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Dynamic changes in the rhizosphere soil of *Davidia involucrata* induced by tunnel construction in a nature reserve

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Introduction: The rapid advancement of tunnel engineering in mountainous
nature reserves may pose disturbance risks to ecosystem stability and rare
plant habitats.

Methods: This study investigated the *Davidia involucrata* tunnel of the Naqing
Expressway by establishing four comparative plots: a wild *Davidia involucrata*
community, a *D. involucrata* community above the tunnel, a cultivated
D. involucrata community, and a community of other dominant tree species
above the tunnel. We characterized community structure of the nationally
protected species *D. involucrata* and monitored temporal dynamics of
rhizosphere soil nutrients (N, P, and K), electrical conductivity (EC), and pH.

Results: Results showed that (1) the *D. involucrata* community above the tunnel
exhibited relatively high species richness, with diversity and evenness indices
among the highest across the four plot types, suggesting stage-specific
community adjustment under construction-related disturbance; (2) across
different control comparisons, the relative changes in rhizosphere N, P, and K
were not directionally consistent, and were expressed as shifts in nutrient
composition and stoichiometric proportions, indicating distinct nutrient
backgrounds between construction-affected sites and natural/cultivated
conditions; (3) The pH of rhizosphere soil associated with *D. involucrata* above
the tunnel was generally near neutral, ranging from approximately 7.00–7.81. EC
showed no consistent directional change across control comparisons, but
fluctuated in the time-series data, indicating stage-specific variation in
rhizosphere soil physicochemical indicators during monitoring. (4) Across the
three comparisons, the cumulative explanatory rates of the first two principal
components for overall soil variation were 98.78%, 99.02%, and 98.49%,
respectively. PERMANOVA indicated distinguishable differences in multivariate
soil properties among comparison groups ($R^2 = 0.7568 - 0.8255$, $p < 0.001$).

Discussion: Overall, under tunnel construction, the rhizosphere soil of
D. involucrata differed from that of control plots in integrated soil
characteristics. These responses were mainly reflected in combined changes
involving N, P, and K nutrient stoichiometry, pH, and EC. It is therefore
recommended that, during tunnel construction and subsequent ecological
management in nature reserves, plant community structure surveys be

integrated with long-term monitoring of rhizosphere soil indicators, including N, P, K, pH, and EC, to improve identification of habitat changes and targeted conservation management of rare plant rhizosphere habitats.

KEYWORDS

Davidia involucrata, dynamic changes in rhizosphere soil, nature reserve, plant community diversity, tunnel construction

1 Introduction

With the rapid expansion of global infrastructure, linear projects such as tunnels are increasingly implemented in and around nature reserves, exerting profound impacts on ecosystem structure and function. By altering topography, hydrological processes, and soil conditions, these projects directly disturb ecosystem stability, reshape plant growth environments, and ultimately threaten species within protected areas (Liu et al., 2017; Wilson et al., 2016). In ecologically sensitive regions, tunnel construction can be especially detrimental to rare and endangered plants, becoming a prominent challenge for global biodiversity conservation. Infrastructure development and biodiversity protection are often planned and executed in isolation, yet their outcomes are tightly linked. Effective governance therefore requires strengthened impact avoidance during site selection and early-stage planning, complemented by subsequent mitigation and restoration measures. Balancing infrastructure expansion with ecosystem integrity has thus become a key issue in conservation policy research (Kyle and van Rees Charles, 2023).

The dove tree (*Davidia involucrata*), a Tertiary relict species, is widely distributed in the humid subtropical montane forests of China and was among the first plants listed as nationally protected (Class I) (Song et al., 2024; Xiang et al., 2000). Owing to limited propagule sources and strict habitat requirements, it is regarded as a “living fossil” and holds high research value in biology, ecology, and endangered-species conservation (Jin et al., 2019; Su et al., 2016). Its root growth is highly sensitive to soil moisture, nutrient availability, and microbial communities; consequently, the rhizosphere soil environment is a critical determinant of plant health (Ning et al., 2022; Philippot et al., 2009).

In recent years, as tunnel projects have expanded into reserves and their surrounding areas, the soil environment of *D. involucrata* habitats has faced unprecedented pressure. Existing studies show that tunnel construction not only disrupts surface and shallow soil structure, but also modifies soil water movement, groundwater dynamics, and soil physicochemical properties. Empirical evidence indicates that groundwater leakage and drainage associated with tunneling can markedly reduce soil moisture in affected zones, while increasing soil pH and bulk density, leading to soils that are drier, more alkaline, and more nutrient-poor—changes that further undermine soil ecosystem functioning and stability (Wang et al., 2019). Tunnel-induced disturbance can also alter soil aggregate structure, organic carbon fractions, and their stability, thereby affecting organic matter cycling and reshaping the distribution of carbon and other nutrients in soils (Yu et al., 2025). In addition, exposed construction surfaces and microenvironmental shifts caused by soil disturbance may trigger complex responses in soil microbial communities and nutrient pools, disrupting rhizosphere conditions and slowing ecosystem recovery (He et al., 2024). At present, research has examined the

ecological impacts of tunnel construction—particularly tunnel drainage and groundwater drawdown—from multiple perspectives, mainly in three areas. First, disturbances to ecosystem structure and functioning, including changes in groundwater systems and hydrological processes, with cascading effects on surface ecosystems through soil–vegetation coupling (Lv et al., 2020). Second, shifts in soil moisture and soil physicochemical–biological properties—such as carbon pools and enzyme activities—that in turn affect soil functions and plant growth conditions (Cagri et al., 2021; Sibo et al., 2023; Wang et al., 2023). Third, biodiversity risks associated with tunnels and other linear transport infrastructure, including habitat fragmentation, reduced connectivity, and heightened risks to population persistence (Rafael et al., 2021; Zhang et al., 2015).

However, most of these studies emphasize broad-scale ecological patterns or general plant communities. Research on *Davidia involucrata* has mainly focused on community distribution, genetic diversity, morphological characteristics, and habitat adaptability. Studies on community ecology have primarily examined its population distribution patterns, associated plant composition, and niche characteristics (Ye et al., 2021; Zhang et al., 2020). Genetic studies have mainly revealed its population genetic structure, genetic diversity, and the basis for defining conservation units (Li and Du, 2025). Morphological and physiological ecological studies have focused on morphological variation, seedling regeneration, and responses to environmental factors such as light and water availability (Zhang et al., 2019). In addition, a limited number of studies have begun to explore the relationship between its growth and habitat conditions from the perspectives of rhizosphere microorganisms or soil microenvironment (Wang et al., 2026). However, relatively few studies have addressed the dynamic responses of rhizosphere soil physicochemical properties, nutrient stoichiometry, and community structure of *D. involucrata* under the disturbance of linear engineering projects such as tunnel construction. This limitation constrains the scientific support for coordinated management between engineering construction and rare plant conservation. Overall, despite significant progress in understanding the impacts of tunnel construction on ecosystems and soils, research focusing on the dynamic effects on the rhizosphere soil of rare plants remains scarce. Consequently, this study investigated the *Davidia involucrata* (dove tree) tunnel of the Naqing Expressway in Guizhou, China. Representative plots were established across wild populations, areas directly overlying the tunnel, cultivated stands, and adjacent dominant plant communities. Analyze changes in plant community richness, diversity, and evenness under the background of tunnel construction, explore the stage-specific adjustment characteristics of community composition across different plot types, and provide an interpretive discussion in relation to the intermediate disturbance hypothesis. The spatial distribution characteristics of rhizosphere soil electrical conductivity, pH, and nitrogen, phosphorus, and potassium nutrients were quantitatively analyzed to explore changes

TABLE 1 Specific locations of the rare plant *Davidia involucrata* above the tunnel.

Item	X coordinate	Y coordinate	Elevation (m)	Chainage	Tunnel bore	Offset distance (m)
<i>Davidia involucrata</i>	2,958,495.5	511,629.6	1713.118	K14 + 349	Right bore	317

in nutrient composition and stoichiometric relationships under the background of tunnel construction. Time-series monitoring and coefficient of variation (CV) analysis were used to examine stage-specific fluctuations in rhizosphere soil indicators, while principal component analysis (PCA) was applied to describe differences in the multivariate combinations of rhizosphere soil properties among different plots.

2 Materials and methods

2.1 Selection and overview of the research area

This study was conducted at the Tunnel along the Nayong–Qinglong Expressway. The tunnel is located in western Guizhou Province, China (26°90'N, 105°39'E), and passes through the Nayong County Provincial *Davidia involucrata* Nature Reserve. It is a separated extra-long tunnel characterized by high gas content. For the right bore, the chainage ranges from YK16 + 512 to YK21 + 635, with a total length of 5,123 m and a maximum overburden depth of 238 m; for the left bore, the chainage ranges from ZK16 + 527 to ZK21 + 660, with a total length of 5,133 m and a maximum overburden depth of 248 m. The Nayong County Provincial *D. involucrata* Nature Reserve is one of the important ecological conservation areas in Southwest China and is often referred to as a “green pearl”. The reserve features diverse topography and supports rich plant resources and animal populations. *D. involucrata* is one of its characteristic dominant species and is listed as a rare and endangered plant. The reserve was established to protect this unique ecosystem, maintain suitable habitats for *D. involucrata*, and promote biodiversity conservation and sustainable development; consequently, the site is subject to stringent ecological, environmental, and soil-and-water conservation requirements. In this study, the wild *D. involucrata* stands were located above the construction tunnel, with specific locations provided in Table 1.

The geological conditions in the study area are complex, primarily due to coal-measure strata and mined-out (goaf) areas. Villages are densely distributed around the tunnel, some sections are shallow-buried, and the construction schedule is tight. Tunnel construction may cause a range of adverse impacts on the natural environment, including land disturbance, soil pollution, water contamination, habitat degradation, noise and vibration, and air pollution. To mitigate these impacts, construction adopted measures such as short advance lengths, controlled blasting, strong support, and early closure. Smooth blasting techniques were applied during excavation to reduce surface settlement. When groundwater was encountered, advance pre-grouting was implemented to prevent large-scale infiltration of surface water. Therefore, construction of the Tunnel must be carried out with great caution, fully considering the ecological importance and vulnerability of the nature reserve.

2.2 Overview of the tunnel project

The Tunnel is located within Yongxi Town, Nayong County. The access roads near the tunnel portals are convenient, providing good transportation conditions. The site lies within an erosion–denudation low-to-middle mountain geomorphic unit. The tunnel entrance in the construction area is situated on a V-shaped valley slope, with a hillside gradient ranging from 40° to 56°. The tunnel crosses a ridge, with a maximum elevation of 1,988.8 m. At the exit portal, the terrain forms a gentle slope with natural gradients of 13°–20°. Within the project study area, elevation ranges from 1,602.0 m to 2,149.8 m, yielding a relative relief of 547.8 m. Along the tunnel alignment, elevation ranges from 1,700.0 m to 2,010.4 m, with a relative relief of 310.4 m. The tunnel portals are shown in Figure 1.

2.3 Plot establishment and community survey

Within the nature reserve, four plots were selected according to the distribution of *Davidia involucrata*, and plant communities were classified into four types: (i) wild *D. involucrata* communities; (ii) non-*D. involucrata* plant communities located above the tunnel; (iii) artificially cultivated *D. involucrata* communities; and (iv) *D. involucrata* communities located above the tunnel. The criteria and principles for plot selection were as follows. For the wild *D. involucrata* communities, areas with relatively aggregated wild *D. involucrata* individuals were selected within the reserve. For the non-*D. involucrata* communities above the tunnel, plots were established above the tunnel and in close proximity to the *D. involucrata* communities located above the tunnel. For the artificially cultivated *D. involucrata* communities, plantation stands of *D. involucrata* within the reserve were selected. For the *D. involucrata* communities above the tunnel, plots were centered on wild *D. involucrata* individuals occurring directly above the tunnel.

Vegetation surveys were conducted for each of the four community types. Each plot measured 30 m × 30 m. Basic surveys were performed for trees, shrubs, and herbs within each plot. For the tree layer, information on community type, species composition, and abundance distribution was recorded within the plot, and the number of trees was counted. For the shrub and herb layers, information on community type, species composition, and abundance distribution was recorded within the plot.

2.4 Instrument-based monitoring

Following the preliminary field survey, long-term continuous monitoring was conducted to better characterize the growth status of *Davidia involucrata*. A representative *D. involucrata* individual located at tunnel chainage K14.703 was selected as the focal target, and its growth condition was tracked systematically and comprehensively. For comparative analysis, three additional plots

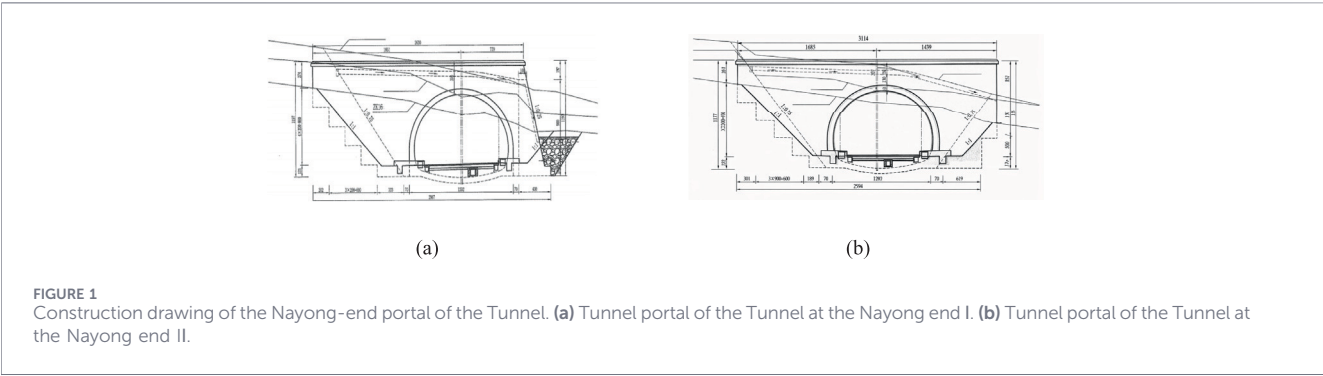


TABLE 2 Monitoring arrangement for each sample plot.

No.	Plot type	Monitored plant	Monitoring indicators	Monitoring period
1	<i>D. involucrata</i> community above the tunnel	Wild <i>Davidia involucrata</i> located above the tunnel at chainage K14.703	Soil K, N, and P contents, pH, electrical conductivity (EC)	1 October 2023–31 January 2024
2	Other plant community above the tunnel	Wild <i>Quercus</i> spp.		1 October 2023–31 October 2023
3	Artificially cultivated <i>D. involucrata</i> community	Artificially cultivated <i>Davidia involucrata</i>		1 November 2023–30 November 2023
4	Wild <i>D. involucrata</i> community	Wild <i>Davidia involucrata</i>		31 December 2023–31 January 2024

were established, and representative plants within these plots were selected for concurrent monitoring. Synchronous monitoring was carried out during the period from September 2023 to 31 January 2024, with a 1-month monitoring campaign conducted within this interval.

During monitoring, real-time data were collected using high-precision instruments, ensuring comprehensive and accurate characterization of soil environmental conditions while effectively reducing human disturbance. The monitoring indicators included soil potassium (K), nitrogen (N), and phosphorus (P) contents, as well as pH and electrical conductivity (EC). These variables are key environmental determinants of plant growth: potassium is involved in plant water regulation, nitrogen promotes photosynthesis, and phosphorus supports root development. Soil pH and EC are directly related to nutrient uptake efficiency and soil salinity status, thereby influencing overall plant health. Monitoring these soil indicators enables a comprehensive assessment of soil health and its suitability for *D. involucrata* growth. The monitoring data are provided in Table 2.

2.5 Data processing

Plant community data were entered into Excel 2016, and important values, diversity indices (Simpson and Shannon–Wiener indices), and evenness (Pielou index) were calculated. During a 24-h monitoring period, plant growth and environmental variables were recorded at fixed hourly time points, including stem water potential, stem inflow and stem outflow, soil potassium (K), nitrogen (N), and phosphorus (P) contents, and soil pH. After daily data were collected via the instrument data app, the

dataset was first preprocessed by removing outliers, and the mean value of each indicator across all time points within a day was calculated. The processed data were analyzed as follows: After organizing the dataset by monitoring time, comparative boxplots of each indicator were generated in Origin 2021. After sorting the dataset by monitoring time, time-series line plots (indicator vs. time) were produced in Origin 2021. In Excel 2021, the overall coefficient of variation (CV) for each indicator was calculated for each comparison group; CV values were then calculated separately for days 0–10, 11–20, and 21–30. In Canoco 5.0, A higher CV value indicates greater fluctuation of the corresponding indicator during the monitoring period and relatively lower temporal stability, whereas a lower CV value indicates smaller fluctuation and relatively higher temporal stability. Fourth, before PCA, EC, N, P, K, and pH were standardized to minimize the influence of differences in measurement units and value ranges among soil indicators on the ordination results. PCA was then performed for each comparison group using Canoco 5.0.

3 Results and analysis

3.1 Plant community characteristics in the *Davidia involucrata* nature reserve

3.1.1 Richness and evenness indices

As shown in Table 3: According to the survey results, the *Davidia involucrata* community above the tunnel possesses the

TABLE 3 Species richness and evenness indices of plant communities.

Indicators	Community type	Tree layer	Shrub-herb layer	Total richness
Species richness	Wild <i>Davidia involucrata</i> community	6	6	12
	Other plant community above the tunnel	9	7	16
	Artificially cultivated <i>D. involucrata</i> community	4	10	14
	<i>D. involucrata</i> community above the tunnel	10	11	21
	Mean value	7.25	8.5	
Pielou index	Wild <i>Davidia involucrata</i> community	0.8820	0.8820	0.8820
	Other plant community above the tunnel	1.3230	1.0290	1.176
	Artificially cultivated <i>D. involucrata</i> community	0.5880	1.4700	1.029
	<i>D. involucrata</i> community above the tunnel	1.4700	1.6170	1.5435
	Mean value	1.06575	1.2495	

TABLE 4 Species diversity indices.

Simpson					Shannon-Wiener				
No.	Community type	Tree layer	Shrub-herb layer	Diversity	No.	Community type	Tree layer	Shrub-herb layer	Diversity
1	Wild <i>Davidia involucrata</i> community	0.8444	0.5657	0.7048	1	Wild <i>Davidia involucrata</i> community	1.859	1.11	1.4295
2	Other plant community above the tunnel	0.8857	0.5645	0.7251	2	Other plant community above the tunnel	2.253	1.329	1.791
3	Artificially cultivated <i>D. involucrata</i> community	0.5901	0.5765	0.5833	3	Artificially cultivated <i>D. involucrata</i> community	1.077	1.419	1.203
4	<i>D. involucrata</i> community above the tunnel	0.9044	0.6573	0.78085	4	<i>D. involucrata</i> community above the tunnel	2.38	1.588	1.984
Mean value		0.80615	0.5912		Mean value		1.8922	1.6018	

highest total species richness (21 species) among the four plant communities, with richness in the tree layer and shrub-herb layer at 10 and 11, respectively, indicating diverse plant species and a complex community structure in this area. This is followed by other plant communities above the tunnel and the wild *D. involucrata* community, while the cultivated *D. involucrata* community has the lowest richness at only 14 species. This pattern illustrates that areas with less anthropogenic interference exhibit greater community heterogeneity, whereas areas with intense human intervention tend toward species uniformity. Regarding evenness, the *D. involucrata* community above the tunnel shows the most balanced species distribution, with an overall evenness index of 1.5435, where the shrub-herb layer reached the highest evenness (1.6170) and the tree layer also performed well (1.4700). Conversely, the wild *D. involucrata* community had the lowest evenness (0.8820), likely due to competitive suppression by the dominant species, *D. involucrata*. Overall, the evenness of the shrub-herb layer is generally higher than that of the tree layer, indicating that *D. involucrata*, as a dominant

tree species, holds a clear leading position in natural communities. This result reflects that while *D. involucrata* occupies a strong ecological niche under natural conditions, its dominance may also inhibit the balanced development of other species within the community.

3.1.2 Diversity index analysis

As shown in Table 4, the survey results indicate that the diversity indices of the *Davidia involucrata* community above the tunnel are the highest among the four community types, with a Shannon-Wiener index of 1.984 and a Simpson index of 0.78085, significantly higher than those of the wild community (1.4295), other plant communities above the tunnel (1.791), and the cultivated community (1.203). Specifically, the diversity indices for both the tree layer and the shrub-herb layer in this community performed exceptionally well, suggesting that despite engineering in-terference, the area above the tunnel has formed a rich species composition and a relatively balanced distribution pattern in the short term. This

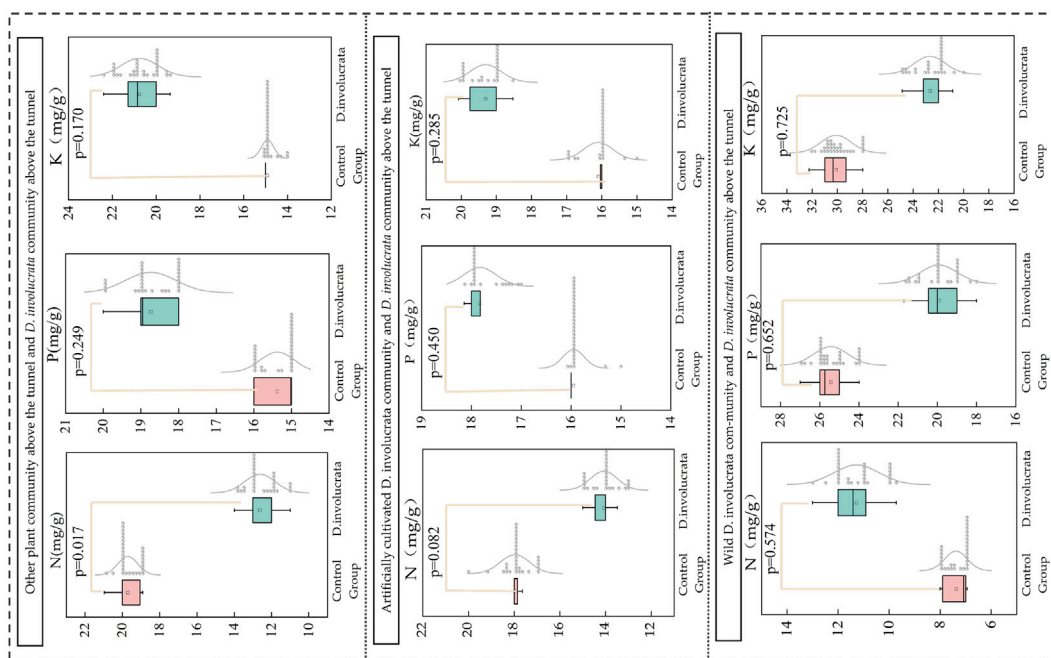


FIGURE 2
Boxplots of soil nutrient indicators across comparison groups during tunnel construction.

phenomenon reflects that after tunnel construction, clear species reorganization occurred in the region, exhibiting characteristics of secondary succession. The increase in diversity may be promoted by local micro-environmental changes following soil disturbance—such as enhanced light intensity and restructured resource allocation—thereby attracting more pioneer species into the community. However, the decline in the dominance of *D. involucreta* within the community indicates that its intra-specific competitiveness has been weakened in complex habitats. In contrast, while the cultivated community was planted with *D. involucreta*, it exhibits lower diversity due to species uniformity and a simple structure; this further suggests that under the influence of human management and intervention, the community structure remains relatively simple with poor ecosystem stability. The wild community, meanwhile, possesses high stability but a closed structure. In summary, although the high diversity of the *D. involucreta* community above the tunnel holds certain ecological restoration potential.

3.2 Distribution characteristics of soil indicators across comparison groups during tunnel construction

3.2.1 Distribution characteristics of soil nutrient indicators across comparison groups during tunnel construction

As shown in Figure 2: Compared to other dominant tree species above the tunnel, the rhizosphere soil of *Davidia involucreta* above the tunnel exhibits lower nitrogen content but higher phosphorus and potassium levels; this indicates that under the same context of tunnel construction disturbance, the soil nutrient composition in

the rhizosphere of *D. involucreta* differs distinctly from that of coexisting dominant species, suggesting that rhizosphere nutrient performance is inconsistent across species and exhibits interspecific variation under construction conditions. Compared to cultivated *D. involucreta*, the nitrogen content of those above the tunnel is also lower, while phosphorus and potassium levels are higher; this demonstrates that the soil nutrient composition and stoichiometric ratios in the rhizosphere of *D. involucreta* under field construction conditions differ from those under cultivated conditions, indicating a consistent discrepancy in the soil nutrient background between the field environment and artificial management. Under different control comparisons, the relative levels of N, P, and K in the rhizosphere soil of *Davidia involucreta* above the tunnel were not consistent. Compared with wild *D. involucreta*, the above-tunnel *D. involucreta* showed relatively higher N but lower P and K contents. In contrast, compared with cultivated *D. involucreta*, it showed relatively lower N but higher P and K contents. This indicates that the construction-related influence was mainly reflected in adjustments to soil nutrient composition and stoichiometric relationships, rather than synchronous changes in a single nutrient element. Integrating the above comparisons, it is evident that the impact of tunnel construction is not merely reflected in unidirectional changes of individual nutrient concentrations, but more prominently in the adjustment of soil nutrient stoichiometric relationships, thereby altering the nutrient equilibrium of the *D. involucreta* rhizosphere soil; under the context of construction disturbance, the *D. involucreta* rhizosphere is characterized by shifts in soil nutrient composition rather than synchronous changes in all elemental concentrations, indicating that construction impacts primarily manifest at the level of soil nutrient composition.

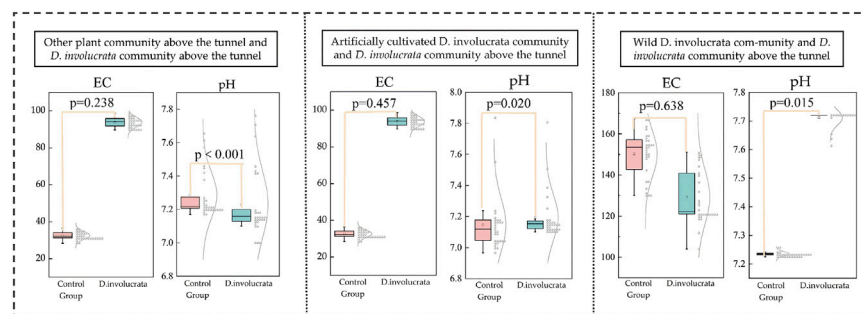


FIGURE 3
Boxplots of soil electrical conductivity and pH across comparison groups during tunnel construction.

3.2.2 Distribution characteristics of soil electrical conductivity and pH across comparison groups during tunnel construction

Figure 3 shows that the electrical conductivity (EC) exhibits a large overall range (30–150), with numerical changes showing both significant increases and decreases across the three comparison types. The pH values generally fall near neutral (approximately 7.0–7.75), where one comparison type shows a decrease while others show an increase, reaching a maximum of 7.7. Regarding EC, the direction of change across the three pairs of comparisons is inconsistent; furthermore, the overlap between boxplots and scatter distributions for each group is substantial, indicating that the inter-group differences in EC are not prominent relative to intra-group dispersion. For pH, a clearer shift in central tendency is observed in all three comparison pairs; notably, in the third comparison, the centers of the two groups are further apart and the distribution of the *Davidia involucrata* group above the tunnel is more concentrated, suggesting that the inter-group separation for pH is generally stronger than that for EC. While EC did not reach statistical significance in any of the three comparisons ($p > 0.05$), pH achieved statistical significance across all three ($p < 0.05$). The rhizosphere soil EC exhibits certain fluctuations in magnitude between different subjects, but these changes lack a consistent direction across comparisons and remain within a similar range without a unified trend of increase or decrease. This suggests that under concurrent monitoring conditions, the overall level of soluble ions in the rhizosphere soil primarily reflects inherent soil differences. Conversely, rhizosphere soil pH exhibits clear and consistent differences across different subjects, maintaining a stable relative positioning in multiple concurrent comparisons. This indicates that the acidity or alkalinity of the rhizosphere soil does not fluctuate randomly.

3.3 Time-series characteristics of soil indicators across comparison groups during tunnel construction

3.3.1 Time-series characteristics of soil nutrient indicators across comparison groups during tunnel construction

Figure 4 indicates that in the comparison between wild *Davidia involucrata* and those above the tunnel, nitrogen exhibited

continuous fluctuations over time, with one curve showing an initial decline followed by a recovery, while the other primarily showed minor oscillations with a slight increase at the end. Potassium showed an upward trend during the fluctuation process followed by a decline, whereas phosphorus exhibited a slow upward trend during fluctuations before leveling off with a slight decrease. This suggests that under the context of tunnel construction disturbance, the temporal variation patterns of soil nutrients for *D. involucrata* in the construction area have diverged from those in natural habitats, with the response to the construction environment manifesting at the level of nutrient dynamic processes. In the comparison between other dominant tree species above the tunnel and *D. involucrata* above the tunnel, nitrogen showed a slow upward trend amidst fluctuations before transitioning to a more stable oscillatory state; potassium generally exhibited a downward trend during fluctuations with a certain recovery at the end; and phosphorus generally showed a downward trend during fluctuations, gradually moving toward a more stable state of change. This indicates that under identical tunnel construction conditions, the temporal nutrient responses of different plant types to construction disturbance are inconsistent, reflecting differences in how construction impacts are expressed in the rhizospheres of different species. In the comparison between cultivated *D. involucrata* and those above the tunnel, nitrogen declined after the monitoring began, followed primarily by fluctuations and gradual stabilization, with a slight decrease at the end; for potassium, one curve showed a slow upward trend during fluctuations, while the other rose after a decline and entered a relatively stable oscillatory state; phosphorus experienced a single decline during the monitoring process, after which it maintained fluctuations and gradually stabilized. This demonstrates that the temporal variation process of rhizosphere soil nutrients for *D. involucrata* under the tunnel construction environment differs from that under cultivated conditions, reflecting the sustained influence of field construction conditions on nutrient dynamics.

3.3.2 Time-series characteristics of soil nutrient indicators across comparison groups during tunnel construction

Figure 5 indicates that in the comparison between wild *Davidia involucrata* and those above the tunnel, electrical conductivity (EC) exhibited continuous fluctuations over time, with one curve showing

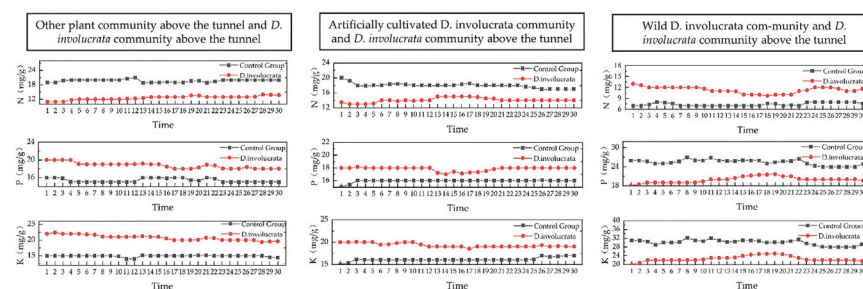


FIGURE 4
Time-series plots of soil nutrient indicators across comparison groups during tunnel construction.

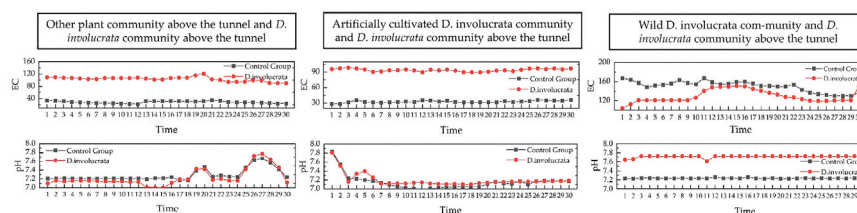


FIGURE 5
Time-series plots of soil electrical conductivity and pH across comparison groups during tunnel construction.

an overall initial decline followed by a recovery, while the other gradually increased during fluctuations and leveled off in the mid-to-late stages; pH variations over time were small, with one curve remaining relatively stable and the other leveling off after a slight increase during fluctuations. This suggests that under the context of tunnel construction disturbance, the temporal variation patterns of rhizosphere soil physicochemical properties for *D. involucrata* in the construction area have diverged from those in natural habitats, with the response to the construction environment manifesting primarily in dynamic processes rather than instantaneous states. In the comparison between other dominant tree species above the tunnel and *D. involucrata* above the tunnel, EC generally showed a slow upward trend amidst fluctuations accompanied by minor oscillations; pH exhibited a gradual upward trend during fluctuations and entered a relatively stable state in the later monitoring stages. This indicates that under identical tunnel construction conditions, the temporal variation patterns of rhizosphere soil physicochemical properties for different plant types are inconsistent, reflecting differences in how construction disturbance is expressed in the rhizospheres of different species. In the comparison between cultivated *D. involucrata* and those above the tunnel, EC declined in the early monitoring period, followed by a gradual recovery and stabilization amidst fluctuations; pH entered a state of continuous fluctuation after an initial decline and gradually stabilized in the later period. This demonstrates that the temporal variation process of rhizosphere soil physicochemical properties for *D. involucrata* under the tunnel construction environment differs from that under cultivated conditions, reflecting the sustained influence of field construction conditions on the dynamic characteristics of the rhizosphere soil.

3.4 Variability characteristics of soil indicators across comparison groups during tunnel construction

Table 5 shows that in the comparison between wild *Davidia involucrata* and those above the tunnel, the coefficient of variation (CV) of each index for the experimental and control groups exhibited periodic changes across different time intervals. Specifically, the experimental group showed higher levels of fluctuation in certain indices during the early and late stages while remaining relatively low in the middle stage, whereas the control group presented a variation pattern that was not fully synchronized with the experimental group across different time periods. This indicates that, under the background of tunnel construction disturbance, the temporal fluctuation characteristics of rhizosphere soil physicochemical properties of *Davidia involucrata* in the construction area differed from those in the natural habitat. These fluctuations varied across different monitoring stages, suggesting stage-specific changes in rhizosphere soil indicators during the monitoring period under the construction background. In the comparison between other dominant tree species above the tunnel and *D. involucrata* above the tunnel, the CV of each index for the experimental and control groups displayed different stage-wise combinations over time; fluctuations in some indices intensified during certain periods while tending toward relative stability in others, and the rhythm of change between the two groups was inconsistent. This indicates that, under the same tunnel construction conditions, the rhizosphere soil physicochemical properties associated with different plant types differed in temporal fluctuation patterns.

TABLE 5 Coefficients of variation (CV) of soil indicators across comparison groups during tunnel construction.

	Experimental group					Control group				
	EC	K	N	P	pH	EC	K	N	P	pH
Tunnel-overlying <i>D. involucrata</i>						Wild <i>D. involucrata</i>				
Overall CV	0.121	0.057	0.081	0.048	0.003	0.074	0.040	0.059	0.034	0.001
Days 1–10 C V	0.052	0.033	0.031	0.020	0.004	0.037	0.028	0.053	0.023	0.001
Days 11–20 C V	0.044	0.036	0.051	0.032	0.004	0.034	0.020	0.032	0.018	0.002
Days 21–30 C V	0.075	0.031	0.055	0.017	0.000	0.062	0.044	0.050	0.037	0.001
Tunnel-overlying <i>D. involucrata</i>						Other plant community above the tunnel				
Overall CV	0.068	0.041	0.065	0.036	0.028	0.121	0.019	0.027	0.030	0.019
Days 1–10 C V	0.018	0.023	0.040	0.026	0.002	0.123	0.004	0.021	0.030	0.001
Days 11–20 C V	0.053	0.026	0.035	0.027	0.022	0.123	0.029	0.038	0.028	0.014
Days 21–30 C V	0.046	0.022	0.031	0.019	0.034	0.125	0.015	0.019	0.025	0.023
Tunnel-overlying <i>D. involucrata</i>						Artificially cultivated <i>D. involucrata</i>				
Overall CV	0.028	0.023	0.042	0.018	0.021	0.063	0.026	0.036	0.013	0.024
Days 1–10 C V	0.027	0.012	0.033	0.003	0.031	0.068	0.023	0.038	0.022	0.035
Days 11–20 C V	0.023	0.012	0.028	0.021	0.002	0.051	0.000	0.011	0.000	0.005
Days 21–30 C V	0.021	0.005	0.000	0.000	0.001	0.048	0.028	0.027	0.002	0.004

TABLE 6 PCA explained variance and PERMANOVA results for rhizosphere soil indicators among different comparison groups.

Group	PC1 explained variance (%)	PC2 explained variance (%)	Cumulative explained variance (%)	PERMANOVA R^2	p value
Above-tunnel <i>Davidia involucrata</i> – wild <i>Davidia involucrata</i>	91.23	7.55	98.78	0.8255	<0.001
Above-tunnel <i>Davidia involucrata</i> – other above-tunnel plants	80.46	18.56	99.02	0.7652	<0.001
Above-tunnel <i>Davidia involucrata</i> – cultivated <i>Davidia involucrata</i>	78.90	19.58	98.49	0.7568	<0.001

The effects of construction disturbance on the rhizosphere of different species did not follow a uniform temporal fluctuation pattern.

In the comparison between cultivated *Davidia involucrata* and those above the tunnel, the overall CV of the experimental group maintained a relatively consistent rhythm of change across all time periods, while the control group showed varying degrees of fluctuation adjustments in certain indices and time intervals. This indicates that the temporal fluctuation characteristics of rhizosphere soil physicochemical properties under tunnel construction site conditions differed from those under cultivated conditions, suggesting that rhizosphere soil indicators of *Davidia involucrata* exhibited a fluctuation pattern during the monitoring period that differed from that observed in the cultivated environment.

3.5 Principal component analysis of soil properties across comparison groups during tunnel construction

Table 6 shows that rhizosphere soil samples from different comparison groups exhibited a relatively clear separation trend in the PCA space. In the comparison between above-tunnel *Davidia involucrata* and wild *D. involucrata*, the explained variances of PC1 and PC2 were 91.23% and 7.55%, respectively, with a cumulative explained variance of 98.78%. In the comparison between above-tunnel *D. involucrata* and other above-tunnel dominant plants, PC1 and PC2 explained 80.46% and 18.56% of the variance, respectively, with a cumulative explained variance of 99.02%. In the comparison between above-tunnel *D. involucrata* and

cultivated *D. involucrata*, PC1 and PC2 explained 78.90% and 19.58% of the variance, respectively, with a cumulative explained variance of 98.49%. These results indicate that the first two principal components effectively summarized the overall variation in multiple rhizosphere soil indicators during the construction period.

Based on sample distribution, above-tunnel *D. involucrata* was separated from wild *D. involucrata*, cultivated *D. involucrata*, and other above-tunnel dominant plants in the PCA space, indicating that the integrated rhizosphere soil characteristics of *D. involucrata* under the tunnel construction background differed from those under natural habitat conditions, cultivated conditions, and the rhizosphere soils of other plants in the same construction-affected area. Combined with the variable loading results, EC, N, P, K, and pH all contributed to sample differentiation, suggesting that changes in rhizosphere soil under construction influence were not manifested as changes in a single indicator, but rather as a combined response of multiple physicochemical and nutrient indicators.

The PERMANOVA permutation test showed that the R^2 values of the three comparisons were 0.8255, 0.7652, and 0.7568, respectively, with p values all less than 0.001, further indicating distinguishable differences in multivariate soil characteristics between above-tunnel *D. involucrata* and the corresponding control groups. Overall, the PCA and PERMANOVA results jointly indicate that the rhizosphere soil environment of *D. involucrata* underwent integrated changes under the background of tunnel construction, mainly reflected in changes in the combined characteristics of EC, N, P, K, and pH, rather than independent changes in a single soil factor.

4 Discussion

4.1 Effects of tunnel construction on the diversity and structure of *Davidia involucrata* communities

The four plots exhibited relatively pronounced differences in plant community diversity and structural attributes. The data indicate that the *Davidia involucrata* community above the tunnel had the highest species richness (21 species), and its Shannon–Wiener index (1.984) and Simpson index (0.78085) were both higher than those of the other three plot types. In terms of spatial structure, this plot showed a relatively balanced allocation of species richness between the tree layer and the shrub–herb layer, reflecting a more even inter-layer composition. In contrast, although the wild *Davidia involucrata* plot displayed typical characteristics of a natural forest, it had the lowest evenness index (0.8820); the plot dominated by other species above the tunnel showed intermediate diversity; whereas the cultivated plot exhibited comparatively lower diversity indices and relatively simple structural features. The high diversity and evenness observed in the *Davidia involucrata* plot above the tunnel may be associated with increased environmental heterogeneity induced by construction disturbance. According to the Intermediate Disturbance Hypothesis, moderate external disturbance can weaken the absolute competitive advantage of a single species, thereby providing opportunities for the coexistence of more species

(Connell, 1978; GRIME, 1973). In the plots above the tunnel, localized habitat alterations during construction may have released vertical space and improved understory light conditions, which may, to some extent, alleviate the suppression of interspecific competition commonly caused by canopy closure of the dominant *Davidia involucrata* in wild plots (SEIDL et al., 2011). Such reorganization of resource patterns may facilitate the selective establishment of species occupying different niches, thereby resulting in a richer species composition during the survey period (A. et al., 2022).

By contrast, due to the lack of external disturbance, the wild plot may have developed a relatively closed understory environment as *Davidia involucrata* potentially maintained strong niche occupancy; such intense interspecific competition may constrain the persistence of associated species, leading to diversity values that are not the highest in horizontal comparisons. The cultivated plot, constrained by a single planting objective and frequent management interventions, artificially filters out non-target species, and thus its community self-regulation capacity and structural complexity may be lower than those of disturbed natural plots (Laurent et al., 2013). Overall, the physical disturbance associated with tunnel construction may have reshaped resource allocation within the plots at the spatial scale. Although the above-tunnel plot showed higher diversity levels in the data, the community's response to disturbance and its stability still require further evaluation based on monitoring data for importance values, canopy closure, light conditions, and soil properties (Hobbs and Huenneke, 1992).

4.2 Characteristics of the dynamic impacts of tunnel construction on rhizosphere soils of *Davidia involucrata*

Monitoring during the tunnel construction period indicated that rhizosphere soils among the different comparison groups exhibited marked differences in nutrient composition, physicochemical properties, and their dynamic trajectories. In terms of lateral distributions, compared with the other dominant tree species above the tunnel and the cultivated *Davidia involucrata*, *Davidia involucrata* above the tunnel showed lower nitrogen contents but higher phosphorus and potassium contents; whereas, relative to wild *Davidia involucrata*, it displayed an opposite pattern, with higher nitrogen and lower phosphorus and potassium. This indicates that the direction of nutrient changes in the rhizosphere soil of above-tunnel *Davidia involucrata* varied depending on the control group. Therefore, it should not be simply summarized as a unidirectional increase or decrease in a particular element, but rather understood as an adjustment in soil nutrient composition and stoichiometric relationships under the background of tunnel construction. Regarding physicochemical properties, electrical conductivity (EC) fluctuated within the range of 30–150, and the directions of change were inconsistent across the three pairwise comparisons; between-group differences were not significant ($p > 0.05$). Soil pH was generally near neutral (approximately 7.0–7.75); all three comparisons showed clear shifts in central tendency and reached significant differences ($p < 0.05$), indicating

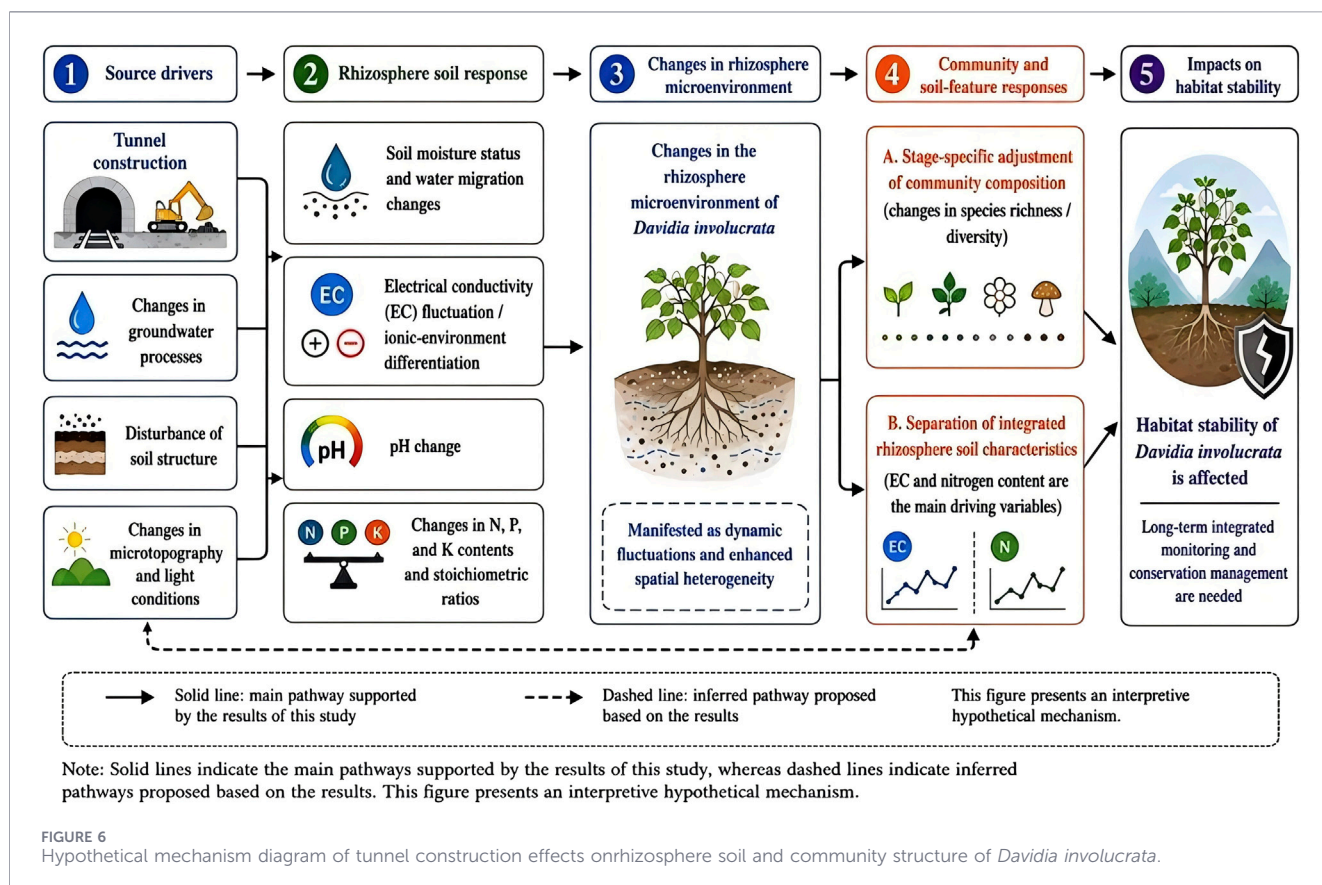
that differences in acidity/alkalinity were more stable. Time-series results showed that nutrients (N, P, and K) as well as EC and pH all exhibited stage-wise fluctuations, yet the trajectories differed among control relationships: the construction-area *Davidia involucrata* displayed differentiated dynamic responses relative to the wild community, co-located other dominant species, and cultivated conditions, indicating that construction disturbance is mainly reflected in “process-oriented changes” rather than a single time-point state. Volatility analysis further showed that the CV values of different indicators fluctuated in stages over time, and the variation patterns of the experimental and control groups were not fully synchronized. This indicates that the fluctuation characteristics of rhizosphere soil indicators differed among different objects during the monitoring period. Volatility analysis further showed that the CV values of different indicators exhibited stage-specific fluctuations over time, and the variation patterns of the experimental and control groups were not fully synchronized, reflecting differences in temporal stability among different objects. Principal component analysis showed that, across the three comparisons, the first two principal components effectively summarized the integrated differences in multiple rhizosphere soil indicators, with cumulative explained variances of 98.78%, 99.02%, and 98.49%, respectively. Above-tunnel *Davidia involucrata* was separated to some extent from wild *D. involucrata*, cultivated *D. involucrata*, and other above-tunnel dominant plants in the PCA space, indicating that the integrated rhizosphere soil characteristics of *D. involucrata* under the tunnel construction background differed from those under natural habitat conditions, cultivated conditions, and the rhizosphere soils of other plants in the same construction-affected area. Combined with the variable loading results, electrical conductivity, nitrogen, potassium, phosphorus, and pH all contributed to sample differentiation, among which electrical conductivity and nitrogen content made relatively greater contributions to the differences in sample distribution. These results indicate that changes in rhizosphere soil under the background of tunnel construction were mainly manifested as integrated differences formed by the combined responses of multiple physicochemical properties and nutrient indicators, rather than independent changes in a single indicator.

The stage-wise fluctuations and increased dispersion of rhizosphere soil physicochemical properties may be associated with the complex habitat stress formed under tunnel construction. Decoupling of water relations and EC differentiation: tunnel excavation may alter groundwater dynamics, thereby changing the coupling relationships among surface water, soil water, and groundwater and affecting the redistribution of surface-soil moisture (Si et al., 2021). Because EC is an important indicator reflecting ionic strength and is influenced by soil moisture status (Heiniger et al., 2003; Shea et al., 2004), the high dispersion of EC and its strong contribution on the PCA axis in this study suggest enhanced spatial heterogeneity of the rhizosphere solute environment under construction disturbance; whether this is attributable to uneven moisture distribution and localized solute concentration still requires further verification using data on soil moisture and/or groundwater level (Pedrera-Parrilla et al., 2016). Soil pH showed

significant differences among the comparison objects ($p < 0.05$), which may be related to changes in the acid–base buffering system induced by factors such as soil-layer disturbance and material inputs during construction. Changes in pH can alter the availability of nitrogen, phosphorus, and potassium by affecting ionic chemical forms (Heiniger et al., 2003; Neina, 2019), and thus may be associated with the observed differences in nutrient stoichiometric ratios. The persistent fluctuations in nutrient contents and the stage-wise variation in CVs (with enhanced variability in some periods) indicate that the dynamic response of the rhizosphere environment to the construction context is sustained and may involve time lags. Such asynchronous fluctuation patterns and shifts in nutrient stoichiometry suggest that the rhizosphere environment is undergoing disturbance-driven dynamic adjustment; the potential implications for the physiological homeostasis of *Davidia involucrata* still need to be evaluated in conjunction with plant physiological indicators (Tang et al., 2017; Yang et al., 2010).

Therefore, rather than directly assessing the effect of the construction process on a single soil indicator, the results of this study support interpreting the influence of tunnel construction on the rhizosphere soil environment from the perspective of an integrated multivariate response. Specifically, soil changes under the construction background were mainly manifested as an integrated shift involving EC, nitrogen content, and N, P, and K stoichiometric relationships.

In summary, changes in the rhizosphere environment of *Davidia involucrata* under the background of tunnel construction were characterized by multidimensional differences. The PCA results showed that the cumulative explained variances of the first two principal components in the three comparisons were 98.78%, 99.02%, and 98.49%, respectively, indicating that they effectively summarized the integrated differences in multiple rhizosphere soil indicators. Above-tunnel *D. involucrata* showed a certain degree of separation from wild *D. involucrata*, cultivated *D. involucrata*, and other above-tunnel dominant plants in the PCA space, indicating that the integrated rhizosphere soil characteristics of *D. involucrata* under the construction background differed from those under natural habitat conditions, cultivated conditions, and the rhizosphere soils of other plants in the same construction-affected area. Combined with the variable loading results, EC, N, P, K, and pH all contributed to sample differentiation, suggesting that the response of rhizosphere soil physicochemical properties under the construction background was not a uniform increase or decrease in a single indicator, but rather an integrated difference formed by the combined changes in multiple physicochemical properties and nutrient indicators. Meanwhile, the time-series and CV results showed stage-specific fluctuations in the indicators, suggesting that the rhizosphere soil environment was in a state of dynamic adjustment during the construction period. Overall, these results indicate that, under the background of tunnel construction, the underlying physicochemical habitat of the *D. involucrata* rhizosphere changed mainly in terms of integrated multivariate variation and nutrient stoichiometric adjustment. To further summarize these findings, Figure 6 was drawn as a mechanistic schematic diagram illustrating the integrated responses of the *D. involucrata* rhizosphere soil environment to tunnel construction disturbance.



4.3 Ecological implications of tunnel construction for habitat conservation of rare surface plants

The results of this study indicate that the impacts of tunnel construction on surface *Davidia involucrata* communities exhibit a complex pattern characterized by the coexistence of “increased macroscale diversity” and “microscale habitat fluctuations.” Although a certain degree of physical disturbance during the construction period may enhance community species richness and diversity by altering resource allocation and competitive structure, the stagewise fluctuation patterns reflected by rhizosphere soil indicators, the significant differences in pH among comparison groups, and the adjustments in nutrient stoichiometric relationships collectively suggest that the underlying habitat is undergoing dynamic adjustment. Based on the preliminary phenomena observed in this study, the results may provide the following reference considerations for the conservation of rare plants under similar engineering contexts in the future:

1. Establishing a multi-indicator monitoring system for rhizosphere soil: The multivariate analysis results of this study showed that the integrated rhizosphere soil characteristics of above-tunnel *Davidia involucrata* differed from those of the different control plots. Across the three comparisons, the cumulative explained variances of the first two principal components were 98.78%, 99.02%, and 98.49%, respectively, and the PERMANOVA results indicated

statistically significant differences in multivariate soil characteristics among groups. These results suggest that changes in the rhizosphere soil of *D. involucrata* under the background of tunnel construction were not determined by a single indicator, but were the result of the combined effects of multiple factors, including nutrient composition, acid–base conditions, and ionic environment (Ding et al., 2020; Gupta et al., 2019; Terrer et al., 2019). Therefore, in subsequent monitoring, N, P, K, pH, and electrical conductivity should be tracked and analyzed as an integrated indicator system, and combined with assessments of community structural changes to improve the identification of habitat changes for rare plants under the background of construction disturbance.

2. Focusing on the potential implications of shifts in rhizosphere nutrient stoichiometry for the long-term persistence of rare species: This study observed that, under different control comparisons, the relative directions of N, P, and K levels in rhizosphere soils were not consistent, and the overall pattern was more prominently expressed as changes in nutrient stoichiometric relationships, suggesting that construction disturbance may interfere with soil mineral nutrient cycling processes. Based on ecological stoichiometry theory, persistent shifts in nutrient ratios may, over long time scales, influence the nutritional balance and regeneration potential of rare plants (Terrer et al., 2019; Wang et al., 2025). Therefore, in subsequent management of habitats affected by construction,

strengthened tracking of soil N:P and N:K ratios is recommended. If follow-up monitoring further confirms stable nutrient limitation or supply imbalance, small-scale, low-intensity adjustments of phosphorus and potassium fertility and substrate improvement measures may be explored, on the premise of not damaging native soil structure and microhabitats, to help alleviate uneven nutrient supply potentially induced by soil-layer disturbance (Raphael et al., 2024).

3. Viewing disturbance-driven diversity gains dialectically and strengthening long-term stability monitoring: Although this study documented a stage-wise increase in community diversity during the construction period, the dynamic fluctuation characteristics revealed by time-series and variability analyses suggest that such gains may have a certain degree of transience and uncertainty (Shea et al., 2004). Conservation practice should not rely solely on short-term increases in diversity as the only criterion for judging habitat recovery success. Considering that changes in the rhizosphere environment may involve lag effects, future work should place greater emphasis on the quality of transitions from post-disturbance stages toward relatively stable stages. By reducing secondary disturbances from subsequent engineering activities to local pH and ionic environments, and by integrating sustained soil-vegetation joint monitoring, long-term ecological stability of habitat reconstruction can be promoted, thereby increasing the probability of long-term persistence of rare species such as *Davidia involucrata* under dynamic succession.

In addition, this study has certain limitations. It is mainly based on stage-specific monitoring and comparative analyses during the construction period; the monitoring duration is relatively limited and thus insufficient to fully reveal long-term successional trajectories of disturbance effects and potential lag responses. It should also be noted that the discussion in this study regarding groundwater changes, soil moisture redistribution, and microbial processes is mainly based on existing literature and the observed changes in soil physicochemical indicators in this study. These interpretations represent potential mechanistic explanations rather than direct measurement results. Future studies should further verify these mechanisms by incorporating indicators such as soil moisture content, groundwater level, microbial communities, and enzyme activities. In the future, extending continuous monitoring before, during, and after construction, and supplementing a more complete set of physicochemical and biological indicators, may improve the explanatory power of the results and their value for guiding conservation management.

5 Conclusion

Under the background of tunnel construction, the key characteristics of changes in the rhizosphere soil of *Davidia involucrata* include adjustments in N, P, and K stoichiometric relationships rather than simple increases or decreases in individual elements; significant and relatively stable differences in pH among different control plots; and PCA results indicating that EC

and nitrogen content were the main variables associated with the integrated separation of samples, which may serve as key indicators for subsequent monitoring. Community diversity remained relatively high during the investigation period, which may reflect stage-specific adjustment, but its persistence still requires verification through long-term monitoring. With respect to nutrient distribution, compared with the cultivated community and the community of other dominant plants above the tunnel, the rhizosphere soils of *D. involucrata* above the tunnel showed, in certain indicators, lower nitrogen contents but higher phosphorus and potassium contents, indicating differences in nutrient composition relative to the control objects; whereas, relative to the wild *D. involucrata* community, an opposite pattern was observed, with higher nitrogen and lower phosphorus and potassium. This suggests that the nutrient background and stoichiometric relationships in the construction area are not consistent with those in the natural habitat, and that the differences are more prominently reflected in adjustments of nutrient composition and stoichiometric relationships rather than uniform, same-direction changes in the contents of individual elements. Regarding EC and pH, EC showed both increases and decreases across different control relationships and generally remained within a similar interval; between-group differences did not reach statistical significance ($p > 0.05$). However, EC displayed high dispersion and stage-wise fluctuations in the time series, suggesting pronounced spatial heterogeneity and dynamism of the rhizosphere ionic environment. Soil pH was overall near neutral (approximately 7.0–7.75) and exhibited statistically significant differences among the different control objects ($p < 0.05$), indicating relatively stable differences in acidity/alkalinity. Multivariate analysis showed distinguishable differences in the integrated rhizosphere soil characteristics among different plots. The first two principal components explained most of the overall variation in soil indicators, indicating that changes in the rhizosphere soil of *Davidia involucrata* under the background of tunnel construction were mainly manifested as integrated differences formed by the combined effects of multiple physicochemical properties and nutrient indicators, rather than independent changes in a single indicator.

Overall, community diversity of *D. involucrata* remained at a relatively high level during the survey period under the tunnel construction context, suggesting that community composition may undergo stage-specific adjustment under disturbance, although the persistence of this pattern requires validation through long-term monitoring. At the soil level, construction effects are more likely manifested as a dynamic adjustment process in rhizosphere physicochemical properties and nutrient stoichiometry, rather than a uniform upward or downward trend in a single indicator; the time-series and variability results suggest that the rhizosphere environment is in a disturbance-driven dynamic state. For conservation and management practice, it is recommended that the linkages between surface plant community changes and rhizosphere soil microenvironments be fully considered during engineering implementation and ecological restoration: on the one hand, optimize construction organization and disturbance control to minimize secondary disturbance to topsoil structure and local physicochemical conditions; on the other hand, continuously track changes in rhizosphere soil ratios such as N:P and N:K, and, when necessary, explore targeted, small-scale, low-intensity phosphorus and potassium fertility adjustments

or substrate improvement measures to alleviate potential nutrient supply imbalance. In addition, based on the multivariate analysis results of this study, a long-term integrated monitoring system for rhizosphere soil could be established, covering indicators such as N, P, K, pH, and electrical conductivity. This system would enable continuous tracking of the integrated rhizosphere soil characteristics of *Davidia involucrata* and habitat evolution trends under the background of tunnel construction, thereby providing practical references for timely regulatory measures and for safeguarding the habitat quality of *D. involucrata* and other rare plants.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZL: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. SL: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. BL: Conceptualization, Data curation, Methodology, Project administration, Resources, Validation, Writing – original draft, Writing – review and editing. BO: Conceptualization, Investigation, Methodology, Project administration, Writing – original draft, Writing – review and editing. ZH: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing.

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