frontiers | Frontiers in Earth Science

TYPE Original Research
PUBLISHED 17 January 2023
DOI 10.3389/feart.2022.1040814



# Micro-topographies formed by erosion can drive seedling emergence by rebuilding micro-habitats on weathered waste dumps in northeastern China

Dongli Wang[1], Jingting Qiao[1], Ye Zhang[1], Mingji Liao[1], Dong Wang[2]*, Xiaoliang Zhao[1] and Yan Qiao[3]

[1]College of Environmental Science and Engineering, Liaoning Technical University, Fuxin, China, [2]College of Mining Technology, Liaoning Technical University, Fuxin, China, [3]College of Business, Chuzhou Polytechnic, Chuzhou, China

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EDITED BY
Dominic E. L. Ong,
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REVIEWED BY
Min Lee Lee,
University of Nottingham Malaysia Campus, Malaysia
Armstrong Ighodalo Omoregie,
University of Technology Malaysia, Malaysia

*CORRESPONDENCE
Dong Wang,
lntu_wd@163.com

SPECIALTY SECTION
This article was submitted to Biogeoscience, a section of the journal Frontiers in Earth Science

RECEIVED 09 September 2022
ACCEPTED 31 October 2022
PUBLISHED 17 January 2023

CITATION
Wang D, Qiao J, Zhang Y, Liao M, Wang D, Zhao X and Qiao Y (2023), Micro-topographies formed by erosion can drive seedling emergence by rebuilding micro-habitats on weathered waste dumps in northeastern China. *Front. Earth Sci.* 10:1040814. doi: 10.3389/feart.2022.1040814



Restoring vegetation on waste dumps is imperative because soil erosion heavily impacts these areas and creates erosion micro-topographies, including bare slopes, rills, ephemeral gullies, and deposit bodies. These micro-topographies may affect seedling emergence by forming special micro-habitats, although the mechanism is vague. This study determined the substrate chemical (i.e., pH and electrical conductivity) and physical (i.e., capillary porosity, capillary water content, and mechanical composition) properties of different micro-topographies. In addition, the temporal dynamics of micro-climates (i.e., air temperature and air humidity), substrate hydrothermal conditions (i.e., substrate temperature and water content), and seedling emergence were investigated. Redundancy analysis (RDA), random forest (RF), and receiver operating characteristic (ROC) curve analysis were then used to identify the main factors affecting seedling emergence and clarify the relationships among the environmental conditions. Our results demonstrate that seedling densities in the rill, ephemeral gully, and deposit body were 1.78 times, 3.42 times, and 3.97 times higher than those on the bare slope, respectively. More species were found in the rill, ephemeral gully, and deposit body (*Artemisia annua*, *Salsola collina*, *Setaria viridis*, and *Tribulus terrestris*) than on the bare slope (*Salsola collina*). The main factors affecting seedling emergence were air humidity, substrate temperature, and substrate water content. The mechanical composition may have affected substrate water content during the initial stage of seedling emergence and substrate temperature during the entire period. We demonstrate that the ephemeral gully and deposit body may provide micro-habitats with a lower substrate temperature and higher substrate water content, which are favorable to seedling emergence, thus guiding vegetation restoration on waste dumps or other disturbed areas.

KEYWORDS

soil erosion, vegetation restoration, opencast mine, arid and semiarid area, micro-habitats

## Introduction

Coal is traditionally the most commonly used fossil fuel to produce electricity. Consequently, global annual coal production has remained at more than 7 billion tones over the past 10 years (Ren et al., 2021). However, coal exploitation, especially in opencast mining, can harm the local ecology and environment because it changes the spatial development and land cover, including waste storage (Hilson, 2000; Abramowicz et al., 2021). Research has shown that 0.22 $hm^2$ of land is destroyed for every 10,000 tons of coal produced through opencast mining (Lechner et al., 2016). In addition, coal exploitation can lead to widespread ground fissures (Yang et al., 2022), rapid decrease of forest resources and grassland (Wu et al., 2021), expose polycyclic aromatic hydrocarbons (PAhs) to the ecological environment (Jiang et al., 2022), and intensify soil erosion and desertification (Jin et al., 2021), which can lead to ecological destruction in the mining area. Many large-scale coal mines in China are located in semiarid and arid regions, where the ecology and environment are easily degraded by mining activities (Pasture, 2021). In particular, the solid waste is usually piled in dumps that have a loose structure (Ren et al., 2020). These sites are often the sources of excessive dust, which can affect trees and plants. These tips also create unsightly landscapes (Zástěrová et al., 2015), are susceptible to soil erosion, and are harmful to the local ecosystem. Consequently, it is necessary to restore the ecology, which is conducive to waste dump reclamation and the long-term stability of engineered post-mining landforms (Miao and Marrs, 2000; Bao et al., 2012; Zhang et al., 2015). Various artificial ecological restoration projects have been implemented on waste dumps, such as agricultural reclamation, phytoremediation, and the building of botanical gardens. However, the evidence suggests that the engineering techniques that have been adopted have experienced some issues, including a lack of systematic thinking, the weak self-sustaining ability of the restored system, the monotonous target, and the lack of pertinence in restorations (Huang et al., 2015; Lei et al., 2022). Meanwhile, the naturally occurring plants have been shown to have a good prospect of surviving and regenerating in disturbed habitats (Prach and Pys, 2001). Therefore, when selecting the reclamation methods, it is essential to consider the ecological, socioeconomic, and territorial technical conditions (Zástěrová et al., 2015). Given the economy of the local government and its limited budget, natural vegetation restoration is a better choice than adopting risky artificial techniques.

The environmental conditions of waste dumps always impose some restrictions on vegetation restoration. For example, badly weathered rocks cover the surface and these dumps usually lack soil. In addition, the substrate that occurs in waste dumps, which forms micro-topographies, is composed of large-sized grains, is unstable, and is susceptible to soil erosion (Markowicz et al., 2015; Błońska et al., 2019). As a result, the environmental conditions of waste dumps can be characterized as saline, nutrient-poor, and arid and have significant fluctuations in hydrothermal activity (Bradshaw, 2000; Chmura et al., 2011). Soil erosion is usually responsible for the loss of nutrients and propagules (Espigares et al., 2011). Previous research has demonstrated that soil erosion can inhibit natural plant colonization processes in artificial slopes by constantly increasing runoff water loss (Bochet et al., 2007; Moreno-de las Heras et al., 2008; Espigares et al., 2011). However, our previous research showed that although the environmental conditions were inadequate for plant colonization on most parts of the waste dumps, some plants were able to colonize and distribute in discrete areas. This indicates that some erosion micro-topographies can drive plant colonization (Wang et al., 2022). Similar results were also found on other waste dumps in this research.

Similarly, a few species can colonize in some extremely eroded sites on Pre-Pyrenean Eocene marls, while not occurring in adjacent well-preserved areas (Rufaut and Craw, 2010). It was also found that micro-topography patterns play a key role in plant colonization in desolate environments that consist of primary volcanic succession (Tsuyuzaki and Haruki, 2008). In addition, it is indicated that micro-topographic heterogeneity can influence the possibility and spatial pattern of seedling establishment by regulating the seed dispersal and soil physicochemical characteristics, including salinity and water content (Wang et al., 2019; Wang et al., 2020). Research has demonstrated that the colonization of plant species among micro-topographies is the result of several factors, including seed trapping ability, the environmental conditions of a given micro-topography, and the ability of a particular plant species to emerge and establish under specific environmental conditions of each micro-topography (del Moral and Bliss, 1993). For example, the specific micro-climate of a given micro-topography within which the seed is trapped may be critical for the germination and growth of specific species. For instance, seedlings of *Polygonum weyrichii* and *Salix reinii* occurred more frequently in gully bottoms and edges but much less frequently on flat areas of the volcanic landscape (Titus et al., 2003), while *Nothofagus pumilio* seedlings survived more frequently in cut forest areas than in the front or tail of ponds (Martínez Pastur et al., 2021). Furthermore, it has also been demonstrated that micro-topographies influence environmental conditions at the level of a seed or seedling (Rufaut and Craw, 2010). For example, certain erosion micro-topographies can trap seeds, litter, and plant debris and change the angles of sunlight radiation to create shades.

The initial revegetation phase forms the basis of any restoration scheme. Once established, this vegetation will help to determine the course of vegetation development, at least in the short- and medium-term of the restoration process (Alday et al., 2010). In addition, the seedling stage is the most fragile and vital stage of the plant life cycle (Ge et al., 2019). Therefore, the success of seedling emergence is a major bottleneck during the seed's development into an established plant (Madsen et al., 2012). For seedling emergence, the term "safe site" was proposed by Harper et al. (1965) to characterize the specific conditions that would allow the seed of a particular species to germinate and emerge successfully (Harper et al., 1965). The conditions that influence seedling emergence in waste dumps are closely related to micro-topography properties, including moisture, bulk density, pH of the substrate, and light regime (Connell and Slatyer, 1977). The various micro-habitats that are formed by micro-topographies may provide safe sites for the seedling emergence of some species. Clarifying the relationship between colonization patterns of native species and micro-topographies that are conducive to seedling emergence is vital in vegetation restoration, which can contribute to effective restoration design schemes and is useful in artificial intervention to ensure the successful restoration of disturbed areas (Elmarsdottir et al., 2003). In some typical ecological degraded areas, micro-habitat control technology has been adopted to promote the colonization of native plant seedlings, community construction, and stability maintenance to alleviate the restrictions of poor environmental conditions on vegetation restoration (Hu et al., 2020). The micro-habitats that influencing seedling emergence patterns include temperature and seed dormancy in the farmland (Royo-Esnal et al., 2022) and light availability and soil moisture conditions in the forest land (García de Jalón et al., 2020). However, while there has been a lack of research on waste dumps. The objective of this study is to investigate the variety of seedling emergence and environmental conditions among erosion micro-topographies to determine whether certain micro-topographies can provide more suitable micro-habitats for seedling emergence. We explored four main questions: 1) Does seedling emergence vary among the erosion micro-topographies on waste dumps? 2) Can some micro-topographies drive seedling emergence? 3) What are the discrepancies in the micro-habitats among different micro-topographies? And, 4) how do micro-habitats influence seedling emergence?

# Materials and methods

## Study area

This research was conducted on a waste dump that is composed of sandstone and shale, which is situated in Xinqiu District (121°1–122°56′ E, 41°41′–42°56′ N) of Fuxin City, northeastern China. The site's characteristics are described in Table 1. According to Google Earth, the waste dump has been shaped for approximately 10 years and only a few plants have colonized this area. The surface is covered by weathered materials and is badly eroded, thus creating several erosion micro-topographies. In this study, a sunny slope with representative erosion micro-topographies—including bare slope, rill, ephemeral gully, and deposit body—was chosen to conduct the research, where bare slope refers to the area where little erosion occurs, deposit body is the deposition formed by sediments brought by runoffs or gravity, and rill is defined with a typical width of approximately 10–20 cm and depth of 10–15 cm, while an ephemeral gully is approximately 30–40 cm wide and 25–45 cm deep, according to the soil erosion degree on the waste dump (Bruland and Richardson, 2005). The specific characteristics of these micro-topographies are described in Figure 1 and Table 2.

The study area belongs to a north-temperate, semiarid continental monsoon climate. The average annual precipitation is 539 mm, where 70% of the total rainfall is recorded between July and September. The average annual potential evaporation is 1800 mm. The average annual temperature is 7.3°C, with a maximum and minimum temperature of 40.6°C and -28.4°C, respectively. Freezing conditions may prevail for almost 150 days per year (Komnitsas et al., 2010). The mean air humidity is 50%–60%, and the main soil types include cinnamon soil, brown soil, meadow soil, and aeolian sand soil. Native plant species representative of the area are mostly meso-xerophytes and xerophytes, including *Arundinella hirta*, *Lespedeza davurica*, *Aster tataricus*, *Salsola collina*, and *Lexlis sonenifolia* (Xu, 2006).

## Seedling emergence survey

A seedling emergence survey was performed from early-April to late-June 2021, primarily three days after precipitation events, during which there were six precipitations. We left out two that were too close to last precipitation. Seedlings were labeled as S1 (15 April), S2 (30 April), S3 (14 May), S4 (28 May), and S5 (21 June). The following survey setup was used: six sample plots for bare slope (0.5 m × 0.5 m), six sample belts for rill (0.2 m × 1 m), six sample belts for ephemeral gully (0.5 m × 1 m), and three sample plots for deposit body (1 m × 1 m). All of the sample plots and belts were randomly and vertically selected to the contour line from the top to the bottom of the slope. The species and numbers of seedlings in each plot were recorded.

## Determination of substrate physicochemical properties

In this study, capillary porosity (CP), capillary water content (CWC), and mechanical composition were chosen to indicate the

TABLE 1 Basic characteristics of the researched waste dump.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Gradient | 39.4°–44.1° | | | | | | |
| Length | 9.5–11.1 m | | | | | | |
| Cation content | K (mg/L) 6.90 | Ca (mg/L) 368.62 | Na (mg/L) 9.83 | Mg (mg/L) 18.26 | | | |
| Nutrient content | Total N (mg/kg) 161.02 | Total P (mg/kg) 356.90 | Total K (g/kg) 41.02 | Available P (mg/kg) 2.33 | Available K (mg/kg) 155.66 | Organic carbon (g/kg) 23.28 | Organic matter (g/kg) 40.13 |
| Management | Uncontrolled | | | | | | |
| Reclamation | No reclamation | | | | | | |
| Colonization | Loose | | | | | | |

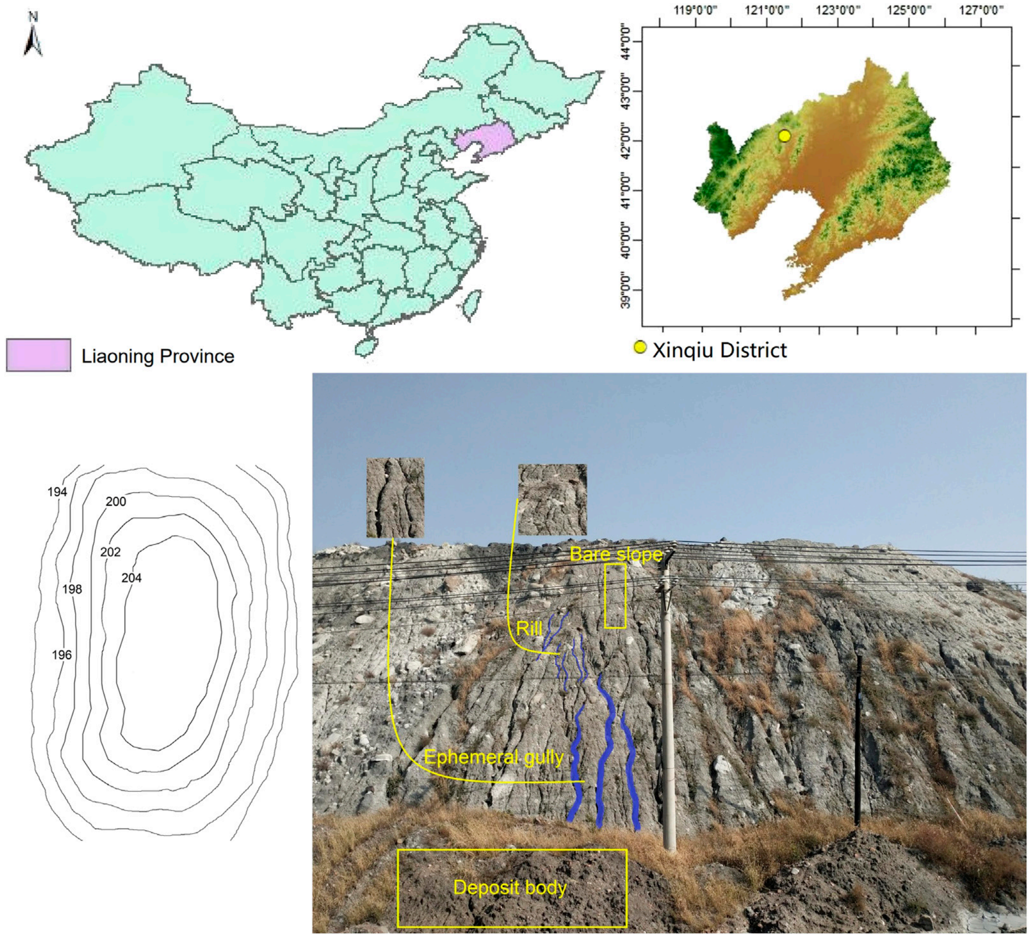


FIGURE 1
Location of the study area, the erosion micro-topographies on the waste dump, and its contour map.

substrate's physical properties, pH, and electrical conductivity (EC). A depth layer of 0–5 cm was selected to indicate the substrate's chemical properties. To determine the substrate's physicochemical properties at different micro-topographies, representative bare slopes, rills, ephemeral gullies, and deposit bodies were selected along the contour lines. Sample plots were selected randomly and vertically from the top to the bottom of the slope (six sampling points, respectively, for bare slope, rill, and ephemeral gully; and three sampling points for deposit body). Undisturbed samples were collected from the 0–10 cm substrate layers with a ring knife at each sampling point from the four micro-topographies to determine CP and CWC. Additionally, undisturbed samples were collected from the 0–2 cm, 2–5 cm, and 5–10 cm substrate layers with a soil

TABLE 2 Soil erosion characteristics of each micro-topography.

| Type | Width/cm | Depth/cm | Cross-sectional area/cm$^2$ |
|---|---|---|---|
| Bare slope | – | – | – |
| Rill | 15–26 | 6–16 | 123–328 |
| Ephemeral gully | 30–40 | 25–45 | 875–1575 |
| Deposit body | – | – | – |

auger at each sampling point from the four micro-topographies to determine the mechanical composition and substrate chemical properties. All of the samples were transported to the laboratory at Liaoning Technical University and the multi-point mixing method was used to process the same substrate layer.

CP and CWC were determined using the cutting ring method (Guo, 2009). The mechanical composition was determined by calculating the content percentage of each particle group using the drainage method. The substrate particles were classified according to the characteristic substrate particle size of the waste dumps (Wang et al., 2022) as fine grain (particle size <2 mm), middle-coarse grain (particle size between 2 and 10 mm), coarse grain (particle size between 10 and 20 mm), and giant grain (particle size >20 mm).

The pH and EC were determined by a DZS-706-A multi-parameter analyzer (Shanghai INESA Scientific Instrument CO., LTD., Shanghai, China).

## Investigation of micro-climates and hydrothermal conditions

The micro-climates (i.e., temperature and air humidity) of each micro-topography were determined near the substrate surface using a handheld weather meter (Kestrel 5000). The hydrothermal conditions (i.e., temperature and water content) of the 0–5 cm, 5–10 cm, and 10–15 cm substrate layers of each micro-topography were determined using the drying method. The sampling and monitoring points of the four micro-topographies corresponded to the points selected for physicochemical properties. The experiments were performed around midday at 13:00 Beijing time (5:00 UTC) for five days from late-April to late-June, which were locally the peak season of seedling emergence (Li, 2020). Samples were labeled as H1, H2, H3, H4, and H5. It is worth noting that samples H1 to H4 had similar sampling dates to samples S2 to S5 of the seedling emergence survey, which was due to the first precipitation not appearing in late-April when the seedling emergence had occurred according to our survey. Therefore, we missed the data of micro-climates and hydrothermal conditions by not bringing the equipment when conducting the first seedling emergence survey. The investigation of micro-climates and hydrothermal conditions on H5 was conducted mainly to comprehensively research the variance and differences during the seedling emergence season.

## Data processing

To explore the differences between micro-climates and hydrothermal conditions among the micro-topographies in each investigation, the D-values of the mean air temperature (ΔAT), mean air humidity (ΔAH), and mean substrate temperature (ΔST) and mean substrate water content (ΔSWC) of each layer were calculated. These values were compared with those determined for the bare slope. To compare the differences in seedling emergence among micro-topographies, we calculated the seedling densities, which were obtained using the seedling number divided by the sample area of each plot. To magnify the difference in seedling densities among micro-topographies in each investigation, the D-values of mean seedling density compared with that in bare slope were calculated. The seedling density data were then standardized in each sample plot using logarithmic transformation to compare the difference in seedling densities among each sample plot for the four micro-topographies.

## Statistical analysis

All statistical analyses were conducted in the R environment (v4.2.1; http://www.r-project.org/) with the violin plot and box plot drawn using the *ggplot2* package, the D-value calculated using the *stat_compare_means* function, RDA was analyzed using the *vegan* package, RF was analyzed using the *randomFOREST* package, and ROC was analyzed using the *pROC* package. Meanwhile, the figures of temporal dynamics were illustrated with Sigmaplot 14.0 by calculating the mean value of replicates and the error bar. First, the differences in general seedling densities and substrate physicochemical properties between each micro-topography were tested by Student's t-test. Redundancy analysis (RDA) was then performed to determine the main environmental factors affecting seedling emergence in different micro-topographies. The analysis was based on

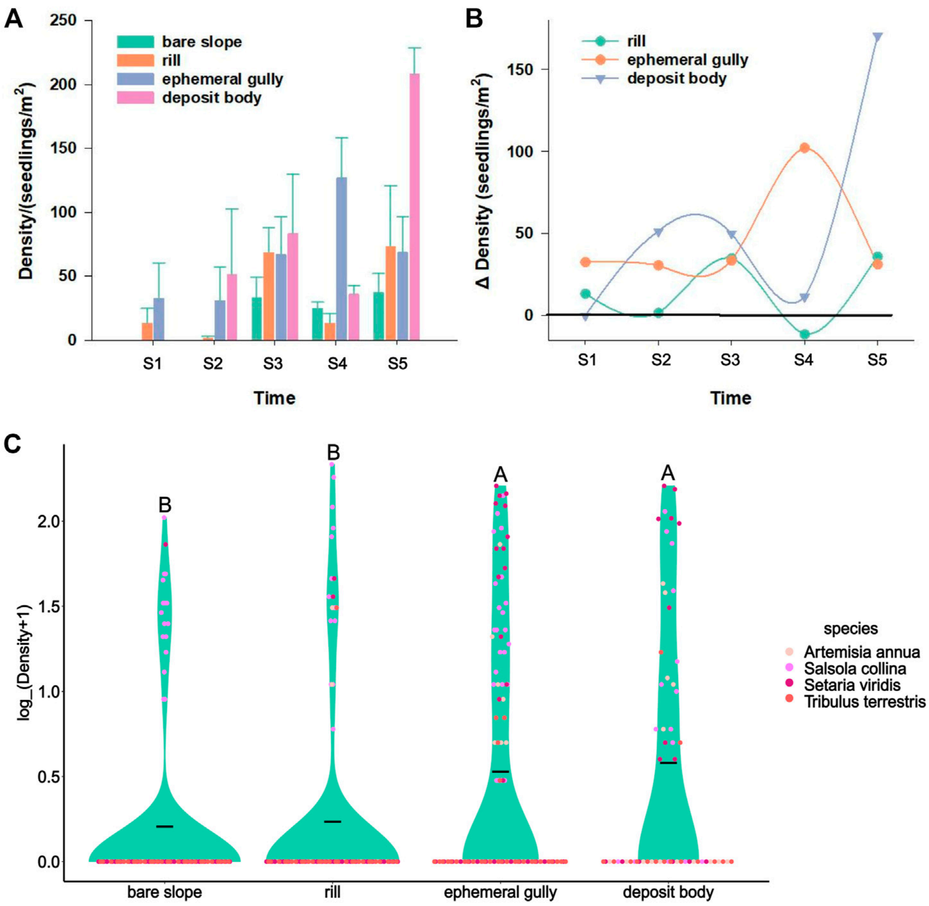


FIGURE 2
Temporal dynamics and total seedling density in the four micro-topographies. **(A)** Seedling densities in each micro-topography. **(B)** D-value of seedling density in each micro-topography compared with the bare slope. **(C)** Overall seedling density of the five investigations in the four micro-topographies. The black segment in each violin graph represents the mean number, and different letters (A,B) above each graph indicate significant differences between the erosion micro-topographies at $p < 0.01$ (Student's t-test).

the substrate's physicochemical properties, micro-climates, substrate hydrothermal conditions, seedling densities, and species in the different micro-topographies. Pearson correlations between each environmental factor in each investigation were analyzed and are depicted as diagrams (Supplementary Figure S1). In addition, classification random forest (RF) analysis was used to identify the main predictors for seedling emergence status for the four micro-topographies. Predictors for the RF models included the substrate's physicochemical properties, micro-climates, substrate hydrothermal conditions, and micro-topography types. Classification of seedling emergence was defined as whether the seedling densities in the rill, ephemeral gully, and deposit body were higher than those on the bare slope. In addition, the receiver operating characteristic (ROC) curve, which evaluates the diagnostic accuracy of an event, was used to assist the RF analysis.

# Results

## Seedling emergence

Overall, the temporal dynamics of seedling emergence for the survey showed that the seedling densities of the rill, ephemeral gully, and deposit body were higher than that of the bare slope (S1 to S5). However, the seedling density in the deposit body for S1 and S4 was similar to that in the bare slope in S1 (i.e., 0 seedlings/$m^2$). The seedling density for the rill was the lowest in S4 (Figure 2).

No significant difference was observed in the overall seedling densities between the bare slope and rill, and the ephemeral gully and deposit body (Figure 2). However, there was a significant ($p < 0.01$) difference between bare slope × rill and ephemeral gully × deposit body. The total seedling densities during the germination stage in each micro-

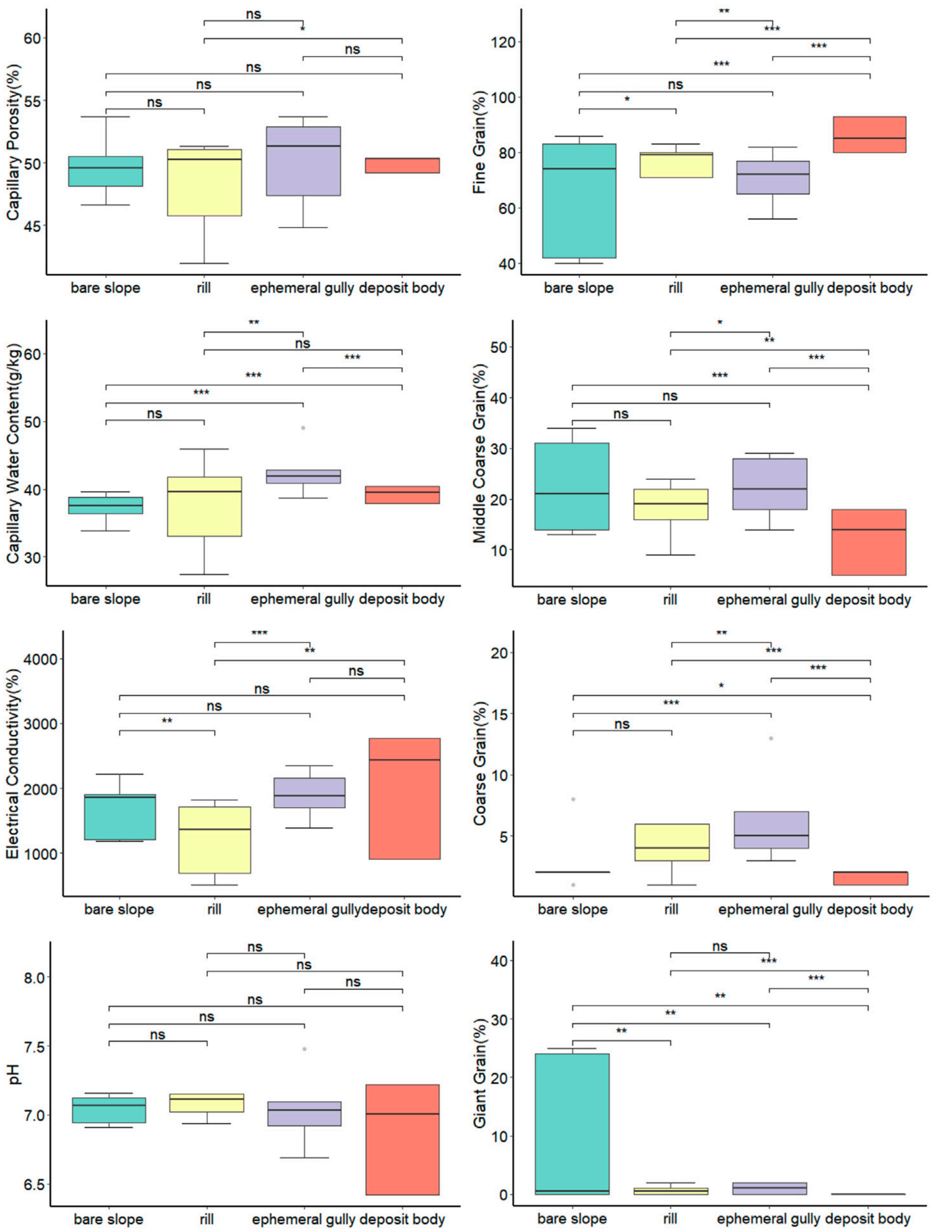


FIGURE 3
Substrate physicochemical properties in the micro-topographies. *, **, and *** indicate significant differences between the two micro-topographies at $p < 0.05$, $p < 0.01$, $p < 0.001$ levels, respectively; ns, non-significant difference. The significance was tested at different probability levels (*P*) by Student's t-test.

topography were in order of deposit body > ephemeral gully > rill > bare slope. The mean densities in the rill, ephemeral gully, and deposit body were 1.78 times, 3.42 times, and 3.97 times higher than those on the bare slope, respectively. However, the density of *Salsola collina* in the rill reached the highest value, up to 215 seedlings/$m^2$. The triangular shape of both the bare slope and rill suggested a low probability of high seedling density in these two micro-topographies. In contrast, the strip shape of the ephemeral gully and deposit body indicated a higher probability of high seedling density. In addition, seedling species that emerged on the bare slope mainly consisted of *Salsola collina*, whereas species in the rill, ephemeral gully, and deposit body included *Artemisia annua*, *Salsola collina*, *Setaria viridis*, and *Tribulus terrestris*. Among these, *Salsola collina* and *Setaria virids* densities were higher than for the other species.

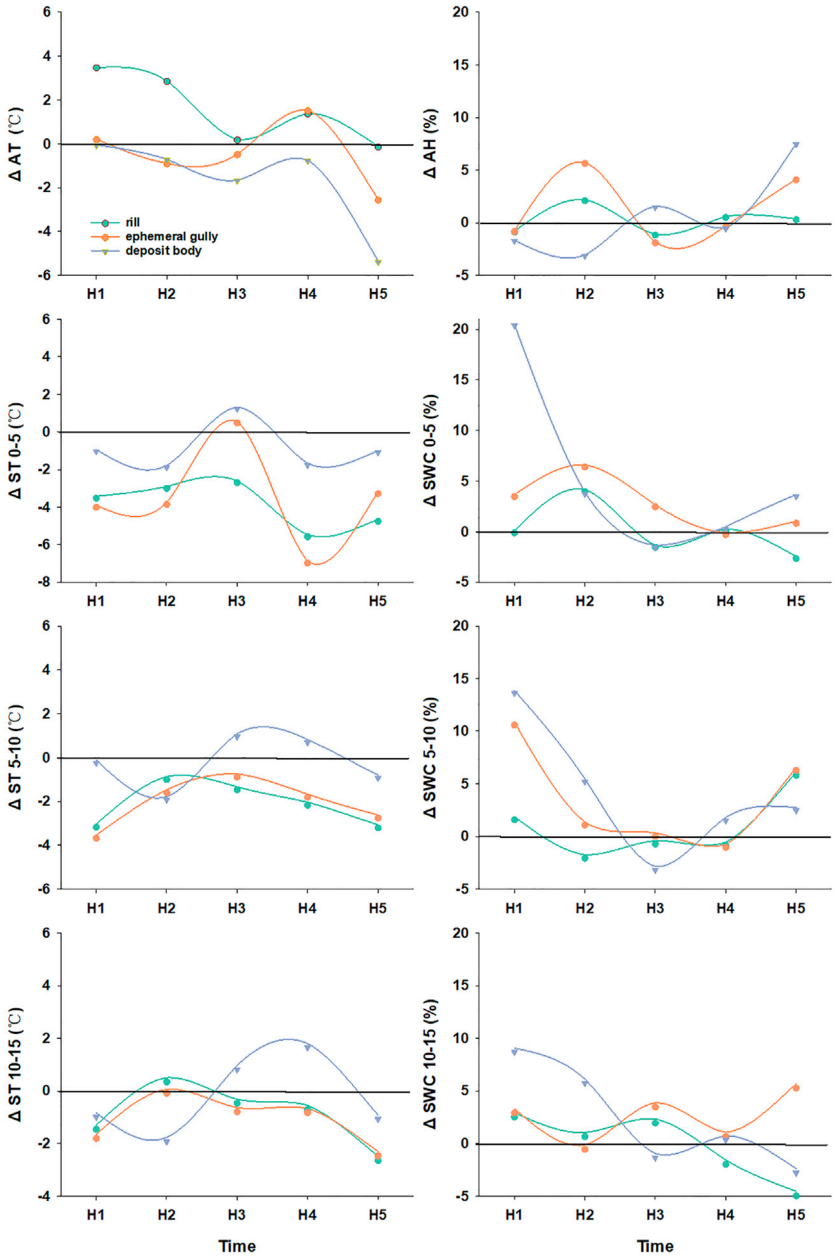


FIGURE 4
Temporal dynamics of micro-climates and hydrothermal conditions in the four micro-topographies. ΔAT for the D-value of air temperature near the substrate surface compared with the bare slope; ΔAH for the D-value of air humidity near the substrate surface compared with the bare slope; ΔST 0–5 cm, ΔST 5–10 cm, and ΔST 10–15 cm for the D-value of a substrate temperature of 0–5 cm, 5–10 cm, and 10–15 cm layers, respectively, compared with the bare slope; ΔSWC 0–5 cm, ΔSWC 5–10 cm, and ΔSWC 10–15 cm for the D-value of the substrate water content of 0–5 cm, 5–10 cm, and 10–15 cm layers, respectively, compared with the bare slope.

## Substrate physicochemical properties

The differences and significance in CP, CWC, EC, pH, and mechanical composition (i.e., content of fine grain, middle-coarse grain, coarse grain, and giant grain) between the four micro-topographies are shown in Figure 3. For CP and pH, there were no significant differences between the various micro-topographies. Conversely, noticeable differences were observed for CWC between each micro-topography, except between the rill and bare slope, and rill and deposit body. The median value for CWC was the highest in the ephemeral gully and lowest on the bare slope. Similarly, significant differences were observed for

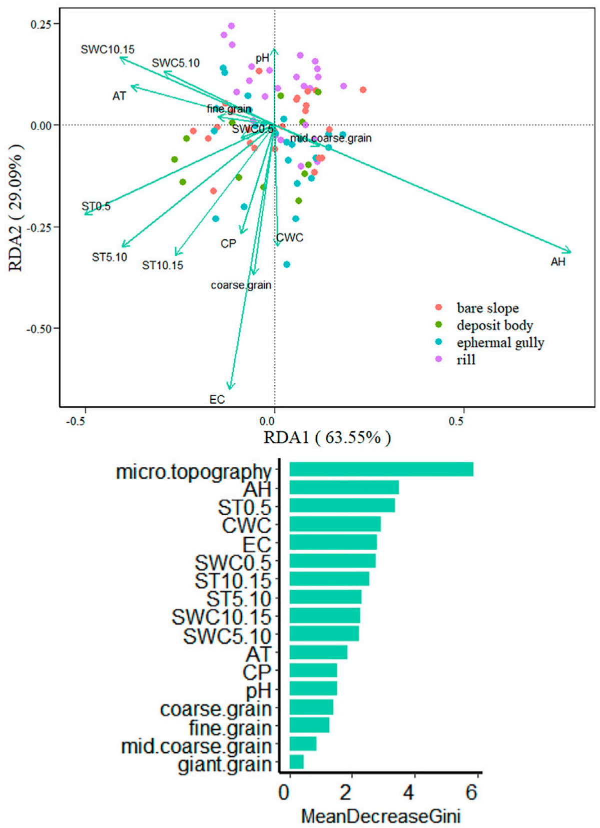


FIGURE 5
Redundancy analysis (RDA) of samples and environmental factors (left-hand), and random forest (RF) analysis of environmental factors and micro-topography types (right-hand) as predictors for the classification of seedling emergence. A mean decrease of Gini values was used to estimate the importance of these predictors: a higher mean decline in Gini values suggested more important predictors.

EC between the rill and bare slope, rill and deposit body ($p < 0.01$), and rill and ephemeral gully ($p < 0.001$). The median EC value was the highest in the deposit body and lowest in the rill. Regarding mechanical composition, significant differences were observed in particle size classification between each micro-topography. The content order for the median values of the four particle sizes, which was similar in all four micro-topographies, was fine grain > middle-coarse grain > coarse grain > giant grain.

## Micro-climates and hydrothermal conditions

As shown in Figure 4, the air temperatures of the rill were the highest among all samples, while those of the deposit body were the lowest. There were no apparent patterns in air humidity, except that the air humidity of the rill and ephemeral gully had an opposite trend to that of the deposit body (from H1 to H4).

For hydrothermal conditions, the substrate temperatures of the rill, ephemeral gully, and deposit body were lower in most investigations than those on the bare slope, except for the substrate temperatures of the deposit body in deeper layers for H3 and H4. As for SWC, we did not observe any distinct patterns but water content demonstrated discrepancies among the different micro-topographies. Most SWC values for the ephemeral gully and deposit body were higher than those on the bare slope, while the SWC values for the rill fluctuated up or down close to that of the bare slope.

## Effects of erosion micro-topography on seedling emergence

The RDA analysis is shown in Figure 5, where axes 1 and 2 explained 63.55% and 29.09% of the sample variation, respectively. The long arrow length indicates that certain factors—including air humidity, EC, substrate temperature of the three layers, and substrate water content of the 5–10 cm and 10–15 cm layers—were more important in affecting seedling emergence. Furthermore, the cosine values of the intersection angles between the environmental factors could indicate potential correlations. The substrate water content of the 5–10 cm and 10–15 cm layers corresponded to air humidity, air temperature, fine grain content, and medium coarse grain content. The EC associated with coarse grain content, CP, and pH was most relevant to CWC.

RF analysis was also conducted to clarify the effects of micro-topography type and to determine the main factors that play a role in seedling emergence (Figure 5). Our results show that micro-topography type was the most important variable for predicting the seedling emergence status by comparing the seedling density in each micro-topography with that in the bare slope. In addition, air humidity, CWC, EC, SWC, and substrate temperature of the 0–5 cm layer were shown to be relatively important.

According to the ROC curve, micro-topography type, air humidity, CWC, EC, and coarse grain content demonstrated good performance of seedling emergence classification because none of the variables remained below the random performance line (Figure 6).

# Discussion

The aim of this study was to investigate the differences in seedling emergence, substrate physicochemical properties, micro-climates, and hydrothermal conditions in different erosion micro-topographies to clarify the effects of micro-habitats on seedling emergence. Generally, research of

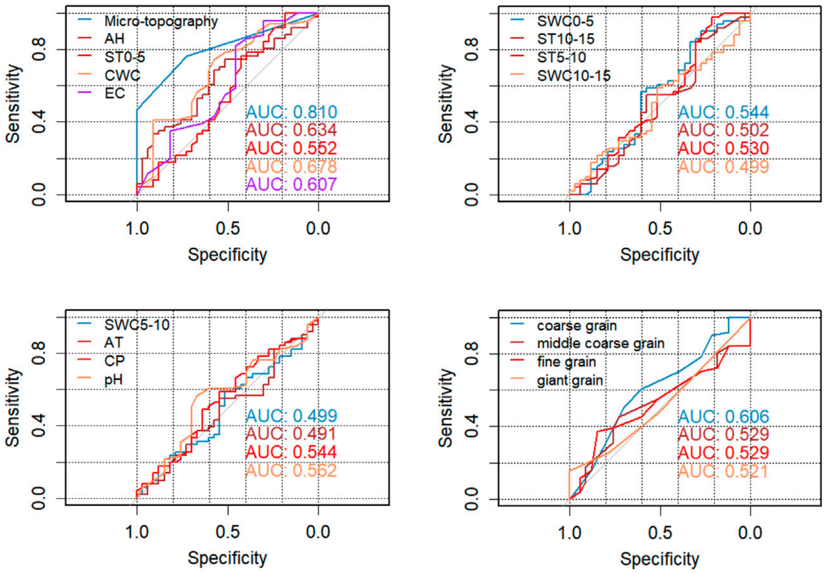


FIGURE 6
Receiver operating characteristic (ROC) curve of environmental conditions and micro-topography types as predictors for the seedling emergence classification.

vegetation restoration on waste dumps has tended to concentrate on the artificial projects and technologies, while we conducted research at a scale of micro-habitat and seedling emergence. In addition, differing from the inhibition, we found that soil erosion can drive the seedling emergence of some species.

## Effects of erosion micro-topography on substrate physicochemical properties

The relationship between topography and the spatial variability of soil properties has received considerable attention (Ceddia et al., 2009; Shit et al., 2016; Wang et al., 2017). Similar to these studies, our study found that the erosion micro-topography on weathered waste dumps influenced the substrate's physicochemical properties. The discrepancy in the mechanical composition may be attributed to the following causes. As the main waste disposal site in the mining process, soil erosion in the waste dumps is more severe than that of original natural surfaces (Shi et al., 2021). Local catchment, infiltration, and freeze–thawing heavily influence the development of soil erosion (Gong et al., 2019), whereas the snowmelt runoff of diurnal and seasonal permafrost mainly affects cold and high-latitude regions (Ban et al., 2017), similar to our study area.

Artificially piled waste dumps consist of loose substrates that can easily be transported and deposited under snowmelt runoff. This can lead to sediment concentrating along the gully and reaching saturation within a short runoff length. As a result, the terrain slope might slightly drop, and expanding roughness of the partial terrain can result in a smaller flow capacity and concentrated sediment deposits (di Stefano et al., 2000). However, the process of gully development can be slow. In contrast, rills often develop much more quickly and can change into a gully if sufficient runoff is available to continue their development (Hancock et al., 2008). Thus, the erosion of rills is relatively milder compared to gullies. In addition, local wind velocity can lead to strong wind erosion on bare slopes. Fine grain content was the lowest in the ephemeral gully and bare slope but the highest in the deposit body. The middle-coarse grain and coarse grain content were the highest in the ephemeral gully and lowest in the deposit body. No significant differences were observed between the bare slope and rill for coarse grains. Giant grains are too heavy to be transported by runoff, and thus likely had the highest content on the bare slope but were extremely low in the deposit body. In contrast, its content showed no significant difference between the rill and ephemeral gully.

The CWC content was highest in the ephemeral gully, which may be attributed to the climate conditions that were associated with the sampling day. Sampling was performed in spring after a long period of the freeze–thawing process. It was found that the soil moisture content increased and soil cohesion decreased in soils that underwent freeze–thawing (Kreyling et al., 2010).

Electrical conductivity is often used as an indicator of soil salinity (Friedman, 2005). In this study, the discrepancy in EC might be explained by other factors affecting the conductivity value, including temperature, moisture, and soil texture. For

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example, when the soil water temperature is higher, ions become more active and move more quickly, leading to higher conductivity flows and thus an increase in EC values (Bai et al., 2013). In addition, higher soil moisture helps to free up the ions and increases the EC values. Soil texture further affects EC through moisture: different sizes of soil particles can create different spaces to hold water particles (Othaman et al., 2020). In this study, EC values were the lowest for the rill and the highest for the deposit body. This result may be attributed to the substrate temperature and SWC of the 0–5 cm layer, which was relatively lower for the rill and higher for the deposit body.

## Effects of erosion micro-topography on micro-climates and hydrothermal conditions

In soil heat physics, the soil temperature is known to be dependent on other factors, including meteorological conditions (e.g., global surface radiation and air temperature), soil physical properties (e.g., water content and texture), topographical variables (e.g., elevation, slope gradient, and aspect), and other surface characteristics (e.g., ground litter stores and albedo of surface) (Kang et al., 2000). The soil albedo can be affected by soil water content and surface roughness (Matthias et al., 2000; Liu et al., 2008). In our study, the substrate temperature of the bare slope in the 0–5 cm layer was higher, while the air temperature in the rill showed the highest values in H1 and H2. The latter is likely to be due to the lower SWC of the 0–5 cm layer, and the surface of the bare slope is coarser than that of the rill due to sheet erosion on the bare slope. Consequently, the rill's substrate albedo was higher, leading to a higher air temperature, while a lower temperature was detected for the 0–5 cm substrate layer in the rill. Air humidity has been shown to act irregularly within micro-habitats. However, the SWC of each layer in the deposit body and the SWC of the 5–10 cm layer in the ephemeral gully for H1 and H2 were noticeably higher than those in other micro-topographies, while it was found that there was no significant discrepancy in the deep soil moisture of different micro-topographies (Gou et al., 2021). This is mainly ascribed to the snowmelt action in the ephemeral gully during early spring, where snow mostly accumulates, but also to the light precipitation before H1, causing water to accumulate in the deposit body with low evaporation (due to low temperature). The rapid decline of SWC in the upper substrate of the deposit body indicated a bad water retaining property. However, it was found on the Loess Plateau of China that the soil water retaining property in platform was better than that in ephemeral gully and bare slope (Ma et al., 2018).

For the specific correlations between each environmental factor (Supplementary Figure S1), especially between substrate mechanical composition and substrate hydrothermal condition, we concluded that during the initial seedling emergence, when the temperature and humidity were lower, SWC did not significantly correlate to substrate mechanical composition. SWC showed a significant correlation to substrate mechanical composition for the middle and late periods when the humidity was higher due to precipitation. For the substrate temperature, the entire period of seedling emergence significantly correlated to substrate mechanical composition, especially in H4, which had a dry and hot climate. As a result, the substrate mechanical composition affected seedling emergence indirectly by influencing the hydrothermal conditions.

## Effects of an erosion micro-habitat on seedling emergence

Overall, seedling densities in the ephemeral gully and deposit body were evidently higher than those in the rill and bare slope, and a discrepancy was observed in the species composition. For example, only *Salsola collina* emerged on the bare slope, while *Artemisia annua*, *Salsola collina*, *Setaria viridis*, and *Tribulus terrestris* were present in other micro-habitats. Furthermore, the *Salsola collina* seedling density in the rill was the highest among the four micro-habitats. This indicates that the rill can provide a safe site for its emergence, which is mainly due to the germination niche of *Salsola collina*. The higher density of *Salsola collina* and *Setaria virids* in the ephemeral gully and deposit body also indicates that these two plants can act as the pioneer species for vegetation restoration. This phenomenon was also found on the Miocene clays of northeast Spain, where plants including *Artemisia herba-alba*, *Lygeum spartum*, and *Salsola vermiculata* tended to colonize in the eroded areas (Guerrero-Campo and Montserrat-Martí, 2004).

The results of the RF analysis indicate that micro-topography type was the main factor affecting seedling density. The temporal dynamics revealed the response of seedling emergence to micro-climates and hydrothermal conditions. In our study, seedling densities on the bare slope and deposit body were lower than those in the rill and ephemeral gully in S1. These results may be explained by the sampling season and climate: sampling was performed in early spring without prior precipitation, where snowmelt occurred more frequently in the rill and ephemeral gully, leading to a higher SWC in the rill and ephemeral gully than that on the bare slope and deposit body. When the first precipitation event occurred after S1, the SWC and the number of seedlings of the deposit body increased rapidly. Concurrently, the runoff carried seeds and destroyed the seedlings in the rill and ephemeral gully. Thus, the seedling densities in the rill and ephemeral gully for S2 and S3 were lower than that in the deposit body. The seedling density in the ephemeral gully was highest for S4, even higher than in the deposit body. However, the seedling density in the rill was the lowest due to the light precipitation between S3 and S4. This led to a slight runoff mostly in the rill, and therefore destroyed the seedlings and transported seeds to the ephemeral gully and bare slope.

Due to the higher temperature and the flat and loose structure of the deposit body, enhanced evaporation led to a lower SWC and fewer seedlings. Seedling density in the deposit body was the highest for S5, exceeding that in the rill. This is mainly due to a heavy rain event between S4 and S5, which led to strong runoff in the ephemeral gully that destroyed the seedlings and transported seeds to the deposit body. The plants that colonized the deposit body can reduce evaporation. In H4 during late spring, the substrate temperature of the rill was much lower than on the bare slope. Thus, the rill may provide a better temperature for seedling emergence than the bare slope. Based on the combined RDA, RF, and ROC curve results, it can be concluded that the ephemeral gully and deposit body were the main micro-topographies that prompted seedling emergence. Many factors led to this phenomenon, mainly consisting of air humidity, substrate temperature, and SWC. The latter was primarily affected by snowmelt action and runoff. In addition, the ability of the micro-topographies to capture a seed can differ. For example, the rill and ephemeral gully may trap a seed *via* debris or cracks, while the bare slope may lose a seed by gravity or wind, and the deposit body may gain seeds through runoff (even though runoff can remove some seeds in the rill and ephemeral gully).

## Inspirations for vegetation restoration on landfills

The waste dumps in arid and semiarid areas face considerable challenges in vegetation restoration due to poor environmental conditions. Here, the mechanism of specific micro-habitats driving seedling emergence was identified, which can provide a framework for natural vegetation restoration. Our study may also be useful for human intervention to successfully rehabilitate disturbed areas. For example, *Salsola collina* was the pioneer species in most of our micro-habitats, especially during early spring when the temperature was lower. The survival strategy of *Salsola collina* is to germinate at lower temperatures using the snowmelt water (or little precipitation) when the evaporation is low. Consequently, the emerged seedlings can root and colonize successfully to resist environmental stress in dry and hot weather. The colonized plants can also provide favorable conditions for the germination of other species. Consequently, we can sow the seeds of *Salsola collina* in suitable micro-habitats with great substrate water content, such as rills, ephemeral gullies, and deposit bodies during early spring. This will enhance the seedling's survival and colonization and provide favorable conditions for other seeds and seedlings, thus ensuring the success of vegetation restoration. We can also follow this approach for other disturbed areas. For instance, it is necessary to first investigate the pioneer species and find micro-habitats that can provide favorable conditions. The seeds of these pioneer species can then be sowed in favorable micro-habitats to establish the initial phase of vegetation restoration, which makes the restoration more precise, sustainable, and economical.

# Conclusion

Erosion micro-topographies, including bare slopes, rills, ephemeral gullies, and deposit bodies, provide micro-habitats whose substrate physicochemical properties, micro-climates, and hydrothermal conditions vary. Our study has shown that the ephemeral gully and deposit body had higher seedling emergence than those on the bare slope and rill. In addition, the rill, ephemeral gully, and deposit body had more species than the bare slope. Specifically, *Salsola collina* and *Setaria virids* emerged as the dominant species and can be considered the pioneer species in the ephemeral gully and deposit body, while the rill can provide a safe site for *Salsola collina*. This phenomenon mainly occurred due to snowmelt and runoff, which contributed to the discrepancy in substrate temperature and substrate water content among the micro-habitats. This led the ephemeral gully and deposit body to provide micro-habitats with lower substrate temperature and higher substrate water content, which were beneficial to seedling emergence. This mechanism can provide a framework for natural vegetation restoration, which is a pressing issue in the mining industry. Combined with the survival strategies of pioneer species, micro-habitats can provide favorable conditions for seed germination and plant colonization to resist environmental stress. This may be useful in generating more successful, precise, sustainable, and economic human restoration interventions. In addition, the seed germination niche of different species can contribute to species variation. Successful restoration also includes the survival of seedlings and plant colonization, which should be considered in future investigations.

# Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

# Author contributions

Conceptualization, methodology, visualization, and investigation: DW; writing—original draft, software, and formal analysis: JQ; visualization: YZ; data curation: ML; funding acquisition: DW; supervision: Xiaoliang Zhao; writing—review and editing: YQ.

# Funding

This work was supported by the National Natural Science Foundation of China (51874160), the Liaoning Province "Millions of Talents Program" funded project, the Scientific Collaborative

Projects "Silk Road 1+1" of the Ministry of Education (P20210121076), and the project supported by the discipline innovation team of Liaoning Technical University (LNTU20TD-01).

## Acknowledgments

The authors thank Yang Liu, Yi Liu, and Ziqian Zhang for their hard work during the field investigation.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary Material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.1040814/full#supplementary-material

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