

Article

Soil Eco-Hydrological Responses to Mining-Induced Ground Fissures and Vegetation Types in a Semi-Arid Coalfield

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Abstract

Ground fissures induced by coal mining severely disrupt eco-hydrological processes in semi-arid regions. To elucidate the underlying coupling mechanisms between fissure physical disturbances and plant–soil system regulation, this study conducted in situ soil infiltration measurements and daytime micro-lysimeter water-loss observations across four distance gradients (20, 50, 100, and 200 cm) from fissures under four surface cover types in the Shendong coalfield. Vertical soil moisture profiles (0–180 cm) and microscopic pore architectures were also reconstructed. Under the summer sunny-day conditions examined, steady infiltration and daytime micro-lysimeter water loss generally increased toward the fissure, indicating a spatially localized enhancement of water entry and atmospheric water loss. The observed transition occurred between 100 and 200 cm, although the current distance design does not permit a universal threshold to be defined. Deep soil moisture beneath *A. desertorum* was lower at 150–180 cm near the fissure; this pattern may reflect the combined effects of fissure-facilitated drainage and root water uptake. BSC-covered surfaces exhibited relatively low infiltration and daytime water loss, consistent with a surface-sealing and moisture-buffering effect reported in previous studies. These findings provide preliminary field-based evidence for spatially differentiated restoration around mining-induced fissures, although the proposed management implications require validation through long-term and multi-season field monitoring.

Keywords: coal mining subsidence; ground fissures; soil infiltration; daytime micro-lysimeter water loss; biological soil crusts (BSCs); ecohydrological trade-offs



Academic Editor: Rajesh Kumar Jyothi

Received: 13 June 2026

Revised: 3 July 2026

Accepted: 7 July 2026

Published: 10 July 2026

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1. Introduction

Against the macroscopic background of intensifying global climate change and land degradation, eco-hydrological processes in arid and semi-arid regions have emerged as a core focus in Earth system science [1–3]. In these water-limited ecosystems, soil moisture serves not only as the critical hub connecting the soil–plant–atmosphere continuum (SPAC) but also as the primary limiting factor determining the survival of surface vegetation, community succession, and overall ecosystem resilience [4,5]. The ecotone between the

Loess Plateau and the Mu Us Sandy Land in central-western China (e.g., the Shendong coal base) is not only one of the most ecologically fragile regions in the world but also the largest coal mining center globally [6,7]. This region constantly faces the dual water stress of scarce precipitation and intense potential evapotranspiration. In recent years, high-intensity longwall mining with large mining heights has triggered severe overburden strata movement and surface subsidence, inducing a massive network of tensile ground fissures on the surface [8,9]. These ground fissures can alter the hydrological functioning of the vadose zone and increase the risk of soil moisture depletion and land degradation in dryland mining areas [10,11].

As unnatural physical disturbance interfaces, mining-induced ground fissures fundamentally reshape the pore hydrodynamic characteristics of the matrix soil and trigger significant leakage-chimney dual effects at the micro-scale [12–14]. The mechanical properties and damage evolution of deep underground strata are fundamentally altered by extreme physical stressors, which further induce complex non-Darcy seepage behaviors in the post-failure matrices [15,16]. Similarly, in the surface soil layer, mining-induced ground fissures fundamentally reshape the pore hydrodynamic characteristics. During precipitation or surface runoff events, fissures may reduce the continuity of capillary barriers in the near-surface soil and facilitate preferential infiltration along cracks and macropores [17–19]. During dry periods, fissure walls may also increase the exchange interface between subsurface soil air and the atmosphere, potentially enhancing vapor diffusion and daytime water loss. These two processes are hereafter referred to as relative infiltration enhancement and daytime water-loss enhancement, rather than direct estimates of deep seepage flux or chimney evaporation flux [20,21].

Studies have shown that the remodeling of soil hydrodynamic parameters by fissures exhibits strong spatial heterogeneity, with the disturbance intensity typically presenting a non-linear spatial decay gradient as the distance from the fissure increases [22].

However, most existing studies still treat the subsidence area as a relatively homogeneous disturbed zone. A knowledge gap remains regarding the spatial transition interval of soil hydrological responses around mining-induced fissures, particularly the vertical redistribution of soil moisture below 100 cm [23,24]. Vegetation restoration is widely recognized as a key pathway for the reconstruction of damaged mine ecosystems (i.e., Nature-based Solutions, NbS) [25]. However, different cover types exhibit distinctly different eco-hydrological regulatory strategies for soil physical structure and evaporation-infiltration (evapo-infiltration) processes through root penetration, canopy shading, and surface coverage [26,27]. In semi-arid sandy mining areas, deep-rooted pioneer semi-shrubs and shallow-rooted herbs are widely applied in ecological reclamation. Concurrently, biological soil crusts (BSCs), which are widely distributed on stabilized sandy surfaces, are commonly regarded as ecosystem engineers [28–31]. Previous studies have reported that BSCs can modify near-surface soil structure, pore connectivity, surface roughness, and hydraulic properties through the development of crust structure, extracellular polymeric substances (EPS), and microbial filaments [32–35]. These changes may influence both water infiltration and soil evaporation. However, the direction and magnitude of the hydrological effects of BSCs vary with crust type, developmental stage, soil texture, antecedent moisture, and environmental conditions. In mining-affected sandy soils, it remains unclear whether BSC-covered surfaces maintain relatively low infiltration and water loss under fissure disturbance and how these responses vary with distance from ground fissures.

In summary, elucidating the coupling mechanisms between the spatial gradient of fissure physical disturbance and plant–soil system regulation is crucial for the precision restoration of impaired eco-hydrological processes in semi-arid mining areas. Based on this, taking typical tensile coal mining subsidence ground fissures in the semi-arid Shendong

mining area as the object, this study selected four representative surface cover types (deep-rooted *Artemisia desertorum*, shallow-rooted *Poa annua*, BSCs, and bare land as a background control) to conduct high-precision in situ soil infiltration and daytime micro-lysimeter water loss experiments along different horizontal distance gradients (20, 50, 100, and 200 cm) perpendicular to the fissures. Additionally, vertical soil moisture profiles up to 180 cm deep and microscopic pore architectures were reconstructed. This study aims to:

- (1) Characterize the distance-dependent gradients of infiltration, daytime micro-lysimeter water loss, and soil moisture profiles around mining-induced fissures;
- (2) Compare the infiltration, daytime water-loss, and soil-moisture responses of deep-rooted vegetation and BSC-covered surfaces along the fissure-distance gradient;
- (3) Evaluate the associations between measured soil physical properties, including bulk density and pore characteristics, and the observed infiltration and daytime water-loss patterns.

This study provides field-based evidence for understanding microhabitat-level eco-hydrological heterogeneity in semi-arid sandy coal-mining areas with comparable soil and vegetation conditions.

2. Materials and Methods

2.1. Study Area

This study was conducted in the Daliuta mining area (110°16' E, 39°15' N), located in the core of the Shendong coal base, China (Figure 1a). Geomorphologically, it represents a typical ecologically fragile ecotone transitioning from the hilly-gully region of the Loess Plateau to the Mu Us Sandy Land. The climate is characterized as an arid and semi-arid plateau continental climate. It exhibits severe “water stress,” with a multi-year average precipitation of merely 413.5 mm (highly concentrated in summer) and an annual average potential evapotranspiration reaching up to 2111 mm. The surface is covered by a ~30 m thick loose loess layer, and the substrate soils are predominantly aeolian sandy soil and hard loessial soil, which are loose in structure and possess extremely poor water-retention and erosion-resistance capacities. In background areas undisturbed by severe mining activities, the dominant surface covers consist of the deep-rooted pioneer semi-shrub *Artemisia desertorum*, the shallow-rooted herb *Poa annua*, and widely developed BSCs.

The in situ experimental site was deployed at the super-large working face (Figure 1b–d). Characterized by a shallow burial depth and a thick coal seam (~7 m), this site belongs to a high-intensity multi-seam secondary mining area. Longwall mining-induced marked surface deformation and tensile ground fissure swarms, with a maximum observed width of 42 cm, thereby altering the native soil–plant hydrological system (Figure 1e).

Based on subsidence contour maps and dynamic surface monitoring, the surface subsidence had passed the active phase and entered a relatively stable state by late April. An unmined area with comparable topographic and vegetation backgrounds was identified during field reconnaissance. However, simultaneous eco-hydrological measurements were not conducted there. Therefore, the present study focuses on relative fissure-distance effects within the subsidence area and cannot fully separate regional subsidence effects from local fissure effects.

2.2. Experimental Design and Spatial Sampling Strategy

The experiment was carried out in July 2024 during the vigorous vegetation growth period (Figure 1f). At this time, the morphology of the surface fissures induced by the advancement of the 122105 working face had fully developed and entered a relatively stable phase. Following comprehensive field reconnaissance, a continuous main tensile

fissure with a typical mechanical morphology (average width of ~30 cm and average visible depth of ~80 cm) was selected as the zero-point baseline for physical spatial disturbance.

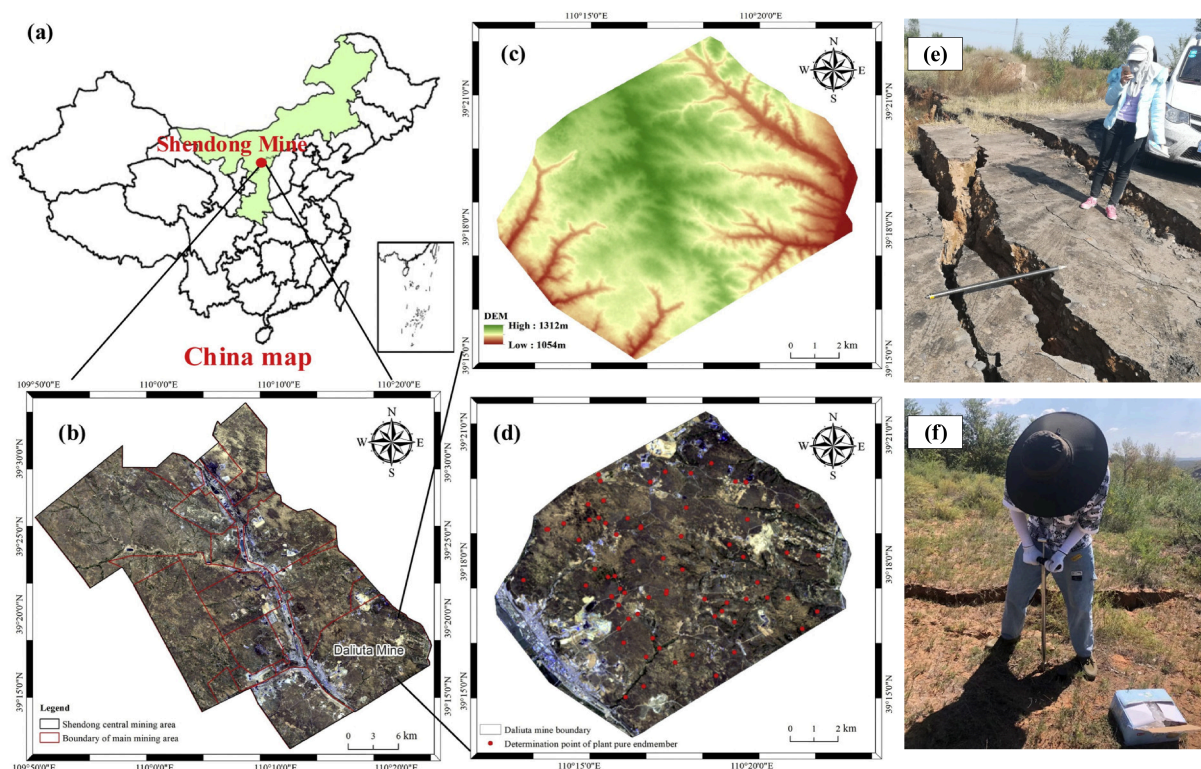


Figure 1. Location of the study area and typical microhabitats in the semi-arid Shendong coalfield. (a) Location of the Shendong coalfield within China; (b) spatial distribution of the Shendong central mining area and the main mining-area boundary, with the Daliuta Mine marked as the study region; (c) DEM-derived topographic characteristics of the study area; (d) remote-sensing image of the Daliuta mining area showing the mine boundary and field sampling points; (e) typical large tensile ground fissures induced by underground coal mining and surface subsidence; (f) field setup for in situ ecohydrological measurements and soil sampling adjacent to a mining-induced ground fissure.

A two-factor completely randomized block design was strictly adopted in this experiment, structured as horizontal distance from fissure $\times$ surface cover type (Figure 2):

- (1) Starting from the edge of the fissure and proceeding along the normal direction perpendicular to the fissure strike, four spatial distance gradients were precisely established: 20 cm (near-fissure zone), 50 cm (intermediate near-fissure zone), 100 cm (transition zone), and 200 cm (far-fissure reference within the subsidence area).
- (2) At each of the aforementioned distance gradients, four typical surface microhabitats were selected for comparative testing: (1) deep-rooted semi-shrub (*A. desertorum*), with an average individual plant height of 60–80 cm; (2) shallow-rooted herb (*P. annua*), with roots primarily concentrated in the 0–20 cm soil layer; (3) BSCs, for which mature and visually intact crust-covered surfaces were selected based on surface continuity. The biological composition and structural properties of the crusts were not measured directly; and (4) bare land, serving as a non-vegetated surface-cover reference, created by manually removing surface litter to ensure no biological cover. To eliminate marginal errors caused by plant individual sizes, all vegetation monitoring plots were strictly controlled within an effective hydrological influence radius of 1 m from the stem base of the target plants. For each distance $\times$ vegetation combination treatment, 3 independent spatial replicates were established, resulting in a total of 48 micro-hydrological observation plots.

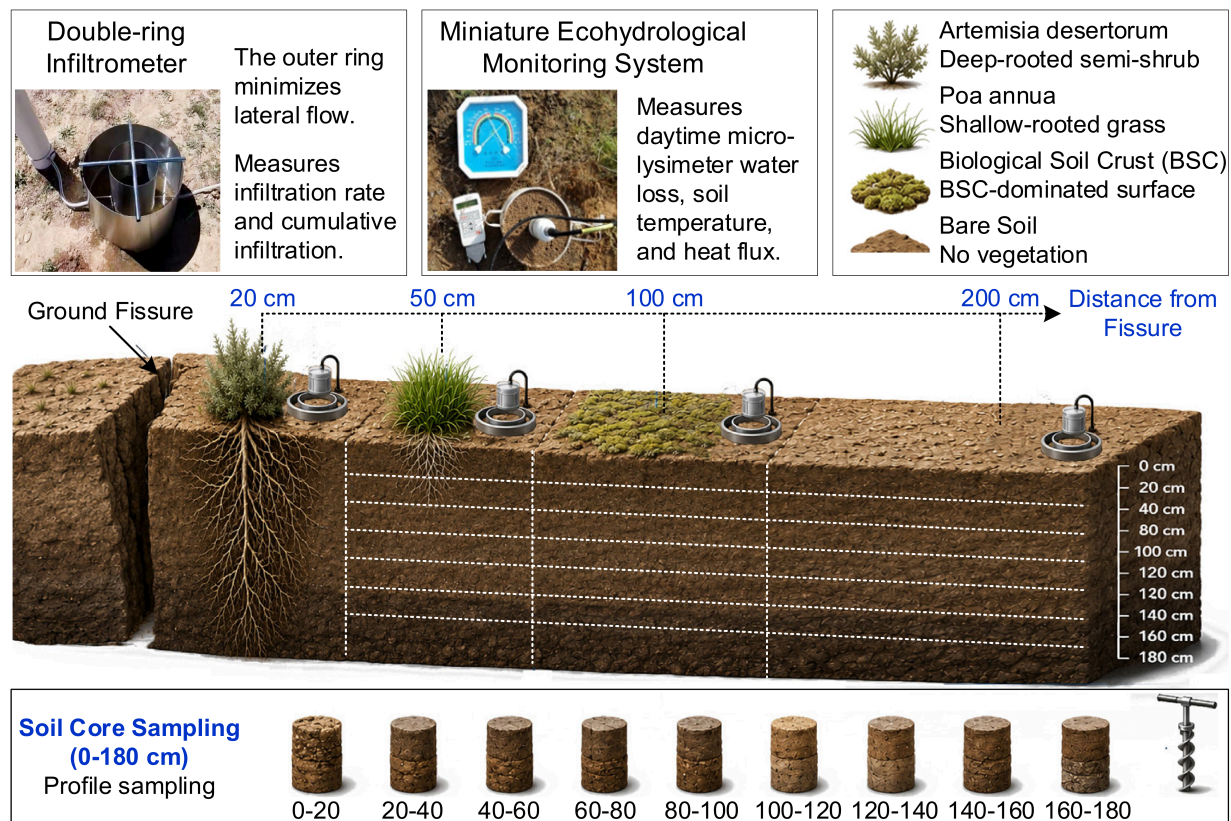


Figure 2. Conceptual diagram of the experimental design and in situ eco-hydrological monitoring layout.

Figure 2 was prepared as a composite conceptual illustration. The ChatGPT image-generation function provided by OpenAI was used to assist in preparing some schematic elements, including the soil profile, plant root systems, and representative background features. The photographs of the double-ring infiltrrometer and miniature ecohydrological monitoring system are original field photographs taken by the authors. GenAI was not used for study design, data collection, data analysis, or interpretation. The authors reviewed and verified the figure and take full responsibility for its content.

2.3. In Situ Measurement of Soil Eco-Hydrological Dynamics

2.3.1. Soil Water Infiltration

An internationally standardized double-ring infiltrrometer was utilized to measure the in situ soil water infiltration rate to block errors caused by lateral seepage. The apparatus consisted of stainless steel double concentric rings (inner ring diameter of 25 cm, outer ring diameter of 50 cm, both 25 cm in height).

The double rings were concentrically and steadily pressed into the soil to a depth of approximately 10 cm. To maximally prevent the hydraulic scouring of the initial water injection from mechanically damaging the fragile surface structure (especially the physical integrity of the BSCs), a porous, flexible plastic buffer mesh was pre-laid on the soil surface within the inner ring and withdrawn extremely slowly once the water level reached a constant height.

The inner ring was automatically supplied with water through a customized Mariotte bottle (height 160 cm, diameter 13 cm, equipped with an external liquid level scale tube accurate to 0.1 cm) to precisely maintain a constant static head of 5 cm. The water level in the outer ring was manually supplemented synchronously to maintain the same height, thereby completely eliminating lateral capillary potential gradients in the matrix.

During the initial 20 min (the intense infiltration period), the liquid level drawdown in the Mariotte bottle was recorded every 1 min. After 20 min, the recording interval was adjusted to every 5 min depending on the deceleration of infiltration. Continuous observation lasted for approximately 60 min (until the fluctuation in the infiltration rate over 3 consecutive periods was <10%, which was deemed as reaching a steady infiltration state). The soil infiltration rate (I , cm/min) was calculated using the following equation:

$$I = \frac{\Delta Q}{A \cdot \Delta t} \quad (1)$$

where ΔQ is the volume of infiltrated water (cm³) during the time interval Δt (min), and A is the surface area of the soil within the inner ring (cm²). Based on this, the initial infiltration rate (average value of 0–3 min), steady infiltration rate, and the overall average infiltration rate were extracted.

2.3.2. Daytime Micro-Lysimeter Water Loss

Because aboveground plant tissues were retained in the vegetated micro-lysimeters, the measured mass loss may include both soil evaporation and short-term transpiration. Therefore, the variable is conservatively termed “daytime micro-lysimeter water loss” rather than pure soil evaporation.

Measurements were conducted from 08:00 to 18:00 on one calm and sunny summer day. Therefore, the observations represent cumulative 10 h daytime water loss rather than 24 h daily evaporation, and nighttime condensation or vapor adsorption was not captured.

Customized undisturbed soil micro-lysimeters were employed to quantify cumulative daytime water loss from each surface-cover treatment.

The evaporator consisted of a thin-walled stainless-steel cylinder (inner diameter 10 cm, height 15 cm). It was vertically pressed into each microhabitat to extract an undisturbed soil core preserving the original pore structure and vegetation cover. After smoothly cutting off the excess soil at the bottom, high-permeability quantitative filter paper was tightly wrapped and sealed at the base. This step aimed to block the downward leakage of gravitational water while allowing natural gas exchange. After precise weighing, the lysimeter was placed back in situ into the pre-dug soil hole, ensuring its surface was completely flush with the surrounding natural ground surface to maintain consistent thermodynamic radiation and aerodynamic roughness boundary conditions.

The monitoring was conducted on a typical calm and sunny day. From 08:00 to 18:00, the lysimeters were carefully extracted every 2 h and rapidly weighed using a portable high-precision windproof electronic balance (accuracy 0.01 g).

The mass deficit between two adjacent time points represented the water loss during that period, which was subsequently converted to water-loss depth (mm) based on the cross-sectional area of the cylinder.

2.4. Deep Soil Moisture Profiling and Physicochemical Analysis

2.4.1. Deep Soil Moisture Profiles

To characterize the vertical distribution of soil moisture along the fissure-distance gradient, profile soil samples were collected using a standard soil auger with an inner diameter of 5 cm. For each distance $\times$ surface-cover combination, three independent soil profiles were collected, corresponding to the three spatial replicates used in the eco-hydrological measurements. Soil augering points were located adjacent to, but not overlapping with, the infiltration and micro-lysimeter measurement points to avoid artificial disturbance.

Each profile was sampled at 11 depths: 0, 5, 10, 20, 40, 60, 80, 100, 120, 150, and 180 cm. In total, 528 soil moisture samples were obtained, calculated as 4 distance levels $\times$ 4 surface-

cover types $\times$ 3 replicates $\times$ 11 depths. Immediately after collection, the soil samples were sealed in aluminum boxes with waterproof tape, refrigerated, and transported to the laboratory. Gravimetric water content (%) was determined using the oven-drying method at 105 °C for 24 h to constant weight. Values shown in the soil moisture profiles represent means of three independent profiles.

2.4.2. Soil Pore Architecture and Mechanical Composition

Microscopic pore structure serves as the physical basis for explaining macroscopic hydrodynamic variations. In the 10–20 cm active soil layer, which dominates plant root-hydrological interactions, undisturbed soil cores were collected using standard 100 cm³ cutting rings (3 replicates per treatment). In the laboratory, the classic cutting ring immersion-weighing method was applied to determine the soil bulk density (ρ_b) and multi-level porosity parameters.

The weighing indicators included: the mass of the empty cutting ring (W_1), the total mass of the cutting ring and saturated soil after water absorption (W_2), the mass of the cutting ring and dry soil after oven-drying at 105 °C (W_3), and the mass of the cutting ring and wet soil after the saturated undisturbed soil rested on a dry sand box for 12 h to drain gravitational water (W_4). The calculation formulas for core physical parameters were as follows:

Soil bulk density (ρ_b , g/cm³):

$$\rho_b = \frac{W_3 - W_1}{V} \quad (2)$$

Total porosity (TP , %):

$$TP = \frac{W_2 - W_3}{V \times \rho_w} \times 100\% \quad (3)$$

Capillary porosity (CP , %):

$$CP = \frac{W_4 - W_3}{V \times \rho_w} \times 100\% \quad (4)$$

Non-capillary porosity/Aeration porosity (NCP , %):

$$NCP = TP - CP \quad (5)$$

where V is the standard volume of the cutting ring (100 cm³), and ρ_w is the density of water (approximately 1.0 g/cm³). NCP characterizes the proportion of macropores dominating the rapid downward infiltration of water.

Furthermore, mixed bulk soil samples from the same depth were collected, naturally air-dried, carefully cleared of animal and plant residues, and passed through a 2 mm sieve. The particle size distribution was precisely determined using a Mastersizer 3000 laser diffraction particle size analyzer (Malvern Panalytical, Malvern, Worcestershire, UK). According to the United States Department of Agriculture (USDA) classification standards, the particles were strictly classified into clay (<0.002 mm), silt (0.002–0.05 mm), and sand (0.05–2 mm).

2.5. Statistical Analysis

All original experimental data were entered into Microsoft Excel 2016, and the results are reported as mean $\pm$ standard error (SE). Statistical analyses were performed using OriginPro 2021 and SPSS Statistics 26.0.

Prior to parametric testing, normality and homogeneity of variance were evaluated using the Shapiro–Wilk test and Levene’s test, respectively. Because the field experiment

followed a factorial design, two-way ANOVA was used to test the main effects of fissure distance, surface-cover type, and their interaction on infiltration parameters, cumulative daytime micro-lysimeter water loss, and soil physical properties. When a significant interaction was detected, simple-effect analyses were conducted within each surface-cover type or distance level. Post hoc comparisons were performed using Duncan's multiple range test at $\alpha = 0.05$.

Pearson correlation analysis was used to evaluate the associations among infiltration parameters, cumulative daytime micro-lysimeter water loss, soil bulk density, porosity variables, and particle-size composition. Statistical significance was assessed at $p < 0.05$ and $p < 0.01$.

To provide a relative quantification of fissure-induced hydrological amplification, the Infiltration Enhancement Coefficient (IEC) and Daytime Water-Loss Enhancement Coefficient (WLEC) were calculated using the 200 cm treatment of the same surface-cover type as the internal far-fissure reference. These coefficients were used as relative indicators rather than direct estimates of seepage flux or chimney-evaporation flux.

$$IEC_{d,v} = \frac{I_{d,v} - I_{200,v}}{I_{200,v}} \times 100\% \quad (6)$$

$$WLEC_{d,v} = \frac{E_{d,v} - E_{200,v}}{E_{200,v}} \times 100\% \quad (7)$$

where *IEC* represents the Infiltration Enhancement Coefficient, *WLEC* represents the Daytime Water-Loss Enhancement Coefficient, *I* is the measured steady infiltration rate, *E* is the cumulative daytime micro-lysimeter water loss, *d* is the distance from the fissure (20, 50 or 100 cm), and *v* denotes the surface-cover type.

These indices quantify the relative enhancement associated with fissure proximity within the subsidence area and should not be interpreted as direct seepage fluxes or chimney-evaporation fluxes.

3. Results

3.1. Spatial Gradient Effects of Subsidence Fissures and Vegetation on Soil Infiltration

Two-way ANOVA showed that fissure distance and surface-cover type had significant main effects on all infiltration variables and cumulative daytime micro-lysimeter water loss, whereas their interaction effects were not significant for these hydrological variables (Tables 1 and 2). For soil physical properties, significant interaction effects were detected for total porosity and non-capillary porosity, indicating that the distance-dependent changes in these pore-structure variables varied among surface-cover types (Table 2).

Table 1. Soil infiltration and daytime micro-lysimeter water-loss characteristics under different surface-cover types at varying distances from subsidence fissures.

Surface Cover Type	Distance from Fissure (cm)	Initial Infiltration Rate (cm·min ^{−1})	Steady Infiltration Rate (cm·min ^{−1})	Average Infiltration Rate (cm·min ^{−1})	Cumulative Daytime Micro-Lysimeter Water Loss, 08:00–18:00 (mm)
BSCs	20	1.639 ± 0.021 ^d	0.844 ± 0.035 ^{ef}	0.979 ± 0.040 ^{de}	1.596 ± 0.120 ^{cd}
	50	1.466 ± 0.065 ^e	0.708 ± 0.048 ^f	0.825 ± 0.055 ^{ef}	1.347 ± 0.155 ^{de}
	100	1.335 ± 0.075 ^{ef}	0.604 ± 0.038 ^g	0.708 ± 0.045 ^{fg}	1.158 ± 0.180 ^{ef}
	200	1.205 ± 0.110 ^f	0.500 ± 0.085 ^h	0.591 ± 0.095 ^g	0.970 ± 0.250 ^f

Table 1. Cont.

Surface Cover Type	Distance from Fissure (cm)	Initial Infiltration Rate (cm·min ^{−1})	Steady Infiltration Rate (cm·min ^{−1})	Average Infiltration Rate (cm·min ^{−1})	Cumulative Daytime Micro-Lysimeter Water Loss, 08:00–18:00 (mm)
<i>Poa annua</i>	20	2.149 ± 0.015 ^b	1.054 ± 0.025 ^b	1.211 ± 0.025 ^b	2.105 ± 0.150 ^b
	50	1.906 ± 0.012 ^c	0.894 ± 0.020 ^{cd}	1.040 ± 0.028 ^c	1.810 ± 0.220 ^{bc}
	100	1.723 ± 0.018 ^d	0.773 ± 0.018 ^{def}	0.910 ± 0.022 ^{cd}	1.587 ± 0.250 ^{cde}
	200	1.539 ± 0.045 ^{de}	0.651 ± 0.035 ^{fg}	0.781 ± 0.042 ^{ef}	1.365 ± 0.320 ^{de}
<i>Artemisia desertorum</i>	20	2.495 ± 0.016 ^a	1.410 ± 0.008 ^a	1.545 ± 0.008 ^a	2.782 ± 0.180 ^a
	50	2.141 ± 0.018 ^b	1.162 ± 0.010 ^{ab}	1.305 ± 0.006 ^b	2.330 ± 0.220 ^{ab}
	100	1.873 ± 0.019 ^c	0.975 ± 0.008 ^{bc}	1.124 ± 0.007 ^{bc}	1.988 ± 0.250 ^b
	200	1.606 ± 0.035 ^d	0.788 ± 0.025 ^{cde}	0.942 ± 0.020 ^{cd}	1.646 ± 0.350 ^{cd}
Bare land	20	2.109 ± 0.065 ^{bc}	0.952 ± 0.055 ^{bcd}	1.130 ± 0.085 ^{bc}	1.677 ± 0.150 ^{cde}
	50	1.844 ± 0.095 ^c	0.814 ± 0.082 ^{cde}	0.975 ± 0.095 ^{cde}	1.460 ± 0.210 ^{cde}
	100	1.644 ± 0.145 ^d	0.710 ± 0.095 ^{efg}	0.858 ± 0.105 ^{def}	1.295 ± 0.240 ^{def}
	200	1.444 ± 0.210 ^e	0.606 ± 0.150 ^g	0.741 ± 0.165 ^{fg}	1.131 ± 0.310 ^{ef}

Note: Data are presented as mean ± standard error (SE). Different lowercase letters in the same column indicate significant differences among treatments at the $p < 0.05$ level. BSCs: Biological soil crusts.

Table 2. Two-way ANOVA results for the effects of fissure distance, surface-cover type, and their interaction on soil eco-hydrological and physical variables.

Response Variable	Distance F(3,32)	<i>p</i>	Surface Cover F(3,32)	<i>p</i>	Distance × Cover F(9,32)	<i>p</i>
Initial infiltration rate	46.65	<0.001	40.11	<0.001	0.97	0.480
Steady infiltration rate	37.74	<0.001	35.70	<0.001	0.89	0.544
Average infiltration rate	32.16	<0.001	30.59	<0.001	0.41	0.921
Cumulative daytime micro-lysimeter water loss	7.93	<0.001	12.60	<0.001	0.23	0.987
Total porosity	19.44	<0.001	0.71	0.552	4.68	<0.001
Capillary porosity	9.87	<0.001	5.64	0.003	0.22	0.989
Non-capillary porosity	1.66	0.194	3.90	0.018	4.18	0.001
Bulk density	6.86	0.001	4.56	0.009	0.33	0.957

Note: Distance and surface cover were treated as fixed factors. The residual degree of freedom was 32 because each distance × surface-cover combination had three independent replicates. Significant effects are indicated at $p < 0.05$.

Soil infiltration varied with both fissure distance and surface-cover type (Table 1; Figure 3). In general, infiltration rates were higher closer to the fissure and decreased toward the 200 cm far-fissure reference. For bare land, the steady infiltration rate was 0.952 cm min^{−1} at 20 cm and 0.606 cm min^{−1} at 200 cm, corresponding to a relative increase of 57.1%.

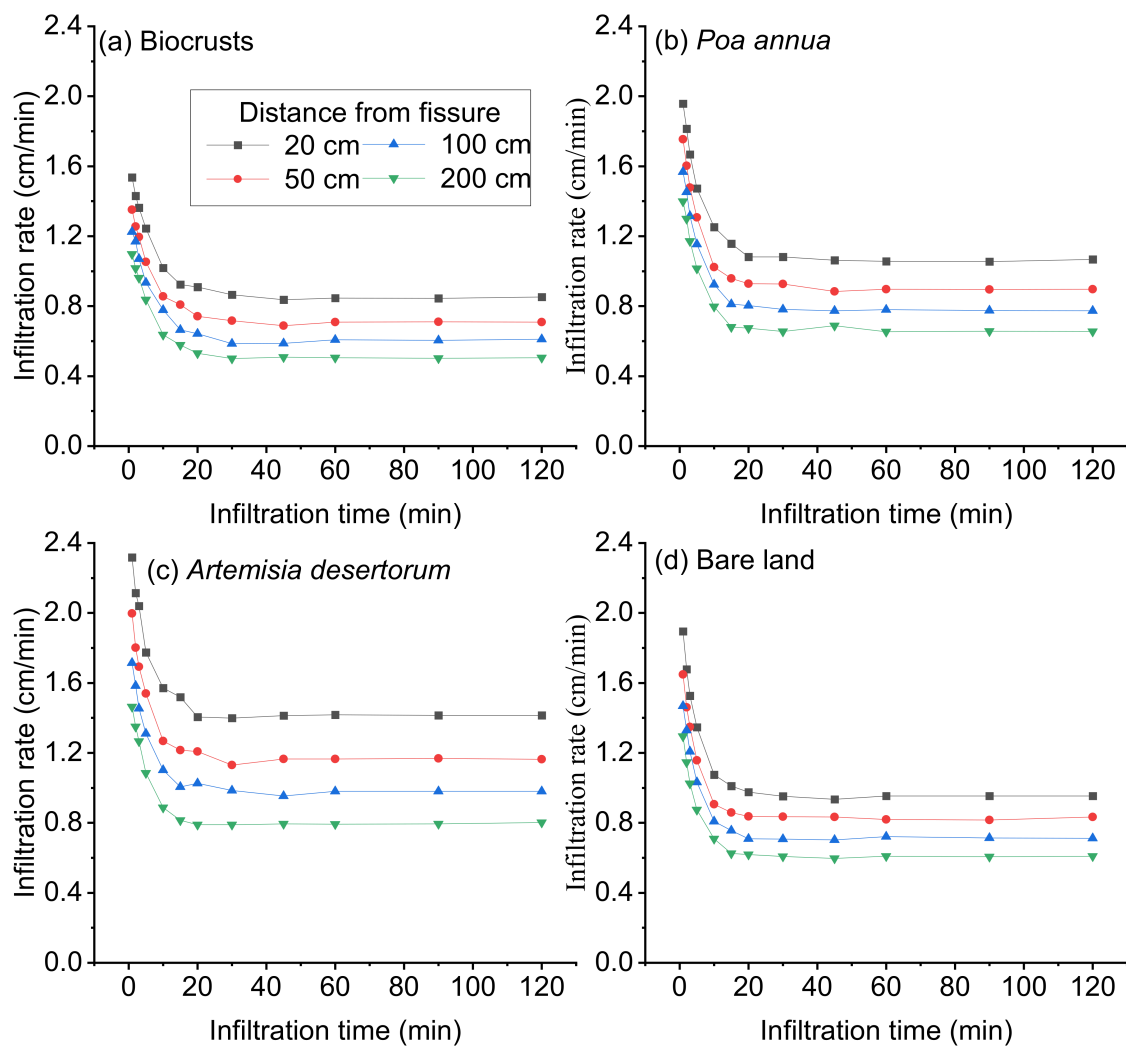


Figure 3. Dynamic curves of soil water infiltration rates under different surface-cover types and fissure-distance gradients.

Surface-cover type further modified the magnitude of this distance-dependent pattern. *A. desertorum* showed the highest numerical steady infiltration rate among all treatments, reaching $1.410 \text{ cm min}^{-1}$ at 20 cm from the fissure. This value was 48.1% higher than that of bare land at the same distance and 78.9% higher than the 200 cm *A. desertorum* treatment (Table 3). In contrast, BSC-covered plots showed comparatively low steady infiltration rates across the distance gradient, with a value of $0.844 \text{ cm min}^{-1}$ at 20 cm.

Table 3. Relative infiltration and Daytime Water-Loss Enhancement Coefficients using the 200 cm treatment as the internal far-fissure reference.

Surface Cover Type	Distance from Fissure (cm)	IEC (%)	WLEC (%)
BSCs	20	68.8	64.5
	50	41.6	38.9
	100	20.8	19.4
<i>P. annua</i>	20	61.9	54.2
	50	37.3	32.6
	100	18.7	16.3

Table 3. Cont.

Surface Cover Type	Distance from Fissure (cm)	IEC (%)	WLEC (%)
<i>A. desertorum</i>	20	78.9	69.0
	50	47.5	41.6
	100	23.7	20.8
Bare land	20	57.1	48.3
	50	34.3	29.1
	100	17.2	14.5

Note: IEC = Infiltration Enhancement Coefficient; WLEC = Daytime Water-Loss Enhancement Coefficient. Both indices were calculated relative to the 200 cm treatment of the same surface-cover type. These values represent relative enhancement within the subsidence area and should not be interpreted as direct seepage fluxes or chimney-evaporation fluxes.

3.2. Diurnal Dynamics of Daytime Micro-Lysimeter Water Loss Across Fissure-Distance Gradients

Cumulative daytime micro-lysimeter water loss showed a clear diurnal pattern, with relatively high increments around midday to early afternoon (Figure 4). Across the four surface-cover types, water loss was generally greater at shorter distances from the fissure and declined toward the 200 cm far-fissure reference (Table 1).

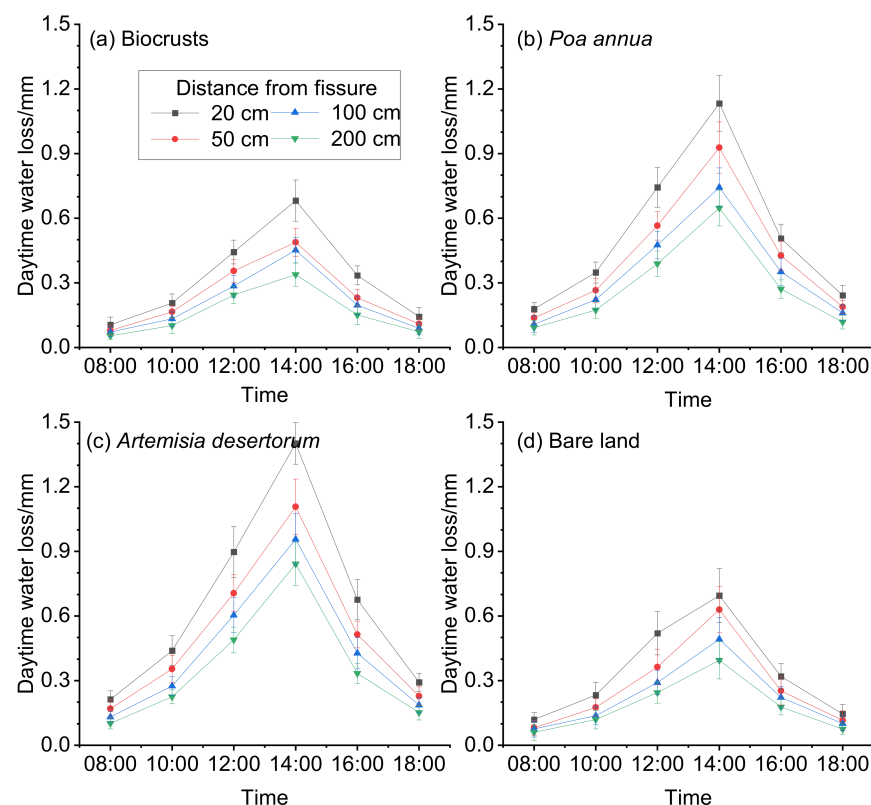


Figure 4. Diurnal dynamics of daytime micro-lysimeter water loss under different surface-cover types and fissure-distance gradients.

At 20 cm from the fissure, *A. desertorum* showed the highest cumulative daytime water loss, reaching 2.782 mm, which was 65.9% higher than bare land at the same distance. BSC-covered plots consistently showed comparatively low cumulative daytime water loss across the distance gradient. At 200 cm from the fissure, the BSC-covered treatment showed the lowest numerical value among all treatments, at 0.970 mm.

3.3. Vertical Redistribution of Deep Soil Moisture Profiles

Vertical soil moisture profiles showed distinct variations with depth, fissure distance, and surface-cover type (Figure 5). The 0–10 cm surface layer generally had relatively low gravimetric water content, whereas relatively higher water contents were observed mainly within the 40–100 cm depth interval.

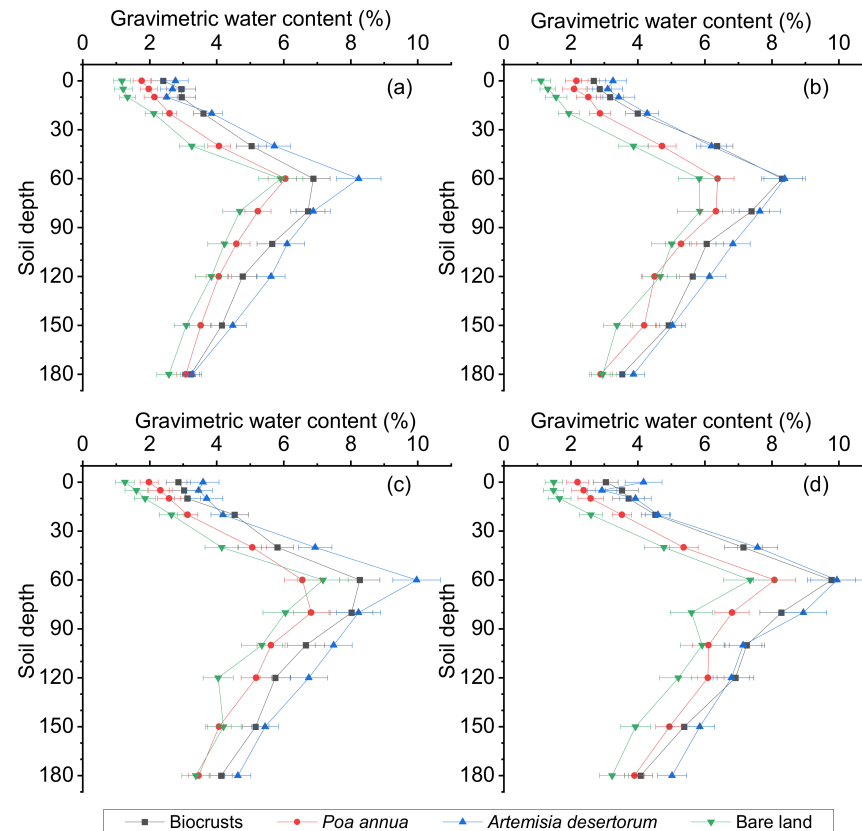


Figure 5. Vertical distribution profiles of soil gravimetric water content under different surface-cover types across the 0–180 cm soil profile at different fissure-distance gradients: (a) 20 cm; (b) 50 cm; (c) 100 cm; (d) 200 cm from the ground fissure.

In bare land, the gravimetric water content at 60 cm was 7.35% in the 200 cm far-fissure reference and 5.91% at 20 cm from the fissure, indicating lower mid-profile soil water content near the fissure.

- (1) In the 200 cm far-fissure reference, the bare land maintained a high moisture peak of 7.35% at 60 cm depth; however, when spatially approaching the fissure at 20 cm, the moisture content at 60 cm in the bare land plummeted to 5.91%.
- (2) The relatively low water content at 150–180 cm beneath *A. desertorum* near the fissure was consistent with a combined influence of fissure-facilitated drainage and deep-root water uptake. Because root water uptake, deep drainage flux, and water-source partitioning were not measured independently, their respective contributions cannot be separated from the present dataset.

3.4. Associations Between Pore Architecture and Eco-Hydrological Variables

As shown in Table 4, the sand content of all treatments exceeded over 92.50%. Such an extremely uniform texture excluded the dominant interference of mechanical composition on hydrological variations (the correlations in Table 5 were all non-significant, $p > 0.05$).

Table 4. Soil physical properties and mechanical composition in the 10–20 cm active layer.

Surface Cover Type	Distance from Fissure (cm)	Total Porosity (%)	Capillary Porosity (%)	Non-Capillary Porosity (%)	Bulk Density (g cm ⁻³)	Sand (%)	Silt (%)	Clay (%)
BSCs	20	40.85±0.85 ^a	16.50±1.20 ^a	24.35±1.80 ^a	1.39±0.02 ^c	93.50±0.45 ^c	6.35±0.40 ^a	0.15±0.05 ^a
	50	39.80±0.95 ^a	15.40±1.15 ^{ab}	24.40±1.50 ^a	1.44±0.02 ^{bc}	96.80±0.25 ^b	3.15±0.20 ^b	0.05±0.05 ^{ab}
	100	39.15±1.10 ^a	13.50±1.25 ^{ab}	25.65±1.00 ^a	1.50±0.03 ^{ab}	97.50±0.20 ^{ab}	2.48±0.18 ^{bc}	0.02±0.02 ^b
	200	37.50±1.45 ^a	11.20±1.55 ^b	26.30±1.20 ^a	1.58±0.05 ^a	98.50±0.50 ^a	1.50±0.50 ^c	0.00 ^b
<i>Poa annua</i>	20	39.85±0.80 ^a	17.85±0.80 ^a	22.00±0.60 ^a	1.38±0.02 ^b	97.50±0.25 ^c	2.45±0.20 ^b	0.05±0.05 ^a
	50	38.80±0.90 ^a	16.30±0.85 ^a	22.50±0.50 ^a	1.41±0.02 ^{ab}	100.00 ^a	0.00 ^d	0.00 ^b
	100	38.45±1.50 ^a	15.00±1.40 ^a	23.45±0.80 ^a	1.44±0.03 ^{ab}	98.50±0.30 ^b	1.50±0.28 ^c	0.00±0.00 ^b
	200	37.80±2.10 ^a	13.80±1.80 ^a	24.00±1.20 ^a	1.48±0.04 ^a	96.50±0.60 ^d	3.48±0.58 ^a	0.00±0.00 ^b
<i>Artemisia desertorum</i>	20	48.50±0.85 ^a	17.15±1.10 ^a	31.35±1.90 ^a	1.40±0.08 ^a	93.20±0.20 ^d	6.70±0.18 ^a	0.10±0.02 ^a
	50	40.50±0.75 ^b	16.95±0.80 ^a	23.55±1.40 ^b	1.42±0.04 ^a	95.30±0.10 ^c	4.68±0.08 ^b	0.02±0.02 ^b
	100	36.10±0.95 ^c	15.50±0.40 ^{ab}	20.60±1.10 ^b	1.43±0.03 ^a	98.20±0.10 ^b	1.80±0.10 ^c	0.00 ^b
	200	34.50±1.50 ^c	13.80±0.50 ^b	20.70±1.30 ^b	1.47±0.04 ^a	100.00 ^a	0.00 ^d	0.00 ^b
Bare land	20	41.50±1.20 ^a	15.50±1.60 ^a	26.00±2.50 ^a	1.46±0.05 ^a	92.50±0.55 ^c	7.35±0.50 ^a	0.15±0.05 ^a
	50	39.50±0.95 ^{ab}	13.10±1.40 ^{ab}	26.40±1.50 ^a	1.49±0.04 ^a	96.50±0.30 ^b	3.45±0.28 ^b	0.05±0.02 ^b
	100	38.30±0.85 ^{ab}	12.00±0.95 ^{ab}	26.30±1.00 ^a	1.53±0.03 ^a	98.50±0.10 ^a	1.50±0.10 ^c	0.00 ^b
	200	37.10±1.10 ^b	11.20±0.90 ^b	25.90±1.50 ^a	1.58±0.04 ^a	96.00±0.40 ^b	3.90±0.35 ^b	0.00 ^b

Note: According to the USDA soil texture classification system, particle sizes are defined as follows: clay (<0.002 mm), silt (0.002–0.05 mm), and sand (0.05–2 mm). Data are presented as mean ± standard error (SE). Different lowercase letters within the same column indicate significant differences among treatments at the $p < 0.05$ level.

Table 5. Pearson correlation analysis between soil eco-hydrological parameters and micro-pore structural properties.

Parameters	Total Porosity	Capillary Porosity	Non-Capillary Porosity	Bulk Density	Sand	Silt	Clay
Initial infiltration rate	0.662 **	0.750 **	0.169	−0.687 **	−0.436	0.438	0.432
Steady infiltration rate	0.691 **	0.802 **	0.16	−0.741 **	−0.443	0.445	0.429
Average infiltration rate	0.664 **	0.797 **	0.133	−0.740 **	−0.44	0.442	0.436
Average evaporation	0.615 *	0.818 **	0.06	−0.765 **	−0.332	0.335	0.31

Note: * indicates a significant correlation at the $p < 0.05$ level; ** indicates a highly significant correlation at the $p < 0.01$ level.

Taking the microhabitat of *A. desertorum* (20 cm near-fissure zone) with the most intense infiltration as an example: under the combined action of biological pore expansion by its thick roots and the mechanical tension of the fissure, the non-capillary porosity dominating rapid preferential flow leakage surged to an astonishing 31.35%, the total porosity climbed to 48.50%, and the soil bulk density was compressed to the lowest extreme of 1.40 g/cm³.

The Pearson correlation coefficient matrix in Table 5 provided a statistical association for this mechanistic deduction: the initial infiltration rate, steady infiltration rate, and cumulative daytime water loss all exhibited extremely significant positive correlations with total porosity ($r = 0.615$ * to 0.691) and capillary porosity ($r = 0.750$ to 0.818); conversely, they showed extremely significant negative correlations with soil bulk density, which reflects soil compactness ($r = -0.687$ to -0.765).

4. Discussion

4.1. Spatial Attenuation and Threshold Boundaries of Fissure-Induced Eco-Hydrological Disturbances

The two-way ANOVA further confirmed that fissure distance and surface-cover type independently affected infiltration and daytime water-loss variables. However, the interaction term was not significant for these hydrological variables, suggesting that the direction of distance-dependent change was broadly consistent among the four surface-cover types. In contrast, significant interaction effects for total porosity and non-capillary porosity indicate that surface-cover types modified the pore-structure response to fissure proximity. Therefore, the observed hydrological patterns should be interpreted as the combined outcome of distance-related fissure disturbance and cover-type-related soil structural differences, rather than as evidence of a single dominant mechanism.

In arid and semi-arid ecosystems, moisture is the primary driving force maintaining system structure and function. Ground tensile fissures induced by longwall coal mining thoroughly disrupt the original hydrological homeostasis of the vadose zone [11,22]. Strong evidence from this study demonstrates that tensile ground fissures trigger significant leakage-chimney dual effects at the micro-scale [13,15,18]. The in situ measured spatial gradient data of infiltration and daytime micro-lysimeter water loss in this study (Table 1, Figures 3 and 4) provide conclusive quantitative empirical evidence for these dual hydrological disturbance effects.

The present observations bracketed a spatial transition interval between 100 and 200 cm under the studied sandy-soil conditions. The data revealed that the hydrological disturbance of the fissure did not spread indefinitely but followed a non-linear spatial decay pattern: its severely impacted zone was highly concentrated in the 0–50 cm near-fissure band, attenuated significantly at 100 cm, and basically fell back to the far-fissure reference level zone with relatively weak direct fissure influence from direct mechanical tension at 200 cm. This finding corrects the extensive cognition in previous macroscopic studies that “treated the entire subsidence area as a homogeneous moisture-depleted zone,” providing extremely valuable measured parameters for defining boundary conditions in mine hydrogeological models and establishing safe distances for ecological restoration [7,20].

4.2. Eco-Hydrological Trade-Offs: Divergent Adaptive Strategies of Plant–Soil Systems

Faced with extreme moisture leakage and evaporative stress induced by fissures, pioneer vegetation with different root architectures exhibited diametrically different eco-hydrological adaptation strategies by remodeling microscopic pore structures. This discovery based on measured profile data constitutes the core scientific breakthrough of this study.

(1) Potential eco-hydrological trade-offs associated with deep-rooted shrubs:

The lower deep-soil water content observed beneath *A. desertorum* indicates a potential eco-hydrological trade-off associated with deep-rooted vegetation in near-fissure habitats. The pattern may result from the combined effects of enhanced preferential drainage through fissure- and root-associated macropores and water uptake by deep roots [12,14]. However, the present measurements do not permit quantitative partitioning of these two processes. Therefore, deep-rooted shrubs should be considered cautiously in severely fissured zones, while their long-term effects require verification using root-distribution measurements, sap-flow monitoring, and stable-isotope tracing [31,32].

(2) Hydrological responses and potential moisture-buffering role of BSC-covered surfaces:

Compared with vascular-plant-covered plots, BSC-covered plots generally exhibited relatively low steady infiltration rates and cumulative daytime water loss (Table 1; Figures 3 and 4). These results indicate that BSC-covered surfaces were associated with restricted water entry and reduced atmospheric water loss under the measured summer conditions. Previous studies have attributed similar hydrological responses to crust-induced changes in near-surface pore connectivity, EPS production, microbial filaments, surface roughness, and aggregate stability [33,34].

However, the present study did not measure crust thickness, EPS content, microbial composition, mycelial density, aggregate stability, surface roughness, or hydrophobicity. Therefore, the specific biological–physical pathways responsible for the observed hydrological responses cannot be directly determined from the current dataset. The relatively low infiltration and daytime water loss should be interpreted as being consistent with a potential surface-sealing and moisture-buffering effect, rather than as direct evidence of EPS-mediated pore sealing or a complete evaporation barrier.

4.3. Implications for Spatially Differentiated Restoration in Semi-Arid Mine Areas

The observed distance-dependent hydrological responses suggest that restoration practices in semi-arid mining areas should consider microhabitat heterogeneity around ground fissures. However, because the present study was based on short-term summer observations at a single study site, the following implications should be regarded as provisional and site-specific rather than general prescriptions.

Areas within approximately 100 cm of the fissure may be treated as potentially strongly affected zones. In these near-fissure zones, large-scale planting of high-water-use deep-rooted shrubs such as *A. desertorum* should not be recommended as a default restoration practice until longer-term soil-water consequences are evaluated. Conservation of existing BSC-covered surfaces and the use of shallow-rooted drought-tolerant herbs may be considered for surface stabilization, but their effectiveness should be tested through site-specific restoration trials.

The 100–200 cm interval may be regarded as a transition zone requiring site-specific assessment. Deep-rooted semi-shrubs may be considered only after evaluating soil texture, antecedent moisture, fissure morphology, vegetation water demand, and long-term soil-water storage. Because distances beyond 200 cm were not tested, the spatial extent of fissure influence should not be generalized beyond the experimental gradient used in this study.

4.4. Limitations and Future Perspectives

The present study represents a process-oriented summer snapshot rather than an annual eco-hydrological assessment. Micro-lysimeter observations were limited to 08:00–18:00 on one sunny day; therefore, nighttime vapor exchange, condensation, and seasonal variability were not captured. Moreover, soil evaporation and plant transpiration were not independently partitioned. The 200 cm treatment was a far-fissure reference within the

subsidence area rather than an unmined control, and the independent effects of regional subsidence and local fissuring could not be fully separated.

Because continuous measurements of precipitation, canopy interception, litter storage, transpiration, groundwater exchange, and deep drainage were unavailable, a complete water-balance analysis could not be performed in the present study. Consequently, the enhancement coefficients proposed here should be regarded as relative indicators of fissure-induced hydrological amplification rather than direct estimates of seepage fluxes or chimney-evaporation fluxes.

5. Conclusions

Based on short-term in situ measurements along fissure-distance gradients and soil profiles to 180 cm depth, this study examined the responses of soil infiltration, daytime micro-lysimeter water loss, soil moisture distribution, and pore structure to mining-induced ground fissures and surface-cover types in a semi-arid coalfield. The core conclusions are as follows:

- (1) The observations bracketed a spatial transition interval between 100 and 200 cm, rather than establishing a universal threshold.
- (2) Pore-structure variables were closely associated with infiltration and daytime water-loss patterns. Initial infiltration rate, steady infiltration rate, and cumulative daytime micro-lysimeter water loss were positively correlated with total porosity and capillary porosity and negatively correlated with soil bulk density. These relationships indicate that pore architecture and soil compactness were important factors associated with the observed hydrological responses, although causal pathways require further verification.
- (3) Near-fissure plots covered by the deep-rooted shrub *A. desertorum* exhibited relatively low soil water content at 150–180 cm. This pattern may reflect the combined effects of fissure-facilitated drainage and root water uptake, whose respective contributions could not be separated.
- (4) BSC-covered plots exhibited relatively low steady infiltration rates and cumulative daytime water loss under the measured summer conditions, suggesting a potential moisture-buffering role. However, because crust thickness, EPS content, microbial composition, and other surface structural properties were not measured, the underlying biological–physical mechanisms remain to be verified.
- (5) The observed patterns provide a preliminary basis for spatially differentiated restoration. Conserving existing BSC-covered surfaces and shallow-rooted herbs may be considered as a provisional strategy in near-fissure zones. However, the hydrological effectiveness of BSC conservation and restoration should be validated through long-term, multi-season, and site-specific field trials before being adopted as a general management measure.

Author Contributions: Conceptualization, methodology, writing, investigation, resources, C.G.; software, data curation, validation, formal analysis, visualization, Z.S., R.H. and J.G.; project administration, M.G.; funding acquisition, Q.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Open Fund of State Key Laboratory of Water Resource Protection and Utilization in Coal Mining, grant number No. GJNY-23-37-13.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article.

Acknowledgments: During the preparation of this manuscript, the authors used OpenAI's ChatGPT image-generation function, for which specific version information was not displayed in the user interface, to assist in preparing some schematic elements of Figure 2, including the soil profile, plant root systems, and representative landscape/background features. The photographs of the field instruments included in Figure 2 were taken by the authors. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: Author Ruimin He was employed by the company CHN Energy Shendong Coal Group Co., Ltd., and authors Mei Guo and Qingguo Song were employed by the company Aimoli (Hebei) Technology Co., Ltd. The remaining 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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