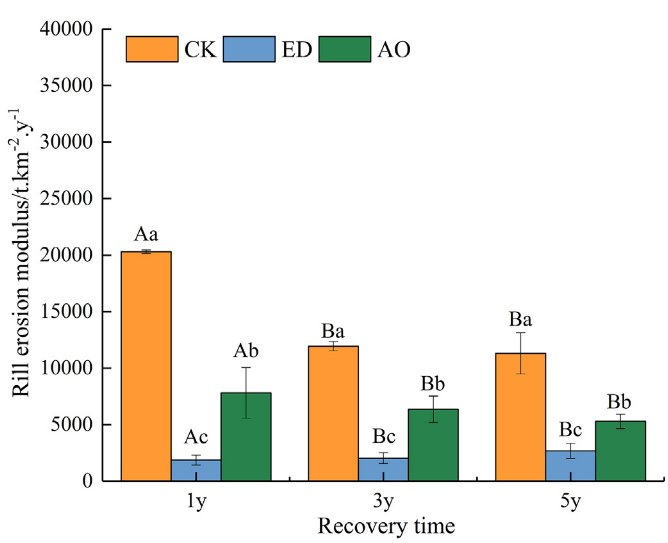

Fig. 7. Rill erosion modulus under different restoration conditions. CK: natural restoration, ED: *Elymus dahuricus* and AO: Artemisia ordosica. Different lowercase letters indicate significant differences among restoration conditions ($P < 0.05$); different capital letters indicate significant differences among recovery times ($P < 0.05$).

to easily generate and concentrate in the areas without AO coverage, which contributed to rill occurrence and development. Previous studies also showed that vegetation type was an important factor affecting the development of rill networks (Duan et al., 2016; Guo et al., 2019; Shi et al., 2016). The development of rills is closely related to the spatial distribution of vegetation, and reasonable planting is important in erosion control on dump slopes.

For rill morphology, Vegetation restorations have significant effects on *W* and *D* (Table 2). A large number of previous studies have also proven that

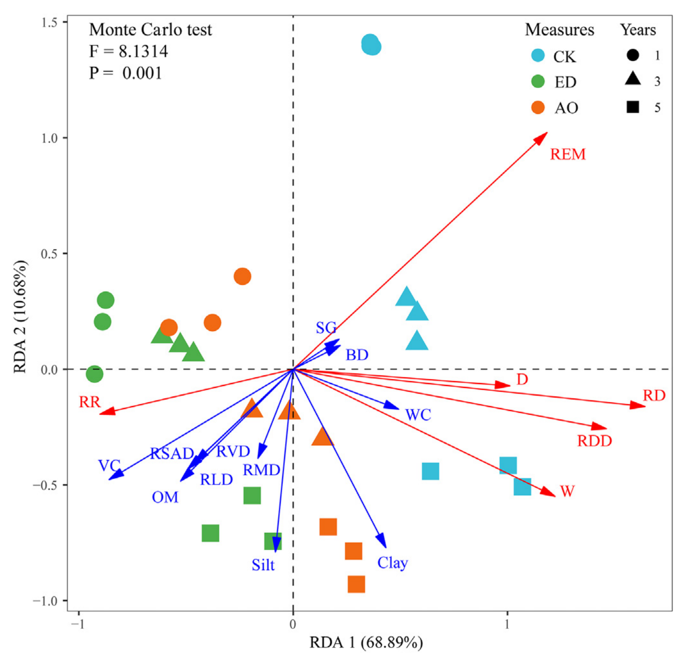

Fig. 8. Ordination plots of the results from the RDA to identify the relationships among the rill morphological parameters (red arrows) and slope gradient (*SG*), soil factors and vegetation factors (blue arrows). Note: Soil factors include soil water content (*WC*), soil bulk density (*BD*), soil organic matter (*OM*), clay, silt and sand content. Vegetation factors include vegetation coverage (*VC*), root length density (*RLD*), root surface area density (*RSAD*), root volume density (*RVD*) and root mass density (*RMD*). The rill morphological parameters included rill width (*W*), rill depth (*D*), rill breadth depth ratio (*RR*), rill density (*RD*), degree of rill dissection (*RDD*) and rill erosion modulus (*REM*).

Table 3
Results of RDA between rill development and influencing factors and the contribution of influencing factors.

Explained variable	RDA1	RDA2	R^2	*P*-value	Explains (%)
VC	−0.91	−0.42	0.90	0.001	34.99
Clay	0.573	−0.82	0.60	0.001	17.24
Sand	−0.12	0.99	0.50	0.001	11.73
Silt	−0.18	−0.98	0.47	0.002	9.47
OM	−0.81	−0.59	0.45	0.002	8.45
RVD	−0.82	−0.57	0.33	0.006	4.49
RSAD	−0.82	−0.57	0.38	0.004	4.37
RLD	−0.82	−0.57	0.38	0.005	3.67
WC	0.97	−0.23	0.25	0.031	3.65
SG	0.90	0.44	0.06	0.503	1.21
RMD	−0.51	−0.86	0.14	0.16	0.76
BD	0.93	0.36	0.06	0.533	0.02

Note: *VC*, *OM*, *RVD*, *RSAD*, *RLD*, *WC*, *SG*, *RMD*, *BD*, clay, silt and sand refer to vegetation coverage, soil organic matter, root volume density, root surface density, root length density, soil water content, slope gradient, root mass density, soil bulk density, clay content, silt content and sand content, respectively.

the existence of vegetation has an important effect on rill morphology (Chen et al., 2017; Guo et al., 2019; Shi et al., 2016). There was no significant difference in the *RR* between ED and AO, but there were significant differences in the *D* and *W* between ED and AO (Fig. 5). Compared with CK, ED significantly reduced the *W* and *D*. These results suggested that the controlling effect of ED on *D* and *W* was significantly better than that of AO, and AO had no obvious controlling effect on rill widening. The main reason for this result is that the root systems of the two vegetation types differ. AO is a straight root plant with a small distribution of lateral roots in the horizontal direction (Zhang et al., 2008). ED is a kind of fibrous root plant, and its fibrous roots are well developed, numerous and dense (Zhu et al., 2005). The entanglement of plant roots can increase soil porosity and infiltration capacity, improve aggregate stability, reduce and delay surface runoff (Zhang et al., 2014) and enhance soil anti-erodibility. In addition, the roots intersect in the soil and form a root network in the shallow soil, which enhances the ability of the soil to resist the downcutting erosion of water flow (Zhang and Zhou, 2015). The entanglement of fibrous roots can hold the soil and reduce erosion on both sides of rills (Gyssels et al., 2005). The developed fibrous roots of ED can effectively control the deepening and widening of rills, but AO has fewer fibrous roots, so the inhibitory effect of AO on rill widening is worse.

5.2. Effect of recovery time of vegetation restoration types on rill erosion on dump slopes

In this study, the *REM* of AO decreased with recovery time, while the *REM* of ED increased with recovery time. This finding suggests that the erosion reduction effect of ED gradually decreases with recovery time. This phenomenon may be caused by the following two factors: As a gramineous plant, ED experienced aging and degradation after three years of planting (Zhang et al., 2013). With plant aging, the aboveground part of ED shrinks, and the rainwater retention effect of ED can be reduced, thus reducing the control on rill erosion. On the other hand, compared with CK, the annual average erosion reduction effect of ED in the first three years was as high as 70% (Fig. 7), and more fine particles were retained on the surface of the dump slope, which was easily eroded. With the degradation of ED, this part of the soil was gradually eroded, causing *REM* to increase over time. Therefore, the artificial intervention of dump slope restoration is a long-term process, and orderly vegetation succession is the main direction of future dump slope restoration. In conclusion, AO and ED can effectively control rill erosion, and the effect of ED is more obvious in the first five years of restoration, but the control gradually weakens.

5.3. Main factors affecting the development of rills

The RDA results showed that *VC* explained 34.99% of the variation in rill development, with the highest degree of explanation. The total cumulative explanation of the root characteristics (*RVD*, *RSAD*, *RLD* and *RMD*) was only 13.20% (Table 3). The results suggested that vegetation coverage is the main factor affecting rill development on dump slopes. Many studies have also shown that soil erosion is negatively correlated with vegetation cover (Krümmelbein et al., 2010; Zuo et al., 2010). Vegetation cover can reduce raindrop kinetic energy, protect the soil surface and increase infiltration time, which is an important factor in inhibiting erosion (Zhang and Zhou, 2015). The single vegetation root index (*RVD*, *RSAD*, *RLD* and *RMD*) did not well explain rill development, implying that the aboveground part of vegetation had more influence on rill development than the underground part. Many scholars have pointed out that vegetation root systems can improve soil physical properties, decrease soil erodibility, and further concluded that vegetation roots have a more important role in controlling soil erosion than aboveground roots (Gyssels et al., 2005). However, as remolded soil, dumps lack nutrients and have a loose structure (Frouz et al., 2013), which may cause poor growth of vegetation roots and then affect the fixation of vegetation roots in the soil. The results from the correlation analysis between rill morphology and influencing factors also showed that *VC* was significantly correlated with all rill development indexes (*W*, *D*, *RR*, *RD*, *RDD* and *REM*) and had the strongest correlation with *REM* (Table 4). This result further suggested that *VC* is the main factor affecting rill development on dump slopes. Furthermore, in the first five years of restoration, the effect of vegetation coverage on rill development was greater than that of the root system. Therefore, in the early stage of restoration, vegetation with better ground coverage should be selected for vegetation restoration on dump slopes.

5.4. Implications of the work for land management

Our results show that ED controlled rill development better than AO and that vegetation coverage had a critical role in controlling rill erosion on dump slopes. Therefore, the key to vegetation restoration in mining areas is to choose vegetation (such as ED) with high coverage, uniform

Table 4
Correlation between different factors and rill development characteristics.

Slope situation	*BD*	*WC*	*OM*	*VC*	*SG*	*RLD*	*RVD*	*RSAD*	*RMD*	*Clay*	*Silt*	*Sand*
W	0.06	0.44*	−0.32	−0.52**	0.31	−0.16	−0.12	−0.14	0.16	0.53**	0.10	−0.27
D	0.38	0.51**	−0.45*	−0.73***	0.10	−0.43*	−0.41*	−0.44*	−0.13	0.47*	0.01	−0.18
RR	−0.29	−0.45*	0.27	0.58**	−0.01	0.42*	0.58**	0.52**	0.28	−0.30	0.02	0.10
RD	0.15	0.45*	−0.44*	−0.78***	0.13	−0.46*	−0.42*	−0.46*	−0.19	0.51**	0.03	−0.21
RDD	0.20	0.47*	−0.40*	−0.73***	0.15	−0.40*	−0.36	−0.40*	−0.12	0.54**	0.06	−0.25
REM	0.16	0.20	−0.71***	−0.90***	0.32	−0.57**	−0.48*	−0.54**	−0.27	−0.22	−0.60**	0.49*

Note: The influencing factors included soil water content *(WC),* soil bulk density *(BD),* soil organic matter (*OM*), clay, silt, sand content, vegetation coverage (*VC*), root length density (*RLD*), root surface area density (*RSAD*), root volume density (*RVD*), and root mass density (*RMD*). The rill morphological parameters included rill width (*W*), rill depth (*D*), rill width-depth ratio (*RR*), rill density (*RD*), degree of rill dissection (*RDD*) and rill erosion modulus (*REM*).

* Correlation was significant at the 0.05 level ($P < 0.05$).

** Correlation was significant at the 0.01 level ($P < 0.01$).

*** Correlation was significant at the 0.001 level ($P < 0.001$).

surface distribution and a strong fiber root system to contain soil erosion of dump slopes. However, the rill-restricted effect of ED weakened with an increase in recovery time. Therefore, we also need to regularly replant and maintain the vegetation on dump slopes to reduce rill erosion on the dump slope and achieve water and soil conservation in the mining area.

6. Conclusions

Based on the investigation of dump slopes with different recovery time in the Minda coal mine in Inner Mongolia, the rill development characteristics of dump slopes under different restoration conditions (CK, ED, and AO) were compared. Both ED and AO were effective vegetation for controlling rill erosion, of which ED controlled rill erosion better than AO, but this effect gradually weakened with recovery time. ED and AO could effectively control the development of rill networks and rill morphology, but AO had no significant effect on the development of rill width. Vegetation coverage explained 34.99% of rill development and was the main factor affecting the development of rills on dump slopes. Vegetation coverage had a more important role in controlling rill development than did the root system. The key to vegetation restoration in mining areas is to select vegetation with good ground coverage, uniform growth patterns and vigorous fibrous root systems for controlling soil erosion on dump slopes. Moreover, slope vegetation should be maintained well in the long term, attention should be given to the degradation of slope vegetation, and artificial intervention should also be implemented.

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CRediT authorship contribution statement

Zhiqiang Cui: Conceptualization, Validation, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. **Hongliang Kang:** Writing – review & editing, Investigation. **Wenlong Wang:** Conceptualization, Methodology, Project administration, Funding acquisition. **Wenzhao Guo:** Writing – review & editing, Investigation. **Mingming Guo:** Writing – review & editing, Investigation. **Zhuoxin Chen:** Methodology, Software.

Declaration of competing interest

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

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